Conservation Easement Acquisitions Amidst Localized Spillover Effects in Grassland Conversions: Analysis using Remotely-Sensed Data

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Abstract

We evaluate the cost-effectiveness of grassland easement acquisitions towards conservation of native grasslands in the Prairie Pothole Region of the United States. We focus on the permanent grassland conversions in North Dakota during 1997-2016 and in eastern South Dakota during 2006-2016. Our spatio-temporal analysis suggests that the region's existing croplands and grasslands occur as large, contiguous tracts and the permanent grass conversions occurred in proximity of the crop-intensive areas. We conjecture that localized spillovers exist in this region's land use decisions and develop a game-theoretic framework that allows evaluating past easement allocations in the presence of strategic complementarities among private landowners. Easement allocations are more cost-effective when acquired as contiguous tracts and on lands that provide weak cropping incentives, e.g. poor soils. We test for the presence of localized spillovers by estimating hazard rate of conversion from a duration model. We find that higher grass density inhibits conversion in its locality, and that easements are strategic complements to grasslands in reducing the conversion risk. The fact that past easements were acquired as relatively large tracts and on poorer quality soils is encouraging because our analytical findings suggest that such easement acquisitions were cost-effective.

Introduction

The U.S. Prairie Pothole Region (PPR) is a biodiversity-rich ecosystem sustained by its mixed-prairie grasslands and wetlands. The perennial grasses generate ecosystem services, provide nesting and breeding habitat for the local waterfowl species, and allow for livestock production. On the east of the Missouri River in North and South Dakota there exists a grass-crop frontier along the western fringes of the Western Corn Belt (WCB, see figure 1). Grasslands enhance agricultural productivity by sustaining the regional soil quality. Dakota's grasslands are a valuable natural resource largely under private ownership and are subject to conversion when crop returns are high. Almost 670,000 acres of grasslands were converted to corn/soy cultivation between 2006 and 2011 (Wright & Wimberley 2013). Past economic analyses suggest that several factors drive grassland conversions in the PPR including commodity prices, soil quality (Rashford et al. 2010; Wang et al. 2016), neighborhood cropping-density (Stephens et al. 2008), technology and crop insurance policies (Wang et al. 2016). Incentive-based land retirement policies exist to motivate the PPR's private landowners to conserve their grasslands.

Conservation easements are a key policy tool of the U.S. Fish and Wildlife Service (FWS) and its partner agencies to protect remaining grasslands in the PPR. Under this policy, landowners voluntarily enter a perpetual contract with the agency to give up their right to cultivate in lieu of a one-time payment, while retaining ownership of the land. The FWS raised Duck Stamp funds and acquired about 2.3 million acres of grassland easements since the 1950s (U.S. GAO, 2007), 80% of which lie in the Dakotas (FWS, 2011; Walker et al. 2013). The FWS plans to enroll additional 12 million acres in future in order to sustain the region's grassland bird habitat. However, at the current rate with insufficient funds the agency might not reach its goal for another 150 years (U.S. GAO, 2007). Such budget constraint impediments are even greater when land values are rising, as they have been in the Dakotas where only 30% of lands could be eased during 2008-'12 relative to 1998-2012 with similar fund allocation (Walker *et al.* 2013). U.S. GAO (2007) recommended acquiring low cost, high-priority habitat, whereby, for example, FWS could have conserved 50% more land in 2006. Rashford et al. (2010) and Stephens et al. (2008) too made similar recommendations.

Various aspects of the incentive-based conservation policies, including the conservation easements, have been analyzed in the literature that are relevant for this study. Walker et al. (2013) recently reported that past easement acquisitions focused mainly on the abundance of waterfowl breeding pairs in the Dakotas' PPR (see figure 2). The authors spatially categorized the remaining grasslands in the PPR based on the land's ecological value, soil quality and cost of acquisition. They subsequently ranked land parcels into categories I-III such that the 'highest duck-pair density, highest conversion risk and least costly' lands are in category-I and should be placed on the highest acquisition priority among other parcels. However, this scheme would lead to fragmented conservation of ecological reserve (see pp. 275 figure 7 in Walker et al. 2007). This is suboptimal in terms of deriving ecological benefits as connected habitats are considered more beneficial for sustaining higher biodiversity as compared to the isolated habitats (Johnson et al. 2010; van Nouhuys, 2009). Braza (2017) found cultivation rates on existing easements to be 15% lower between 2001 and 2006 when compared to their matched counterfactuals.

Miao et al. (2016) recently developed a two-period model to evaluate landowners' willingness to accept towards easing their lands in a dynamic setting of their conversion decisions. Their findings suggested that acquiring easements when landowners are uncertain about cropping/grazing returns should be avoided as their willingness to accept would be high in such a scenario even when their propensity to convert would be low.

Johnson et al. (2010) have identified large, contiguous patches of remnant prairie that would allow conserving the PPR's grassland bird population. The importance of conserving such contiguous spatial habitat arrangement for specie-protection has also been recognized in the economics literature. Economists have proposed agglomeration bonuses to promote voluntary conservation of contiguous parcels through land retirement policy. Drechsler et al. (2010) found that a policy that provides a premium towards newly retired lands that border previously conserved reserves generates efficiency gains relative to the spatially homogenous conservation payments. Parkhurst et al. (2002) suggested that agglomeration bonus would enhance the chances of conserving contiguous habitat reserves, whereas a no-bonus scenario always lead to fragmented habitat reserves.

In this paper, we study grassland conversions and the role of easements when land use related returns (costs and benefits) are spatially dependent in a locality. We conjecture that local spillovers exist from the advent of more cropped land in an area such that the spatially connected cropland will provide higher cropping incentives than the same amount of spatially separated land. When more cropland emerges in a locality the cropping costs may decline as more agricultural services and related infrastructure like tillage equipment, tillage entrepreneurs and input suppliers enter the area. Similarly, higher density grassland in the area may inhibit conversions as the cost of grass-based production would be lower than crop-based production. So strategically placed easements could complement grass acres in an area and disrupt the network of croplands to inhibit further conversion. In that sense, we extend the conservation targeting literature by examining the effectiveness of easement acquisitions when grassland conversions are dependent on the localized spillovers on a parcel's cost of conversion.

To the best of our knowledge, ours is the first study to consider the role of networks in conservation planning by easement acquisitions. We first develop a conceptual model with strategic complementarities among farmers who are deciding upon 'convert to crop' or 'stay in grass' options. We present analytical results as well as simulations of land use decisions when social spillovers are present in landowner payoff function. We compare the welfare effects of acquiring spatially connected easements from when the agency acquires easements in isolation. We then conduct an empirical analysis to test for the existence of social spillovers in the region's land use dynamics. We employ remote sensing tools and implement a hazard modelling framework to estimate the risk of permanent grass conversion to crop. We evaluate how the risk of conversion varies local grass-density and the presence of easements.

This paper is divided into several sections. We first discuss our empirical and economic basis for considering strategic complementarities in the Dakotas' land use decisions. We then present a game-theoretic model of permanent grassland conversions and the related analytical results on the role of easements, followed by simulation results. We then underline our empirical strategy, present our estimation results, and conclude with a brief discussion.

Spatial Spillovers in Grassland Conversions: Motivation

Our conjecture that localized spillovers exist in Dakotas' land use conversion decisions is based on an exploratory analysis of this region's past land use changes. Spatially-delineated pixel-level imagery from USDA's Cropland Data Layers (CDL) characterize land use for North Dakota (ND) during 1997-2016 and for South Dakota (SD) during 2006-2016. We condense this pixel-level land use time-series into two categories: crop (c) and grass (g) for the eastern portions of ND and SD, which overlaps with the Prairie Pothole Region. Thereafter, all possible sequences of pixel-level transitions between c and g are characterized between every consecutive year, i.e., *c* to *c*; *c* to *g*; *g* to *c*; or *g* to *c*, leading to a set of 2^{20} (2^{11}) unique possible combinations during 1997-2016 (2006-2016) in eastern ND (SD). To characterize long-term changes we focus on three specific combinations: always crop (C); always grass (G); and permanent grass to crop conversion (GC). The GC category represents North Dakota pixels, for example, that were *g* in 1997, underwent a single transition to *c*, and remained in *c* thereafter. We map C, G, GC transitions in the eastern Dakotas along with the past US Fish and Wildlife Service's (USFWS) easement allocations in figure 1 below.

The descriptive analysis suggests that 2 million acres (7 million acres) of permanent croplands or category C in eastern ND (SD) during 1997-2016 (2006-2016). Among the permanent grasslands or category G, a total of 485,000 acres (2.5 million acres) were present in eastern ND (SD) during 1997-2016 (2006-2016). Among permanent conversions or the GC switches, 57,000 acres (600,000 acres) of these occurred in eastern ND (SD) during 1997-2016 (2006-2016). A noticeable characteristic is that while C and G seem to resemble large, contiguous tracts, GC switches occurred in proximity of permanent croplands. Moreover, easements seem to have been allocated near permanent grasslands, away from the observed permanent conversions. This seems to suggest that easements were allocated in localities where lands did not convert anyway. These observations signify the scope in accounting for network effects in studying grassland conversions and evaluating the efficiency of existing easements.

The observed spatial conformity in landowner choices towards crops or grass and GC transitions being proximate to the existing croplands lead us to conjecture that these production systems exhibit strategic complementarity. That is, higher cropping density in an area seems to incentivize more cropping, and likewise higher grasses seem to have lowered the incentive to crop. The economic argument for such conformity is that strategic complementarity exists in the cost of production among neighboring landowners. To formally express cost complementarity we denote a price-taking farmer *i*'s profit from producing quantity q_i as $\pi_i = pq_i - C(q_i, q_j, w)$ where *p* is price of output, and $C(.)$ is the cost of production that depends on q_i, average local output q_j, and input price *w*. Crop complementarity exists when *i*'s marginal cost is decreasing in local output level, i.e. $\partial^2 C / \partial q_i \partial q_j < 0$. The plausible scenarios of cost complementarity are when cropping attracts grain elevators, ethanol plants better roads, insurance agents and entrepreneurs, which in turn attract more cropping since costs are lowered as access to demand terminals and supporting services increases.

Conceptual Model

Our conceptual framework is motivated from the binary choice model proposed by Brock and Durlauf's (2001) who utilized a statistical mechanical structure to account for average group behavior in the utility maximization problem. A mathematical connection was drawn between the localized interactions among atoms on a lattice that yield magnets and social interactions among decision-makers in a socioeconomic setup to determine aggregate economic outcome (Durlauf, 1999). The authors adapted a mean-field version of the Curie-Weiss model of ferromagnetism that yielded analytical solution of the average group behavior at equilibrium for an interconnected population. The Curie-Weiss model is an advanced version of a simpler and more popular statistical mechanical model, called the Ising model (Ellis, 1985 Ch. IV). The Ising model accounts for pairwise interactions among neighbors rather than the mean group behavior in Curie-Weiss model, and yet both models provide qualitatively similar results (Ellis, 1985). The mean-field version was developed to facilitate analytical solution for the many-body systems on four-or higher dimensional lattices. Ours is a two-dimension lattice with heterogeneous grassland owners distributed across the eastern Dakotas so we choose to adapt the Ising model.

The Ising model offers many advantages over the earlier implemented framework. Social spillovers from an agent's actions are only localized and all of his/her designated neighbors may not be neighbors to each other. Our modelling framework allows for interactions among multiple neighborhoods through nodal agents to generate equilibrium strategies, while Brock and Durlauf (2001) analyzed one neighborhood at a time as the population. Furthermore, pairwise interactions allow simulating the game's Nash equilibria using a simple algorithm on a standard statistical package. Model extensions that incorporate heterogeneous agents and analyze easement allocations are more tractable with pairwise interactions among agents.

We model permanent grass conversions as a one-shot simultaneous move game among non-cooperative landowners with localized spillovers from grass conversions on neighboring lands. Formally, a representative agent *i* among *I* grassland owners decides between 'stay in grass' and 'convert to crop' options. Each individual player's binary choice set is denoted as $a_i \in \{-1,1\}$, where $-1 \triangleq$ stay in grass and $1 \triangleq$ convert to crop. The overall strategy set is denoted as $a = \prod_{i \in I} a_i$, while the set containing strategies for players other than i is denoted as $a_{-i} = (a_1, a_2, ..., a_{i-1}, a_{i+1}, ..., a_{I-1}, a_I)$. To characterize localized spillovers among neighbors we define set $N_i \in I$ containing agent *i*'s neighbors such that $\# N_i = n_i$. Finally, the game's payoff function is denoted as $\pi(a) = (\pi_i(a_i, a_{-i}))_{i=1}^{I}$ with $\pi_i(a_i, a_{-i})$ defined as

$$\pi_i(a_i, a_{-i}) = \pi_i(a_i) + \sum_j \sigma_{ij}(a_i, a_j); \; a_j \subseteq a_{-i}, \; j \in N_i, \; i, j \in I \tag{1}$$

The total payoff for individual *i* from action a_i in equation (1) is assumed to be the sum of a private payoff component, $\pi_i(a_i)$, and a social payoff component of localized spillovers from pairwise interactions among neighbors, $\sigma_{ij}(a_i, a_j)$. We define $\pi_i(1) = \pi_i^c$ and $\pi_i(-1) = \pi_i^g$. This private component is likely to be dependent on tract-level soil quality, weather, access to the region's transport infrastructure and demand-terminals, whereas the social payoff component is derived from *i*'s pairwise-interaction with his/her neighbors. For strategic complementarity to hold *i*'s payoff function must satisfy the property of increasing differences in each neighbor's choice, i.e. $\sigma_{ij}(1,1)-\sigma_{ij}(-1,1)>\sigma_{ij}(1,-1)-\sigma_{ij}(-1,-1) \ \ \forall\, j\in N_i,\ i,j\in I$. In other words, converting to crop will yield a higher payoff when neighbors too follow, else there will be a penalty from converting when neighbors choose to stay in grass.

Agent *i* will choose action a_i only if $\pi_i(a_i,a_{-i})>\pi_i(-a_i,a_{-i})$, or

$$\pi(a_i)-\pi(-a_i)>-\sum_j(\sigma_{ij}(a_i,a_j)-\sigma_{ij}(a_i,a_j));\ j\in N_i,\ i,j\in I \tag{2}$$

To facilitate further insights on the agent's decision problem we define $\sigma_{ij}(a_i,a_j)=\sigma_1$ $a_i=a_j$ or σ_2 if $a_i\neq a_j$, where $\sigma_1>\sigma_2$ for the increasing differences property of strategic complementarity to hold. Hence, equation (2) becomes $\pi_i^c-\pi_i^g>-(\sigma_1-\sigma_2)n_i$. An alternative specification with $\sigma_{ij}(a_i,a_j)=Ja_ia_j$ and $J=(\sigma_1-\sigma_2)/2>0$ leads to identical ramifications for equation (2), only now with a single parameter *J* that is proportional to the difference in social payoffs from conforming to (σ_1) and defecting from (σ_2) each neighbor's action. Brock and Durlauf (2001) originally proposed this alternative specification with *J* but to account for average group-behavior, i.e., $\sigma_{ij}(a_i,a_j)=Ja_in_i^{-1}\sum_{j\in N_i}a_j$, in social payoffs. Likewise for notational simplicity, we too use this parameter to model pairwise interactions in our model.

We briefly discuss the existence and various properties of Nash equilibria. Generally, in case of one-shot simultaneous move games pure N.E. exists when each player's strategy set is complete, finite and compact, and $\pi_i(a_i,a_{-i})$ is continuous in (a_i,a_{-i}) and quasiconcave in a_i for all $i\in I$ (MWG, 1995 Ch. 8 pp. 253). Vives (1990) analyzed games with strategic complementarity using the lattice approach and reported that payoffs may not be quasiconcave for pure N.E. to exist. His analysis suggested that the set of pure N.E. is non-empty for such games when the payoff function is supermodular in the game's strategy set ($a = \prod_{i \in I} a_i$ here). The concept of supermodularity and increasing differences coincide when the game's strategy set a is a product of ordered sets (Topkis, 1978 Theorems 3.1-3.2; Vives, 1990). In this study the players' payoff functions exhibit strictly increasing differences and the strategy sets a_i too are (trivially) ordered for all *i*. Hence, pure N.E. exist for our permanent conversion game. Note that we do not need $\pi_i(a_i)$ to be linear in a_i unlike Brock and Durlauf (2001) to ensure the existence equilibria.

Vives (1990) also found that the set of pure N.E. consisted of the smallest and largest element from the game's strategy set, see Theorem 4.2 (i), which implies that all landowners staying in grass or converting to crop are candidate equilibria here. Echenique (2003) showed that in the games of strategic complementarity when individual strategy spaces are one-dimensional mixed strategy equilibria exist. Echenique and Edlin (2003) later found mixed strategy equilibria to be unstable, which reduce to the game's extremal equilibria when a player's beliefs about the opponents play are slightly wrong. Therefore, we focus on pure strategy N.E. for our analysis.

We now turn to characterizing Nash equilibria (N.E.) for this game. We present simulations to illustrate the analytical results for a special case where $I = 6$ and players are placed on a torus having three neighbors each (figure 4). Players $i = 1$, 2 and 3 are placed on the upper ring of the torus and $i = 4$, 5 and 6 on the lower ring. This structure of players' interconnectedness is hoped to provide richer illustrations of the game's equilibria compared to a circle, especially with heterogeneous players. A simple algorithm to simulate this game's pure N.E. on a statistical software package is provided in an appendix.

We next analyze grassland conversions with spatial spillovers for homogenous players having same private payoff towards cropping and staying in grass, followed by an extension to heterogeneous agents with differing private payoffs. We finally estimate a duration model to evaluate whether easement allocations impact grassland conversions when localized spillovers are present in land use decisions.

Homogeneous Players

Players are considered homogenous when the private costs of staying in grass and converting to crop are same across them. So we know from equation (2) suggests that agent *i* chooses action a_i if $\pi(a_i) - \pi(-a_i) > -2Ja_i \sum_j a_j;\ j \in N_i,\ i, j \in I$. A set of strategies are Nash equilibrium when none of the agents can improve their payoff by unilaterally updating their strategy. So here the N.E. is the set of strategies $\{a_i^*\}_{i=1}^{I}$ that satisfy the following condition

$$\frac{\pi(a_i) - \pi(-a_i)}{J} > -2a_i^* \sum_j a_j^* \quad \forall\ i, j \in I, j \in N_i \tag{3}$$

Equation (3) here is the equilibrium characterizing equation and notice that for every player *i* the only unknown is a_j, i.e., the neighbors' actions. Hence, we have our first result for this case.

R1: *When strategic complementarities exist among players with binary choices the N.E. is characterized by a ratio of the difference in the individual player's private payoffs from the two choices* ***to*** *the strength of strategic complementarity between the player and his/her neighbors*.

For notational convenience we denote $\pi(1)-\pi(-1)\triangleq\Delta\pi^{c,g}$ and $\pi(-1)-\pi(1)\triangleq\Delta\pi^{g,c}$ hereafter. An interesting implication of **R1** is that higher $\Delta\pi^{c,g}$ will have a similar consequence for the game's N.E. as would the lower *J* value, i.e., weaker spillover effects. Further, the right-hand-side (R.H.S) of equation (3) is bounded such that $-2a_i\sum_j a_j \in[-2n_i, 2n_i]$. This means that if the left-hand-side (L.H.S.) is greater than $2n_i$ then $a_i=1$ is the unique payoff maximizing choice for player *i*. Conversely, if $\text{L.H.S.} < -2n_i$ then $a_i=-1$ is the payoff maximizing strategy. An interpretation is that, given *J*, the landowners choose to crop (stay in grass) when the private payoffs towards cropping (grass-based land use) are strong enough to overcome any losses due to defecting from neighbors' actions. Since the bounds of R.H.S. in equation (3) are increasing in n_i we need $\Delta\pi^{c,g} > \max_i(2n_i)$ for all homogenous agents to convert to crop. Similarly, we need $\Delta\pi^{g,c} > \max_i(2n_i)$ (or $\Delta\pi^{c,g} < \min_i(-2n_i)$) for all agents to stay in grass.

In addition, when private payoffs are relatively weak this game may generate multiple equilibria. To see this let's consider a case where *J* is fixed and $0<\Delta\pi^{c,g}\le 2n_i$ for all *i*. Clearly, $a_i=1\ \forall i$ is still a N.E. because any unilateral deviation by a player by choosing to 'stay in grass' will decrease his/her total payoff due to the negative spillovers from all neighbors who convert and because the private payoff from cropping is relatively higher. However, in this case $a_i=-1\forall i$ too yields to a local maxima. Here conforming to the neighbors earns each player *i* a total payoff of π^g+n_i, which is $2n_i-\Delta\pi^{c,g}$ higher than the payoff in case *i* defects and converts to crop. Given that $2n_i-\Delta\pi^{c,g}\ge 0$, staying in grass is as good or a better option than 'convert to crop'. Consequently, if $\text{L.H.S.} \in[-2n_i, 2n_i]\ \forall i$ then $a_i=-1\ \forall i$ also constitutes an equilibrium where no player would deviate unilaterally to improve their payoffs. With the condition that

$\Delta\pi^{c,g} > 0$ $a_i = 1\ \forall i$ generates a higher payoffs for all players compared to $a_i = -1\ \forall i$. So, our next result on permanent grassland conversions in presence of localized spillovers is as under.

R2: *The one-shot game of permanent grassland conversion supports multiple equilibria among neighbors when strategic complementarities are present. Whether a unique or multiple equilibria will emerge is characterized by a threshold,* $T = \max_i(n_i)$, *and the landowner's private incentives from conversion. The threshold that characterizes the game's equilibria depends on an agent's degree of interconnectedness or the number of neighbors.* That is,

(i) If $\left|\dfrac{\pi(a_i) - \pi(-a_i)}{J}\right| > T\ \forall i$, then there exists a unique equilibrium such that $a_i^* = 1\ \forall i$ if $T > 0$ and $a_i^* = -1\ \forall i$ if $T < 0$.

(ii) If $\left|\dfrac{\pi(a_i) - \pi(-a_i)}{J}\right| < T\ \forall i$, then there exist multiple equilibria, i.e., $a_i^* = 1\ \forall i$, $a_i^* = -1\ \forall i$, and the combinations of $a_i^* = 1$ for some players and $a_i^* = -1$ for the remaining ones. However, $a_i^* = 1\ \forall i$ (or $a_i^* = -1\ \forall i$) is a Pareto-superior or payoff-dominant strategy set when $\Delta\pi^{c,g} > 0$ ($\Delta\pi^{c,g} < 0$).

Example: We now turn to illustrating the analytical results **R1** and **R2** by simulating the game's outcomes for a specialized case where I = 6, $n_i = 3\ \forall i$, J = 1 are fixed and $\Delta\pi^{c,g}$ is variable. The simulation results are presented in tables 1-7. Tables 1-6 showcase the scenarios where the game of strategic complementarities among players having binary choice sets generate multiple N.E. This is in line with what **R2 (ii)** suggests, which is that $\Delta\pi^{c,g} / J \le 2n_i$ (= 6 here) generates multiple equilibria. Further, as soon as $\Delta\pi^{c,g} / J > 2n_i$ (= 6 here) is satisfied there is a unique N.E. such that all players convert, as we assert in **R2 (i).** Upon comparing tables 4 and 5 we find equilibrium choices to be identical given $\Delta\pi^{c,g} / J$ remains the same, as asserted in **R1**. Although we present only one case where **R1** holds we find this true for all other cases (results not shown to save space).

Also notice that when $\Delta\pi^{c,g} / J \le 2$ the game generates more than two N.E. In particular, when $\Delta\pi^{c,g} / J < 2$ the game generates four N.E.: all players convert, none convert, and players on the upper (lower) ring convert and players on the lower (upper) ring stay in grass. For $\Delta\pi^{c,g} / J = 2$ the game generates three additional N.E. where the combinations of two players convert on each ring and the one remaining player stays in grass. Finding more than two N.E. for lower $\Delta\pi^{c,g} / J$ values can be explained by the increased opportunity to stay in grass because the private payoff from conversion decreases while the extent of social spillover remains fixed, i.e., constant J and n_i. These intermediate equilibria are mainly driven by the players' location arrangement on the structure imposed by a torus. In addition, for all the cases with multiple equilibria we find $a_i^* = 1 \; \forall i$ where all players convert to crop to be the Pareto superior equilibrium as each player earns a relatively higher payoff compared to the other equilibria.

<u>Equilibrium Selection</u>

Milgrom and Shannon (1994) showed for the games with strategic complementarities that pure strategy N.E are supremum and infimum of the set of equilibria obtained from the method of iterated elimination of strictly dominated strategies (Kultti and Salonen, 1997). Kultti and Salonen (1997) built upon this work and showed that these extremal equilibria are 'undominated' to other pure and mixed strategy N.E. The authors defined undominated equilibrium as one where no player's strategy is weakly dominated by another pure strategy. For our study the undominated extremal equilibria are $a_i^* = 1 \; \forall i$ and $a_i^* = -1 \; \forall i$.

In our illustrative example more than two pure N.E. exist when $\Delta\pi^{c,g} / J \in [0, 2]$. However, $a_i^* = 1 \; \forall i$ provides every player relatively higher payoff compared to other equilibria, except for $\Delta\pi^{c,g} / J = 0$ where $a_i^* = 1 \; \forall i$ and $a_i^* = -1 \; \forall i$ yield equal payoffs. These extremal equilibria overall yield as good or higher payoff for each player, and strictly higher payoff for at least one player, compared to the other additional equilibrium strategies. Moreover, the additional equilibria emerge due to the structure imposed by the torus and number of neighbors assigned to each player.

We now seek to select the game's solution among the two extremal equilibria using the deductive principles of payoff-dominance (PD) and risk-dominance (RD). The PD criterion selects the equilibrium where each player's payoff is strictly higher. That is, among the undominated equilibrium strategies $\{a_i^{*,pd}\}_{i=1}^{I}$ is payoff-dominant if

$$\pi_i(a_i^{*,pd}, a_{-i}^{*,pd}) > \pi_i(-a_i^{*,pd}, -a_i^{*,pd}) \; \forall i \tag{4}$$

Clearly, $a_i^{*,pd} = 1$ if $\Delta\pi^{c,g} / J > 0$ and $a_i^{*,pd} = -1$ if $\Delta\pi^{c,g} / J < 0$.

A payoff-dominant best response offers strategic risk as a player's expectation about neighbors' choices may not be accurate. The RD criterion searches for an equilibrium that offers the highest payoff while exhibiting the least strategic risk on the part of each player's actions. Harsanyi (1995) provided a theoretical basis for selecting among multiple equilibria and found that when PD and RD diverge on equilibrium selection, the selection criteria should be RD (or the N.E. with highest probability of emergence considering the strategic risk). We will now evaluate whether these criteria diverge on their equilibrium selection for this game.

To formally present the idea of risk-dominance consider the unique strategy sets of the neighbors for each player *i*. There are a total $M = 2^{n_i}$ such strategy vectors that can be represented as $((a_{j,m})_{j \in N(i)})_{m=1}^{M}$. For example, there are eight distinct strategy vectors for each player with three neighbors on a torus. Let $m = 1$ be the strategy vector where all neighbors stay in grass, i.e., $a_j = -1 \; \forall \; j \in N_i$, and $m = M$ be the strategy vector where $a_j = 1 \; \forall \; j \in N_i$. Further, let $p_{i,m}$ denote the probability *i* places on strategy vector *m*. Then, strategy a_i is risk-dominant if $E_i \pi_i(a_i, a_j) > \; E_i \pi_i(-a_i, a_j)$. That is,

$$\frac{\pi(a_i) - \pi(-a_i)}{J} > -2a_i \sum_m \sum_j a_{j,m} p_{i,m}; \; j \in N_i, m = 1, 2, ..., M \tag{5}$$

Now each player would assign $p_{i,m} > 0$ only for those strategy sets that remain undominated, that is the extremal N.E.. So, we know that $p_{i,m} = 0$ for $m = 2, 3, \ldots, m - 1$ and $p_{i,1} + p_{i,M} = 1$ with $(p_{i,1}, p_{i,M}) \geq (0, 0)$. Hence, $a_i^* = 1$ is *i*'s risk-dominant strategy if

$$\frac{\Delta \pi_i^{c,g}}{J} > -2n_i(2p_{i,M} - 1); \; j \in N_i \tag{6}$$

Equations (4) and (6) suggest that the PD and RD criteria converge on the equilibrium selection for $p_{i,1} = p_{i,M} = 0.5$ for all *i*, that is $\Delta \pi_i^{c,g} / J > 0 \;\; (< 0)$ will imply $a_i^* = 1 \; \forall i \;\; (a_i^* = -1)$. Moreover, there is no reason to believe for homogenous agents to place a higher probability weight on either of the two plausible extremal equilibria.

Heterogeneous Agents

We posit agent heterogeneity as players having different private payoffs while keeping the strategic complementarity parameter *J* constant with cross-sectional invariance. Such a framework for analyzing heterogeneity is dual to varying parameter *J* while keeping the private payoffs same across players (as noted earlier in **R1**). We evaluate the impact of heterogeneous private payoffs on each player's profit maximization problem by examining its implications for equilibrium characterizing equation (3). For example, we know that $a_i = 1$ is *i*'s unique payoff maximizing strategy if $\Delta\pi_i^{c,g} / J > -2\sum_j a_j$. Intuitively, the condition for the strength of private conversion incentives towards 'convert to crop' uniquely maximizing *i*'s total payoff is less stringent when more number of players in his/her neighborhood convert to crop. We now examine the implications of this intuition formally.

Consider a scenario where a fraction of player *i*'s neighbors convert to crop. That means these neighbors have $\Delta\pi_j^{c,g} / J > T; j \in N_i$ satisfied, see **R2 (i)**. Such strong incentives to crop in a neighborhood may arise due to better soils, strong commodity basis and better access to demand-terminals, or due to even idiosyncratic reasons such as ability or willingness to convert. For the purpose of exposition we let $\tilde{N}_i$ be the set of *i*'s neighbors who convert such that $\# \tilde{N}_i = \tilde{n}_i \in (0, n_i)$. Under this scenario, *i* will choose action $a_i = 1$ if

$$\frac{\Delta\pi_i^{c,g}}{J} > -2\left(\sum_j a_j + \tilde{n}_i\right);\ j \in N_i \setminus \tilde{N}_i \tag{7}$$

Now, the R.H.S. in equation (7) is bounded in the range $[-2n_i, 2(n_i - 2\tilde{n}_i)]$. Therefore, when $\tilde{n}_i$ of *i*'s neighbors will certainly to choose convert to crop and therefore the threshold on $\Delta\pi_i^{c,g} / J$ that ensures $a_i = 1$ to be the payoff maximizing strategy is $4\tilde{n}_i$ units lower than when $\tilde{n}_i = 0$. In other words, for every additional neighbor converting to crop reduces the threshold on $\Delta\pi_i^{c,g} / J$ that asserts conversion to be the payoff-maximizing strategy is reduced by 4 units. An implication for the Dakotas is that the social spillovers from the pre-existing croplands would increase the propensity to convert on existing grasslands. Our model specification exhibits social spillovers favorable towards cropping to compensate for low private payoffs from conversion leading to the possibility of grass conversions on lands with moderate soil quality. The inference is symmetrically opposite for the 'stay in grass' option that higher stock of grasses in an area can inhibit conversion even on relatively good lands as the social payoffs lower the incentive towards conversion.

See that to a land use decision-maker having neighbors with strong private incentives to pursue crop-based or grass-based production with certainty in our static framework is similar to existing stock of cropland and grassland in the neighborhood in time-varying setting. Thus our earlier observation that recent grass conversions are 'islands' within contiguous croplands in North Dakota is also what our analytical findings suggested above. Hence, our next result.

R3: *Localized spillovers from existing or projected* (*with certainty*) *croplands or grasslands in a neighborhood compensates for potentially moderate private payoffs thereby encouraging the remaining decision-makers to either* '*convert to crop*' *or* '*stay in grass*' *respectively. That is, agent i with has higher incentives towards choosing* $a_i = 1$ *than* $a_i = -1$ *when* $\sum_{j \in N_i} a_j > 0$, *and vice versa, irrespective of the relative private payoffs from the two strategies, i.e.,* $\Delta\pi_i^{c,g}$.

Examples: We present three specialized cases to understand the implications of agent heterogeneity on individual land use decisions and the game's N.E.

(i) Set $\Delta\pi_i^{c,g} = 6.1$ for $i = \{1, 4\}$. Our earlier result **R2** suggests that $a_1^* = a_4^* = 1$ irrespective of their neighbors' actions. Based on the locations all the remaining players on the torus, say $k \in \{2, 3, 5, 6\}$, have exactly one neighbor who is projected to 'convert to crop' with certainty (see figure 4). We find that whenever $\Delta\pi_k^{c,g} > 2$ the remaining players support a unique N.E.

where all players 'convert to crop'. This is consistent with our analytical finding that for every neighbor who converts to crop the threshold for private payoffs that sustains conversion as the unique optimal strategy is reduced by 4 units.

An alternative structure of agent heterogeneity is achieved by setting $\Delta\pi_i^{c,g} = 6.1$ for $i = \{1,6\}$. In this case each of the remaining players, say $k \in \{2,3,4,5\}$, have two neighbors each who convert with certainty. We find that $\Delta\pi_k^{c,g} > -2$ for $k \in \{2,3,4,5\}$ would sustain a unique equilibria where all players 'convert to crop'. This too is consistent with our analytical exercise, but exhibits an interesting case where even though the private incentives favor grass-based production the local spillover effects, if strong enough, can lead to conversion of grasslands.

Conversion cascades

A specialized and more interesting theoretical possibility emerges from simulating N.E. for our proposed structure when analyzing players with heterogeneous private payoffs. Conversion 'cascades' emerge parallel to the concept of information cascades introduced by Bikhchandani et al. (1992). Information cascades occur as limited information from predecessors transcends to the successive generations as social norms leading to uniformity in social behavior. For our study, cross-sectional interdependence among players can generate similar results through spatial lags as shown by Bikhchandani et al. (1992) in presence of temporal interdependence. Conceptually, a conversion cascade is a result of lower conversion thresholds from local spillover effects from existing croplands or neighbors who are certain to convert.

It is easiest to visualize this effect with players placed on a circle of finite radius with each player having two neighbors. The threshold that these players will convert will certainty is characterized as $\Delta\pi_i^{c,g} / J > 4$ (because $T = 2n_i$ as found earlier). Consider a scenario where every player on this circle has private incentives such that $\Delta\pi_i^{c,g} = 2.1J$. A conversion cascade appears if any one player converts with certainty. Consequently, the two neighbors on either side of player *i* will convert because the total payoff from cropping is certainly higher than staying in grass. Further, the two neighbors of the two newly cropped nodes will convert for the same reason as above, and the chain continues until all players convert.

To visualize a conversion cascade for our illustrative example in figure 4, we divide the six player on the torus in four cohorts: $s \in \{1,3\}$, $t \in \{2\}$, $u \in \{4,6\}$, and $v \in \{5\}$. We set $\Delta\pi_s^{c,g} > 6$ so that $a_s^* = 1 \forall s$. Hence, player 2 with two neighbors projected to convert to crop with certainty will convert as well if $\Delta\pi_t^{c,g} > -2$. Next the system in figure 4 with $\Delta\pi_s^{c,g} > 6$ and $\Delta\pi_t^{c,g} > -2$ will lead to $a_u^* = 1 \forall u$ if $\Delta\pi_u^{c,g} > -2$, which in turn would mean $a_v^* = 1$ as long as $\Delta\pi_t^{c,g} > -6$. So, this conversion cascade portrays a situation where two agents with very strong private incentives to crop lead cropping into the regions where grass-based land use was relatively more profitable. Although cascades are only an interesting theoretical possibility, it is relevant for our region of study where more cropland is added on relatively poor quality soils along the western fringes of the WCB characterizing its westward expansion in the past decade.

Easement Allocations

As discussed earlier, easements are perpetual contracts that landowners enter voluntarily permanently giving up their right to cultivate in lieu of a payment. Although the landowners should be willing to be considered for these easement contracts, the conservation agencies are usually facing more grassland acreage than their budgetary allowance to acquire easements. Therefore, it is critical to analyze the efficiency of past allocations and seek to achieve more cost effective allocations in the future that also lead to a higher ecological output. In this study, we evaluate acquisition costs and the overall social welfare from easement acquisitions when strategic complementarities exist among landowners.

Easements generate ecological benefits from conserved mixed-prairie in return of a cost of acquisition. The ecologists recommend conserving large, contiguous tracts to support higher biodiversity and the economists have proposed agglomeration bonuses for efficient voluntary conservation of contiguous lands. Here, we evaluate how local spillover effects in production impact the social welfare from acquiring easements. We set the ecological benefits derived from each grass unit to be a constant, while the easement acquisition cost accounts for the strategic complementarity among players through individual returns from cropping and grass-based production. It would be interesting to incorporate benefits that differ by acquiring easements on contiguous tracts and isolated lands if the acquisition costs offered a trade-off. Instead, higher benefits are accrued when new easements are acquired in contiguity with other easements, which also lowers the cost of acquiring easements. Not incorporating such different level of benefits might under- or over-estimate the level of social welfare generated but the underlying recommendations towards future easement acquisitions will hold.

Consider a scenario where all agents in a neighborhood have strong private incentives to crop such that $a_i^* = 1 \ \forall i$ in absence of any intervention. Define the social welfare function as $W^E = Be - C^E$, where W^E is the social welfare generated from acquiring a set *E* of easements on existing grasslands such that $\#E = e$. *B* is the fixed level of ecological benefits accrued from each eased unit and C^E is the total cost of acquiring easements in *E* such each eased agent $i \in E$ can no longer cultivate, i.e., $a_i = -1$. Easement acquisition costs have two components: (i) cost to FWS, which is *i*'s minimum willingness to accept (WTA) upon ceding the right to cultivate, denoted as C_i, (ii) social cost of easements due to spillover effects to *i*'s neighbors who continue to cultivate crop thereby defecting from eased player *i*'s action, denoted as $C_{j \in N_i}$. That is,

$$\begin{aligned}&\text{(i) } C_i = \Delta\pi_i^{c,g} + 2Jn_i \\ &\text{(ii) } C_{j \in N_i} = \sum_j 2J = 2Jn_i\end{aligned} \tag{8}$$

Hence, the total cost of easement acquisition with $E = \{i\}$ is given as $C^E = C_i + C_{j \in N_i} = \Delta\pi_i^{c,g} + 4Jn_i$. Equation (8) reveals that acquiring easements is less costly when the private returns to crop are relatively lower as compared to staying in grass (but high enough that ensures $a_i^* = 1$)

Now consider a case of easing two neighboring units at once, say $E = \{i, k\}$ such that $k \in N_i$, $i \in N_k$, which will convert to crop in absence of any intervention. The total easement benefits equal 2*B* and the two cost components are

$$\begin{aligned}&\text{(i) } C_l = \Delta\pi_l^{c,g} + 2J(n_l - 1);\ l \in \{i, k\} \\ &\text{(ii) } C_{j \in N_l} = 2J(n_l - 1);\ l \in \{i, k\}\end{aligned} \tag{9}$$

Equation 9 (i) reveals that the players' WTA when eased alongside an immediate neighbors is lower by *J* units. That is because *i* and *k* conform to each other gaining extra payoff from the localized spillovers. Another advantage of acquiring these two neighbors is lower social cost of these easements because each eased player has one less defecting neighbor. Therefore, the social cost is lower by *J* units for each eased player, see equation (9). So, the total cost of these two easements is $C^E = 2\Delta\pi_i^{c,g} + 4J(n_i + n_k) - 8J$. Clearly, the per-unit cost of easing *i* and *k* as immediate neighbors is lower when eased in isolation, i.e., $C^{E=\{i\}} + C^{E=\{k\}} > C^{E=\{i,k\}}$ such that $k \in N_i$ and $i \in N_k$. Also that the cost incurred per unit of ecological benefit through land conservation is lower when easements are established among immediate neighbors.

In evaluating easements we find that due to social spillover effects the cost payable by the conservation agency for acquiring easements are lower when their target units are neighbors to the existing easements. But with this knowledge our analysis above also assumed that easement acquisition, in isolation or in contiguity, was a terminal exercise such that no new easements will be established going forward. This is because in case easements are sequentially acquired (which they are in the real world) each player *i* will incorporate the difference between what the agency would have pays for easing his/her neighbors with and without player *i* entering the contract. As a result, C_i in equation 8 (i) will now include an additional cost of $2Jn_i$ units, which is the potential reduction in the agency costs of acquiring *i*'s neighbors in the future. Therefore, the total cost to FWS while acquiring agent *i* now equals $C_i = \Delta\pi_i^{c,g} + 4Jn_i$, while the social costs remain the same as earlier. We next analyze the over social welfare generated from acquiring easements keeping in mind such potential cost spillovers in the neighborhood of eased lands.

Since the conservation agencies operate under budgetary constraints, it is appropriate to analyze the structure of easement acquisition that maximizes the social welfare under a given budget. Consider a scenario when conservation agencies target easements on two neighboring units, i.e., *i* and *k* such that $k \in N_i$, $i \in N_k$. Alternative easement structures emerge with simultaneous acquisition, i.e., ease *i* and *k* at once, or sequential acquisition, i.e. ease *i* first and then ease *k*. Overall benefit accrued will be 2*B* either way. The cost components of the simultaneous acquisition arrangement are

$$\begin{aligned} &\text{(i) } C_l = \Delta\pi_l^{c,g} + 4J(n_l - 1);\ l \in \{i,k\} \\ &\text{(ii) } C_{j\in N_l} = 2J(n_l - 1);\ l \in \{i,k\} \end{aligned} \tag{10}$$

So, the total cost of conserving these neighboring units, *i* and *k*, simultaneously equals $\Delta\pi_i^{c,g}$ + $\Delta\pi_k^{c,g} + 6J(n_i + n_k) - 12J$. Notice that the social cost of easement remains the same as earlier in equaton 9 (ii). The social welfare under this arrangement equals $W^{\{i,k\}} = 2B - (\Delta\pi_i^{c,g} + \Delta\pi_k^{c,g} + 6J(n_i + n_k) - 12J)$.

Now consider the case of sequential acquisition with *i* being the first player to be eased in the sequence, without loss of generality. So the cost components in this case are

$$\begin{aligned} &\text{(i)} \quad C_i = \Delta\pi_i^{c,g} + 4Jn_i \\ &\text{(ii)} \quad C_k = \Delta\pi_k^{c,g} + 4J(n_k - 1) \\ &\text{(iii)} \quad C_{j\in N_i} = 2Jn_i \\ &\text{(iv)} \quad C_{j\in Nk} = 2J(n_i - 1) \end{aligned} \tag{11}$$

Here the cost of conserving the first unit in the sequence is higher than under simultaneous acquisitions case because this player gets an opportunity to extract the future spillover cost reduction for neighbor *k*, while ignoring the social cost to *k* when eased. Total social cost in this case is higher by 2*J* units, which is equal to the additional cost to player *k* for being second in the sequence. So, the total cost of conserving these neighboring units, *i* and *k*, in a sequential manner equals $\Delta\pi_i^{c,g} + \Delta\pi_k^{c,g} + 6J(n_i + n_k) - 6J$. The social welfare under this arrangement equals $W^{\{i,k\}} = 2B - (\Delta\pi_i^{c,g} + \Delta\pi_k^{c,g} + 6J(n_i + n_k) - 6J)$. Clearly, the total welfare achieved is higher when the easements are acquired simultaneously compared to the sequential arrangement of easement acquisition, given that the agency budget allowance for two easement units. In other words, the cost incurred per unit of ecological benefit attained is lower through simultaneous acquisitions compared to the sequential arrangement. An implication for the Dakotas is that easements should be acquired on relatively large, contiguous group of land parcels, and once such group is identified the acquisition scheme should acquire all-parcels-at-once rather than one-parcel-at-a-time for different disconnected groups. Of course, ecological value of land and budgetary constraints will drive how and where the group of parcels are identified, which is out of scope for this study.

R4: *When localized spillovers are present in farmers' returns from production, the cost per-unit of ecological benefit attained from acquiring multiple easements in contiguity is lower than acquiring those easements in isolation. Overall social welfare is higher when all contiguous parcels are eased at the same time, rather than in a sequential scheme of acquisition.*

Example: We can visualize the easement costs, both to the conservation agency and social costs, and the total welfare for players located on a torus. Let us consider the easement set is comprised of $E = \{1, 2, 3\}$ where all three players are neighbors to each other. For simplicity of exposition let the players be homogenous in their private returns to cropping and grass-based production. If either of these players is eased in isolation the total cost as per equation (10) will be $\Delta\pi^{c,g} + 18J$ against one unit of benefit (*B*) attained. Instead, if two players are eased simultaneously then total cost will be $2\Delta\pi^{c,g} + 24J$ against the total benefit of 2*B*, and if the entire set of three players are eased then the total cost will be $3\Delta\pi^{c,g} + 18J$ against total benefit of 3*B*. Hence, the total cost per unit benefit attained is reduced to $\Delta\pi^{c,g} + 12J$ when two neighbors are eased, and further reduced to $\Delta\pi^{c,g} + 6J$ when three neighboring players are eased. This shows that contiguous easing of land parcels can reduce the cost per unit benefits attained when strategic cost complementarities are present among landowners.

Secondly, when the players in set E are eased sequentially in a way that first player 1 is eased, then player 2 and then player 3. The total cost of first easing player 1 is $\Delta\pi^{c,g} + 18J$, then for easing player 2 equals $\Delta\pi^{c,g} + 12J$, and then finally for easing player 3 the total cost is

$\Delta\pi^{c,g} + 6J$. The total cost under this sequential acquisition scheme equals $\Delta\pi^{c,g} + 36J$ against the total benefit of 3*B*, which is clearly higher from the cost of easing the same set of players simultaneously.

<u>Can easement acquisitions trigger non-conversion in their neighborhood?</u>

We now evaluate whether easements can trigger non-conversion in their neighborhood and analyze the social welfare implications of such a scenario. Easements lock lands in grass thereby taking away the option to crop. An uneased player will only forgo conversion if the relative private payoffs from cropping are less than the penalty generated by defecting from his/her eased neighbors. Formally, if e_i denotes the number of *i*'s eased neighbors in set $N_i^e \subseteq N_i$ then $a_i^* = -1$ is optimal when

$$\pi_i^c + J\left(\sum_j a_j - e_i\right) < \pi_i^g + J\left(e_i - \sum_j a_j\right);\ j \in N_i \setminus N_i^e$$
$$\text{or} \tag{12}$$
$$e_i > \frac{\Delta\pi_i^{c,g}}{2J} + \sum_j a_j;\ j \in N_i \setminus N_i^e$$

Since $\max \sum_{j \in N_i \setminus N_i^e} a_j = n_i - e_i$, e_i easements lead to non-conversion by player *i* only if

$$e_i > \frac{1}{2}\left(\frac{\Delta\pi_i^{c,g}}{2J} + n_i\right) \tag{13}$$

Equation (11) suggests that the number of easements that would lead to non-conversion is specific to each player's private incentive to crop and the degree of interconnectedness. So easements may trigger non-conversion when placed strategically such that in a population of *I* players each player has at least $\max_{i \in I} 0.5\left(\Delta\pi_i^{c,g} / 2J + n_i\right)$ neighbors who are eased.

We now evaluate the total social welfare when easements indeed trigger non-conversion, and these easements were acquired all-at-once. Since all players are eased as grasslands the total benefit equals *IB*, which is obviously the highest achievable ecological benefit. Among the components of acquisition costs, only the loss of private payoff from staying in grass are relevant as social costs are equal to zero since all players conform to each other and no more easements need to be established in the area. Hence, the total acquisition cost equals the total WTA for all individuals, i.e. $\sum_i \Delta\pi_i^{c,g}$. When easements do not trigger non-conversion at least one player converts to crop, say player *j* converts, and so the cost of acquiring *j* is greater than $\Delta\pi_j^{c,g}$ due to social spillover effects. Therefore, the cost of acquisition per unit ecological benefit attained will be minimized when easements are strategically allocated to trigger non-conversion. Further, the social welfare is also maximized if all easements that trigger non-conversion simultaneously. Hence, our next result.

***R*6**: *When localized spillovers exist among landowners deciding between 'convert to crop' and 'stay in grass' strategically placed easements can trigger non-conversion. Further, the cost of acquisition per unit ecological benefit attained will be minimized and overall social welfare is maximized when all easements that trigger non-conversion are acquired simultaneously.*

Empirical Analysis

The analytical results of this study are conditional upon the presence of strategic complementarities among the Dakotas' landowners. In order to test this conjecture statistically we employ an empirical strategy that utilizes a duration model to estimate the risk of permanent grassland conversion. Specifically, we track the dynamics of parcels that were classified as grass in 1997 for eastern North Dakota and record the 'duration-to-convert' as number of years from 1997 each parcel stayed in grass before it was permanently converted to crop. We model this 'duration-to-convert' as a function of the neighborhood grassland density. Notice that our empirical strategy is appropriate due to the availability of spatially-delineated land use data and an extensive application of remote-sensing techniques that provided us the G and GC sequences of land use conversions. We next provide the data used to estimate a duration model followed by a discussion on the workings of a duration model and our identification strategy. We then present estimation results.

<u>Data</u>

As mentioned above, our dependent variable is the duration to permanent conversion or years to conversion for parcels that were classified as grass in 1997. We designate 0.5 km, 1 km and 2 km outer rings that correspond to each parcel's designated neighborhood, i.e. n_i. We attribute percent grass from the CDL and percent easements from the National Conservation Easement database for the outer rings as spatial lags to capture the localized spillovers among landowners, see figure 5 for spatial schematics. We obtain parcel level and neighborhood soil quality data from the Web Soil Systems portal of USDA-National Resource Conservation Service (NRCS). We calculate weighted Land Capability Classification (WLCC) and slope (WSLP) as control variables for soil quality. Briefly, LCC groups soils into eight categories each representing the degree of impediments towards cropping with higher categories meaning greater impediments. We also control for access to infrastructure for each parcel as its Euclidean distance to the nearest principal highway and town center, for which the data were acquired from U.S. Census Bureau's TIGER portal. The variable summaries are listed in table 8 and will be discussed hereafter.

<u>Modelling Strategy</u>

We model duration-to-convert T assumed to be drawn from a differentiable cumulative distribution function $F(T)$ with probability distribution function defined as $f(T) = F'(T)$. For our case $F(T)$ is the cumulative probability that a representative grassland parcel is permanently converted to crop T years after 1997 in ND (2006 in SD), i.e., or $T = 0$ when year = 1997 in ND (year = 2006 in SD). Further, the probability of surviving conversion until T years is defined as the survival probability or $S(T) \triangleq 1 - F(T)$. The instantaneous risk of conversion at T, known as the hazard rate, is defined as $\lambda(T) = f(T)/S(T)$. We estimate this hazard rate as a function of neighborhood characteristics and other soils quality/infrastructural controls.

We implement a semi-parametric Cox-proportional hazard model to estimate the risk of permanent conversions due to a covariate vector Z. That is ,

$$\lambda_i(T \mid Z_i; \beta) = \lambda_o(T)\exp(Z_i^{'}\beta) \tag{14}$$

Here, λ_o is defined as the baseline hazard due to cross-sectional heterogeneity among parcels (Greene, 2003, p. 799). The parameter coefficient, β, translates into a $100(\exp(\beta)-1)\%$ change in hazard rate due to a unit increase in the explanatory variable corresponding to the parameter. Notice that we begin with a panel dataset of dependent and explanatory variables but the regression framework is static because the dependent variable is duration and we record time-varying explanatory variables at the time of each parcel's conversion. Under the Cox-proportional specification the likelihood function is specified as

$$L(\beta) = \prod_{i=1}^{n}\left(\frac{\exp(Z_{i,T}^{'}\beta)}{\sum_{j=1}^{n} C_{ij}\exp(Z_{i,T}^{'}\beta)}\right)^{\delta_i} \tag{15}$$

where *T* is *i*'s duration to event and $\delta_i = 1$ if event occurred and $\delta_i = 0$ if censored, i.e., permanent grass parcels, G, where the event did not occur. Note that when $\delta_i = 0$ that parcel's likelihood function is reduced to 1. The hazards included in the denominator are those grass parcels that are at risk of conversion at *T*, which is ensured by $C_{ij} = 1$ if $T_j \geq T_i$, and $C_{ij} = 0$ if $T_j < T_i$.

The vector $Z_{i,T}$ contains 1) parcel-level explanatory variables, denoted $X_{i,T}$, like soil quality, distance from city/highway, 2) neighborhood-level explanatory variables, average neighborhood-level land use choice variables, i.e., percent grassland and easement acreage in the 500 mouter-ring, denoted as $\omega_{n_i,T}$, and $Y_{n_i,T}$, like soil quality, percent wetland acreage, area-weighted duck pair density for the 500 m outer-ring. Here, n_i denotes the set of *i*´s neighboring agents. However, the neighborhood decision level, $\omega_{n_i,T}$, is likely to be linearly related to variables in vector $Y_{n_i,T}$ leaving the coefficient of $\omega_{n_i,T}$ unidentified. This is the classic reflection problem introduced by Manski (1993) and addressed by Brock and Durlauf (2007) for the discrete choice problems. We briefly discuss this identification strategy in the context of our study below.

Identification Strategy

Manski (1993) pointed out that the social interactions parameter is difficult to identify because $\omega_{n_i,T}$ is likely functionally dependent upon $Y_{n_i,T}$. To see this, let us consider the following reduced form framework that models individual decision level to social interactions below.

$$a_{i,T} = \beta_o + \beta_1 X_{i,T} + \beta_2 Y_{n_i,T} + \beta_3 \omega_{n_i,T} + \varepsilon_{i,T} \tag{16}$$

In equation (16), $\beta_o, \beta_1, \beta_2$ and β_3 are regression parameters. $\beta_3 = J$ in the conceptual model described above. Under rational expectations we can write $\omega_{n_i,T} = E(a_{i,T} \mid X, Y)$ (Brock and Durlauf, 2001 pp. 240). Hence, $\omega_{n_i,T} = (1-J)^{-1}(\beta_o + \beta_1 X_{i,T} + \beta_2 Y_{n_i,T})$ implies a linear dependence of $\omega_{n_i,T}$ on $X_{i,T}$ and $Y_{n_i,T}$ leaving β_3 unidentified. However, in this study we estimate equation (14) and not equation (16), which implies

$$E(a_{i,T}) = \Pr(t = T \cap I_{i,T} = 1) - (1 - \Pr(t = T \cap I_{i,T} = 1)) \tag{17}$$

For a duration model with Cox-propositional hazard specification we have

$$\Pr(t = T \cap \delta_i = 1) = \frac{\exp(Z'_{i,T}\beta)}{\sum_{j:t_j \geq T} \exp(Z'_{j,t}\beta)} \tag{18}$$

which implies under rational expectations that

$$\begin{aligned} E(a_{i,T}) &= 2\frac{\exp(Z'_{i,T}\beta)}{\sum_{j:t_j \geq T} \exp(Z'_{j,t}\beta)} - 1 \text{ and} \\ \omega_{n_i,T} &= 2\int \frac{\exp(Z'_{i,T}\beta)}{\sum_{j:t_j \geq T} \exp(Z'_{j,t}\beta)} dF_{X,Y} - 1 \end{aligned} \tag{19}$$

Clearly, $\omega_{n_i,T}$ is not linearly dependent on $X_{i,T}$ and $Y_{n_i,T}$ and hence the identification issue proposed by Manski (1993) does not hold here. Note that the fact that the coefficients in model (14) will be identified is hinged upon the fact that $\omega_{n_i,T}$ is restricted between 1 and –1 whereas the explanatory variables in $X_{i,T}$ and $Y_{n_i,T}$ are distributed over a relatively large space (Brock and Durlauf, 2007).

Even though we use duration as dependent variable, which induces non-linearity between $\omega_{n_i,T}$ and the parcel-level characteristics, neighborhood decisions may still be co-determined. In order to ensure that the coefficient to neighborhood-level variables, i.e., $\omega_{n_i,T}$, is identified we follow the instrumental variable regression approach. We require the instrumental variables to be correlated with the dependent variable, i.e. *duration*, but uncorrelated with the residuals in equation (14). Therefore, soil quality and access to infrastructure are valid instruments, in that they would determine the relative profitability towards crop-based and grass-based land uses for neighboring land parcels. In addition, we know that the FWS's strategy for past easement acquisitions is likely to be determined by an area's duck-pair density (Walker et al. 2013). Since wetlands are critical to sustain breeding of ducks, we introduce neighborhood-level wetlands density to instrument the presence of easements. Furthermore, wetlands also generate marketable ecosystem services, and so would serve as an appropriate instrument for the grasslands. Specifically, we instrument the neighborhood-level variables (grassland and easement density here) on (i) wetland density, (ii) soil quality, and (iii) distance to the nearest city/highway.

Estimation Results

We estimate equation (13) and denote our dependent variable $T \times I_{i,t=T}$ as 'duration'. Table 8 summarizes the dependent and explanatory variables for the full sample containing land parcels under GC and G sequences. Table 8 reveals that the unconverted parcels (sequence G) during 1997-2015 had higher slopes, poorer soils for cropping (or higher LCC), and were more distant to the highways and city centers as compared the ones that did convert during this period (sequence GC). Further, the neighborhood grass density of unconverted parcels is much higher than the ones that underwent permanent conversion. Notice that the standard deviation of soil quality variables is high, so we utilize a t-test to find the mean the soil quality is statistically different across sequences G and GC, see table 9.

Next, we find parcel-level soil quality regressors to be highly correlated with neighborhood-level regressors, especially for the neighborhood designations as 0.5 km and 1 km outer-rings, see table 10. High correlation exists despite increasing the size of the outer-ring to 2 km. A typical U.S. farm of 160 acres roughly translates into a square shaped plot with 0.8 km sides. This means that our designation of 0.5 km (1 km, 2km) outer ring roughly accounts for the average neighborhood decision level of one (two, three) adjoining farms on each side of the parcel. Since soil quality is highly correlated even to the extent of thirst-order neighbors, include parcel-level land quality for an amenable interpretation towards conversion decisions.

It is a standard practice in case of duration analyses to present the estimated survival probabilities, $S(T)$, in each period of the study. We estimate the non-parametric Kaplan-Meier survival probabilities based on the recorded duration to permanent conversion in our sample, see figure 6. We find that a large proportions of the regression sample (more than 90%) contains parcels in the sequence G. Among the ones that did convert, i.e. the GC sequence, more than 85% converted in just one year. Table 8 shows that among the converted parcels average duration was about 2.6 years. A highly skewed sample is a caveat of this analysis and warrants more work to reconcile this issue. Since the number of observations in sequence G is much greater than that in GC, we estimate two separate regressions for the full sample and only the GC category in order to document any relevant differences in estimation results.

The hazard regression estimates for the 'full' sample are listed in Table 11 and the corresponding hazard rates are listed in Table 12. We find that a unit increase in the proportion of grasses within a representative parcel's 0.5 km neighborhood would decreases the conversion risk by 99%. Correspondingly, higher grass density within larger neighborhoods of 1 km and 2 km decrease the hazard rate by 97% and 94% respectively. This suggests a non-increasing strategic response to larger neighborhood. We find that the easements reduce hazard rates by a 100% meaning that the advent of an easement completely halts conversion. These results are driven by the fact that permanent conversions are concentrated in areas that were historically cropped and past easements were allocated away from the converted parcels. 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. For robustness we estimate hazard rates for only the GC sequence, results are presented in tables 13 and 14. Briefly, higher grass density as well as more eased acres are related to lower hazard rates, although the impact of easements is insignificant.

In order to ensure that the coefficients to spatial lags are identified we first instrument grass density and easement density variables for the pre-designated outer rings on their proximity to near-by wetlands, their soil quality and access to infrastructure, see tables 15 and 16. Here, we find higher grass density as well as more eased acres are related to hazard rates. This means that easements were strategic complements to higher grass density towards inhibiting permanent conversions. 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 on the environmental conscience in neighborhoods with near-by easements.

Long-term grasses: Filter for one-time permanent grassland conversions

A concern with pooling the G and GC categories for our hazard model estimation is that the mean duration to convert is only 2.6 years, which is indicative of the fact that 'grass' in 1997 could have been converted earlier and these parcels were possibly switching between grass and crop prior to 1997. This is problematic since GC parcels that were out of grass before 1997 do not represent one-time permanent grass conversions as currently incorporated in our hazard rate estimation framework.

To ensure estimating the hazard rates for one-time conversions we utilize our findings from Chapter 3 to characterize long-term grasses. Specifically, we utilize the Landsat5 sensor data for North Dakota (path 31, rows 27-28, ch.3 p.202) for years 1984 and 1987 as 'filters' for determining parcels that were grass historically. We then exclude parcels that were grass in 1997 but not grass in 1984/87 from our dataset, thereby designating the remaining parcels as long-term grasses. Rest of the components of the regression analysis are kept the same as earlier, including the IV regressions for the spatial lags. One issue with this strategy of characterizing long-term grasses is that since we only generate historical data for only a portion of eastern North Dakota (figure1-ch.3 p.202) this new filtered parcel-level data is truncated in an arbitrary manner.

Upon filtering the original dataset, we are left with only 60 GC category parcels (out of 972) and only 734 G category parcels (out of 12,420 compared to the original dataset). Consequently, the resulting mean duration is now double at 5.2 years, see figure 7. The coefficient estimates of the resulting hazard regressions for the three outer-rings are significant in only some cases indicating lost estimation power due to truncation. Higher density grasses are still found to inhibit conversions in all cases, whereas easements reduce conversion risk for 0.5 km and 1 km and not in case of the 2 km neighborhood. We caution the reader of the discrepancies in these results compared to the ones obtained from using the unfiltered dataset earlier. The loss of parameter significance may be associated with the noise introduced due to filtering, and so we designate these results preliminary.

Concluding Remarks

We evaluate the role of strategic complementarities among private decision makers on permanent grassland conversions and how in this scenario conservation easements can be cost-effectively allocated. We focus on the recent land use dynamics in the PPR where extensive grassland losses occurred in the past decades. These grasslands are critical to the native and migratory birds habitat in North America and FWS actively engages in buying perpetual easements to conserve these habitats. Past studies have investigated conservation targeting, including conservation easements, by contrasting scenarios that determine conversion probability as a function of the tract-level benefits and costs. We evaluate conservation targeting by incorporating network effects into the private landowners decision problem. We conjecture that strategic complementarities exist on land use decisions such that higher crop density encourages more cultivation in the neighborhood through better access to agricultural services, supporting infrastructure and demand terminals.

We first present a game-theoretic discrete choice model of strategic complementarities based on our conjecture that grassland owners derive a positive social payoff by conforming to their neighbors' actions. We specify pairwise strategic interactions among players to incorporate agent heterogeneity, neighborhood-level interactions, and to evaluate easement allocations. We find that multiple equilibria are supported where all players 'convert to crop' or 'stay in grass'. Positive social spillovers can encourage landowners with weak cropping incentives to convert to crop following their neighbors' choice. We evaluate easement allocations by calculating overall social welfare that accounts for spatial spillovers among neighbors. We find that easements can inhibit conversion more efficiently when the private incentives to convert are weak (poor soils) and when easements are acquired on neighboring plots of land.

We support our conceptual model by empirically testing whether or not localized spillovers exist in permanent grassland conversion in the Dakotas. Our analysis suggests that localized spillovers do exist such that higher density grassland inhibits conversion in its neighborhood. We find easements to be strategic complements to existing grasses as they too inhibit conversion. Overall, our analysis is based on the fact that croplands and grasslands exist as large, nearly-contiguous tracts in the eastern North Dakota where permanent conversions have occurred as islands within the crop-intensive areas. Easements, on the other hand, were allocated near permanent grasslands as contagious tracts in proximity to the grasslands that did not convert anyway. However, the fact that existing easements are contiguous tracts on relatively poor soils is in agreement with our conceptual model's recommendation for cost-effective acquistions when peer-to-peer networks affect private landowner decisions.

TABLES

Table 1. Simulated N.E. for the illustrative example. $\Delta\pi^{1,-1} = 0$, $J = 1$.

a_1^*	a_2^*	a_3^*	a_4^*	a_5^*	a_6^*	π_1^*	π_2^*	π_3^*	π_4^*	π_5^*	π_6^*
-1	-1	-1	-1	-1	-1	3	3	3	3	3	3
-1	-1	-1	1	1	1	1	1	1	1	1	1
1	1	1	-1	-1	-1	1	1	1	1	1	1
1	1	1	1	1	1	3	3	3	3	3	3

Table 2. Simulated N.E. for the illustrative example. $\Delta\pi^{1,-1} = 1$, J = 1.

a_1^*	a_2^*	a_3^*	a_4^*	a_5^*	a_6^*	π_1^*	π_2^*	π_3^*	π_4^*	π_5^*	π_6^*
-1	-1	-1	-1	-1	-1	3	3	3	3	3	3
-1	-1	-1	1	1	1	1	1	1	2	2	2
1	1	1	-1	-1	-1	2	2	2	1	1	1
1	1	1	1	1	1	4	4	4	4	4	4

Table 3. Simulated N.E. for the illustrative example. $\Delta\pi^{1,-1} = 2$, J = 1.

a_1^*	a_2^*	a_3^*	a_4^*	a_5^*	a_6^*	π_1^*	π_2^*	π_3^*	π_4^*	π_5^*	π_6^*
-1	-1	-1	-1	-1	-1	3	3	3	3	3	3
-1	-1	-1	1	1	1	1	1	1	3	3	3
-1	-1	1	-1	-1	1	1	1	1	1	1	1
-1	1	-1	-1	1	-1	1	1	1	1	1	1
1	-1	-1	1	-1	-1	1	1	1	1	1	1
1	1	1	-1	-1	-1	3	3	3	1	1	1
1	1	1	1	1	1	5	5	5	5	5	5

Table 4. Simulated N.E. for the illustrative example. $\Delta\pi^{1,-1} = 3$, $J = 1$.

a_1^*	a_2^*	a_3^*	a_4^*	a_5^*	a_6^*	π_1^*	π_2^*	π_3^*	π_4^*	π_5^*	π_6^*
-1	-1	-1	-1	-1	-1	3	3	3	3	3	3
1	1	1	1	1	1	6	6	6	6	6	6

Table 5. Simulated N.E. for the illustrative example. $\Delta\pi^{1,-1} = 9$, $J = 3$.

a_1^*	a_2^*	a_3^*	a_4^*	a_5^*	a_6^*	π_1^*	π_2^*	π_3^*	π_4^*	π_5^*	π_6^*
-1	-1	-1	-1	-1	-1	9	9	9	9	9	9
1	1	1	1	1	1	18	18	18	18	18	18

Table 6. Simulated N.E. for the illustrative example. $\Delta\pi^{1,-1} = 6$, $J = 1$.

a_1^*	a_2^*	a_3^*	a_4^*	a_5^*	a_6^*	π_1^*	π_2^*	π_3^*	π_4^*	π_5^*	π_6^*
-1	-1	-1	-1	-1	-1	3	3	3	3	3	3
1	1	1	1	1	1	9	9	9	9	9	9

Table 7. Simulated N.E. for the illustrative example. $\Delta\pi^{1,-1} = 6.1$, $J = 1$.

a_1^*	a_2^*	a_3^*	a_4^*	a_5^*	a_6^*	π_1^*	π_2^*	π_3^*	π_4^*	π_5^*	π_6^*
1	1	1	1	1	1	9.1	9.1	9.1	9.1	9.1	9.1

Table 8. Variable Summaries

Variable	**Mean**	**Median**	**Std Dev**	**Minimum**	**Maximum**
PERMANENT CONVERSIONS (i.e. sequence GC, N = 972)					
Parcel Characteristics					
Duration	2.59	1.00	3.99	0.00	18.00
Acres	12.76	8.23	13.08	5.12	142.55
WSLP	3.25	2.80	1.87	1.00	11.30
WLCC	2.41	2.00	0.77	2.00	7.00
%LCC ≤ 2	72	100	44	0.00	100
Highway (km)	4.49	3.87	3.49	0.00	16.60
City (km)	7.57	7.11	3.70	0.52	21.09
Neighborhood-level Characteristics					
%Eased (0.5 km)	0.00	0.00	0.90	0.00	20.00
%Eased (1 km)	0.10	0.00	2.30	0.00	46.00
%Eased (2 km)	0.20	0.00	1.60	0.00	30.00
%Grass (0.5 km)	31.00	28.00	17.00	0.00	94.00
%Grass (1 km)	26.00	23.00	15.00	0.00	95.00
%Grass (2 km)	24.00	21.00	14.00	0.00	97.00
NEVER CONVERT (i.e. sequence G, N= 12,420)					
Parcel Characteristics					
Duration	19.00	19.00	0.00	19.00	19.00
Acres	16.98	9.34	21.98	5.12	199.49
WSLP	7.68	7.00	3.60	1.10	29.00
WLCC	3.07	2.00	1.69	1.82	7.00
%LCC ≤ 2	65	100	47	0.00	100
Highway (km)	6.22	5.63	4.37	0.00	27.14
City (km)	10.15	9.67	4.60	0.26	25.21
Neighborhood-level Characteristics					
%Eased (0.5 km)	1.50	0.00	0.082	0.00	100
%Eased (1 km)	1.40	0.00	0.063	0.00	87.30
%Eased (2 km)	1.40	0.00	0.046	0.00	71.80
%Grass (0.5 km)	67.00	69.00	24.00	0.00	100.00
%Grass (1 km)	56.00	57.00	26.00	0.00	100.00
%Grass (2 km)	49.00	48.00	26.00	0.00	100.00

Table 9. 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 10. 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 11. Cox-Proportional Hazard Regression Estimates. Dependent Variable: **Duration**.

Variable	0.5km Outer Ring	1km Outer Ring	2km Outer Ring
Grass Proportion	-4.31***	-3.56***	-2.83***
Eased Proportion	-14.53***	-11.74***	-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 12. Cox-proportional hazard rates.

Variable	0.5km Outer Ring	1km Outer Ring	2km Outer Ring
Grass Proportion (0.5km)	0.01	0.03	0.06
Eased Proportion (0.5km)	0.00	0.00	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 13. Cox-Proportional Hazard Regression Estimates for the GC sequence. Dependent Variable: **Duration**

Variable	0.5km Outer Ring	1km Outer Ring	2km Outer Ring
Grass Proportion	-1.33***	-1.27***	-1.34***
Eased Proportion	-0.30	-0.81	-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 14. Cox-proportional hazard rates for the GC sequence.

Variable	0.5km Outer Ring	1km Outer Ring	2km Outer Ring
Grass Proportion	0.26	0.28	0.26
Eased Proportion	1.35	0.44	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

Table 15. Cox-Proportional Hazard Regression Estimates using instrumental variable approach for ‘Grass proportion’ and ‘Eased Proportion’ variables. Dependent Variable: **Duration**

Variable	**0.5km Outer Ring**	**1km Outer Ring**	**2km Outer Ring**
Grass Proportion	-7.74***	-12.91***	-14.77***
Eased Proportion	-67.12***	-62.68***	-29.10***
WSLP	-0.51***	-0.33***	-0.30***
%LCC ≤ 2	-0.08	-0.38***	-0.30***
Highway (km)	-0.0004	0.02	-0.03***
City (km)	0.01	0.04**	0.01
-2LogL	15,814.13	15,735.96	15,657.73
AIC	15,826.13	15,747.96	15,669.73

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

Table 16. Cox-proportional hazard rates using instrumental variable approach for ‘Grass proportion’ and ‘Eased Proportion’ variables.

Variable	**0.5km Outer Ring**	**1km Outer Ring**	**2km Outer Ring**
Grass Proportion	0.00	0.00	0.00
Eased Proportion	0.00	0.00	0.00
WSLP	0.60	0.72	0.70
%LCC ≤ 2	0.92	0.68	0.70
Highway (km)	1.00	1.02	1.00
City (km)	1.01	1.04	1.00

Table 17. Variable Summaries for the truncated sample that represents long-term grass.

Variable	Mean	Median	Std Dev	Minimum	Maximum
PERMANENT CONVERSIONS (i.e. sequence GC, N = 60)					
Parcel Characteristics					
Duration	5.15	1.50	6.03	1.00	18.00
Acres	11.58	8.45	9.50	5.12	55.15
WSLP	3.91	3.60	1.90	1.70	10.94
WLCC	2.40	2.00	0.95	2.00	6.00
%LCC ≤ 2	0.80	1.00	0.39	0.00	1.00
Highway (km)	5.63	4.92	4.33	0.00	15.29
City (km)	8.35	8.23	4.14	1.74	17.35
Neighborhood-level Characteristics					
%Eased (0.5 km)	0.00	0.00	0.00	0.00	0.00
%Eased (1 km)	0.00002	0.00	0.0001	0.00	0.001
%Eased (2 km)	0.001	0.000	0.01	0.00	0.04
%Grass (0.5 km)	0.43	0.38	0.23	0.13	1.19
%Grass (1 km)	0.36	0.34	0.19	0.11	1.12
%Grass (2 km)	0.34	0.31	0.18	0.10	1.08
NEVER CONVERT (i.e. sequence G, N= 674)					
Parcel Characteristics					
Duration	19.00	19.00	0.00	19.00	19.00
Acres	13.23	8.45	13.82	5.12	119.43
WSLP	7.10	7.00	2.90	2.30	11.30
WLCC	3.03	2.00	1.58	2.00	7.00
%LCC ≤ 2	0.64	1.00	0.47	0.00	1.00
Highway (km)	6.70	6.40	4.18	0.00	19.10
City (km)	9.98	9.28	4.49	0.86	22.63
Neighborhood-level Characteristics					
%Eased (0.5 km)	0.01	0.00	0.04	0.00	0.34
%Eased (1 km)	0.02	0.00	0.06	0.00	0.61
%Eased (2 km)	0.03	0.00	0.07	0.00	0.38
%Grass (0.5 km)	0.67	0.69	0.23	0.04	1.60
%Grass (1 km)	0.57	0.56	0.25	0.00	1.59
%Grass (2 km)	0.49	0.45	0.25	0.00	1.40

Table 18. Cox-Proportional Hazard Regression Estimates using instrumental variable approach for ‘Grass proportion’ and ‘Eased Proportion’ variables. Dependent Variable: **Duration**

Variable	0.5km Outer Ring	1km Outer Ring	2km Outer Ring
Grass Proportion	-9.06	-8.70**	-6.12*
Eased Proportion	-21.44	-10.39	60.04
WSLP	-0.25*	-0.25*	-0.39***
%LCC ≤ 2	0.20	0.06	-0.10
Highway (km)	0.05	0.05	0.04
City (km)	0.02	0.02	-0.08
-2LogL	702.86	706.71	706.85
AIC	714.86	718.71	718.85

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

Table 19. Cox-proportional hazard rates using instrumental variable approach for ‘Grass proportion’ and ‘Eased Proportion’ variables.

Variable	0.5km Outer Ring	1km Outer Ring	2km Outer Ring
Grass Proportion	0.00	0.00	0.002
Eased Proportion	0.00	0.00	1.2E+26
WSLP	0.78	0.78	0.68
%LCC ≤ 2	1.22	1.06	0.90
Highway (km)	1.06	1.05	1.04
City (km)	1.02	1.02	0.92

FIGURES

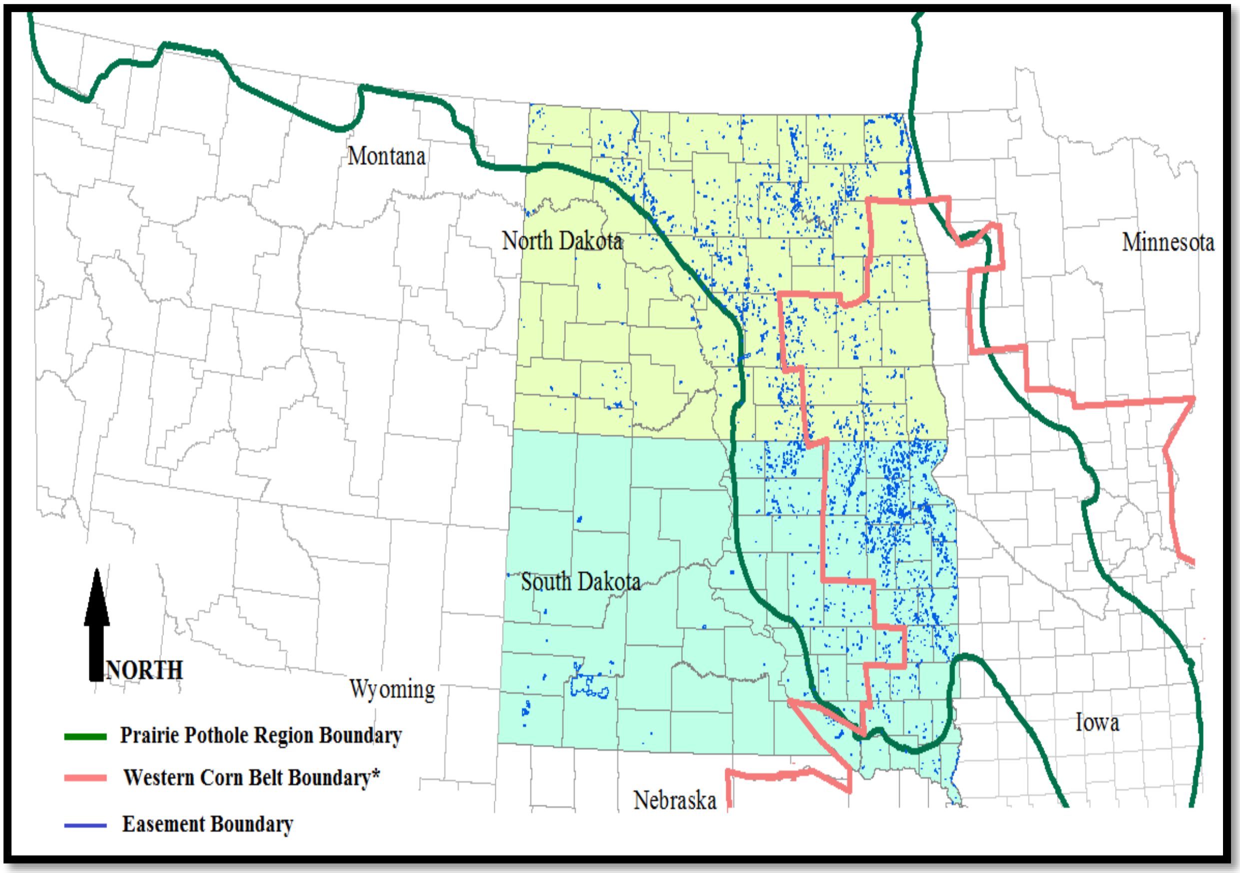

Figure 1. The U.S. Prairie Pothole Region, Western Corn Belt frontier and easement allocations in North and South Dakota. Not to scale.
*Notes: The representation of the Western Corn Belt frontier is approximate and manually built with the 2010 county-level map of the United States Department of Agriculture-National Agricultural Statistics Service's as a reference. Downloadable from: https://www.nass.usda.gov/Charts_and_Maps/Crops_County/.

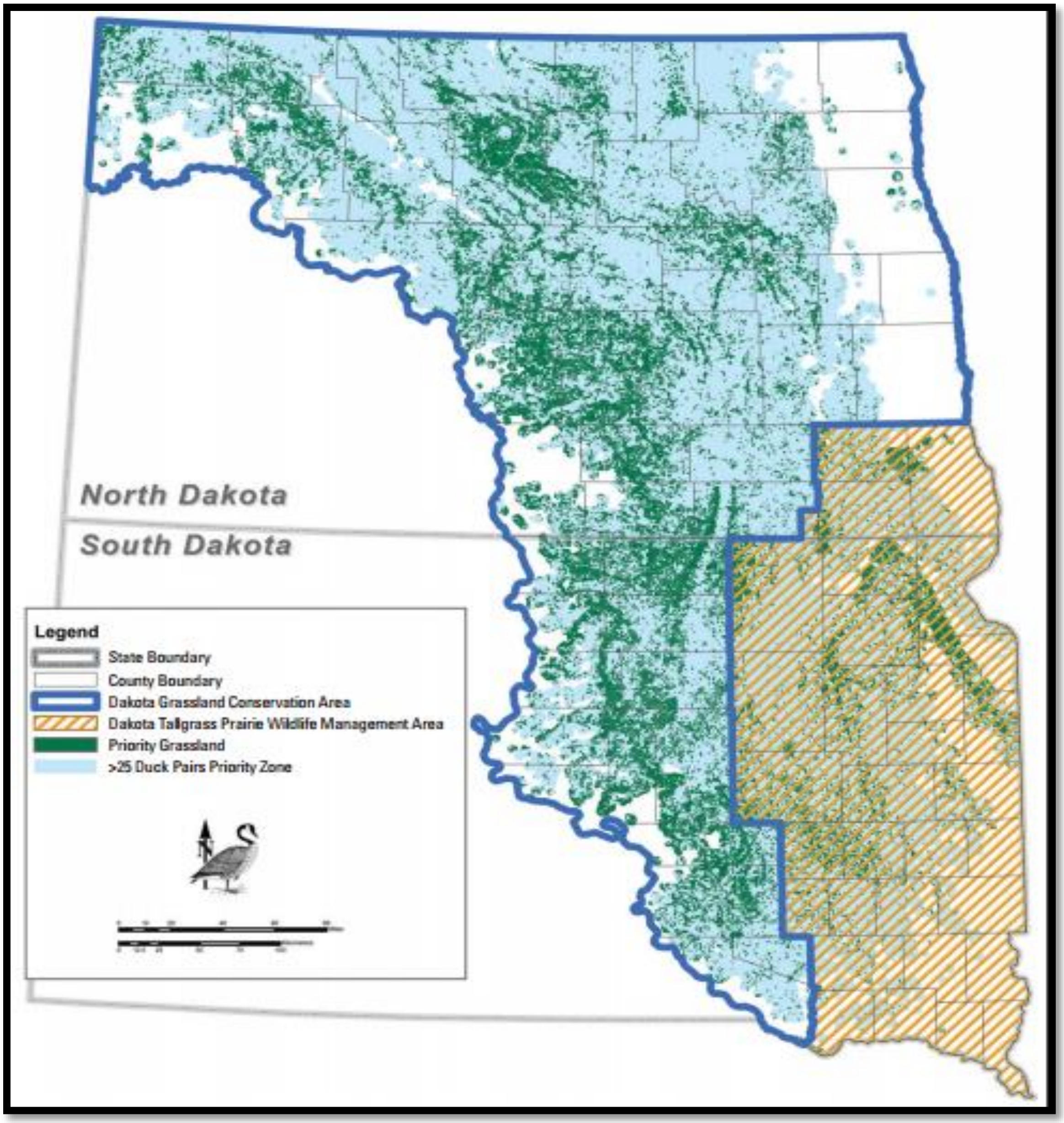

Figure 2. Waterfowl breeding density and USFWS Priority Conservation Acres. The figure has been taken from USFWS Land Protection Plan, 2011 pp. 4. Source: https://www.fws.gov/mountain-prairie/planning/lpp/nd/dkg/documents/dkg_lpp_final_all.pdf

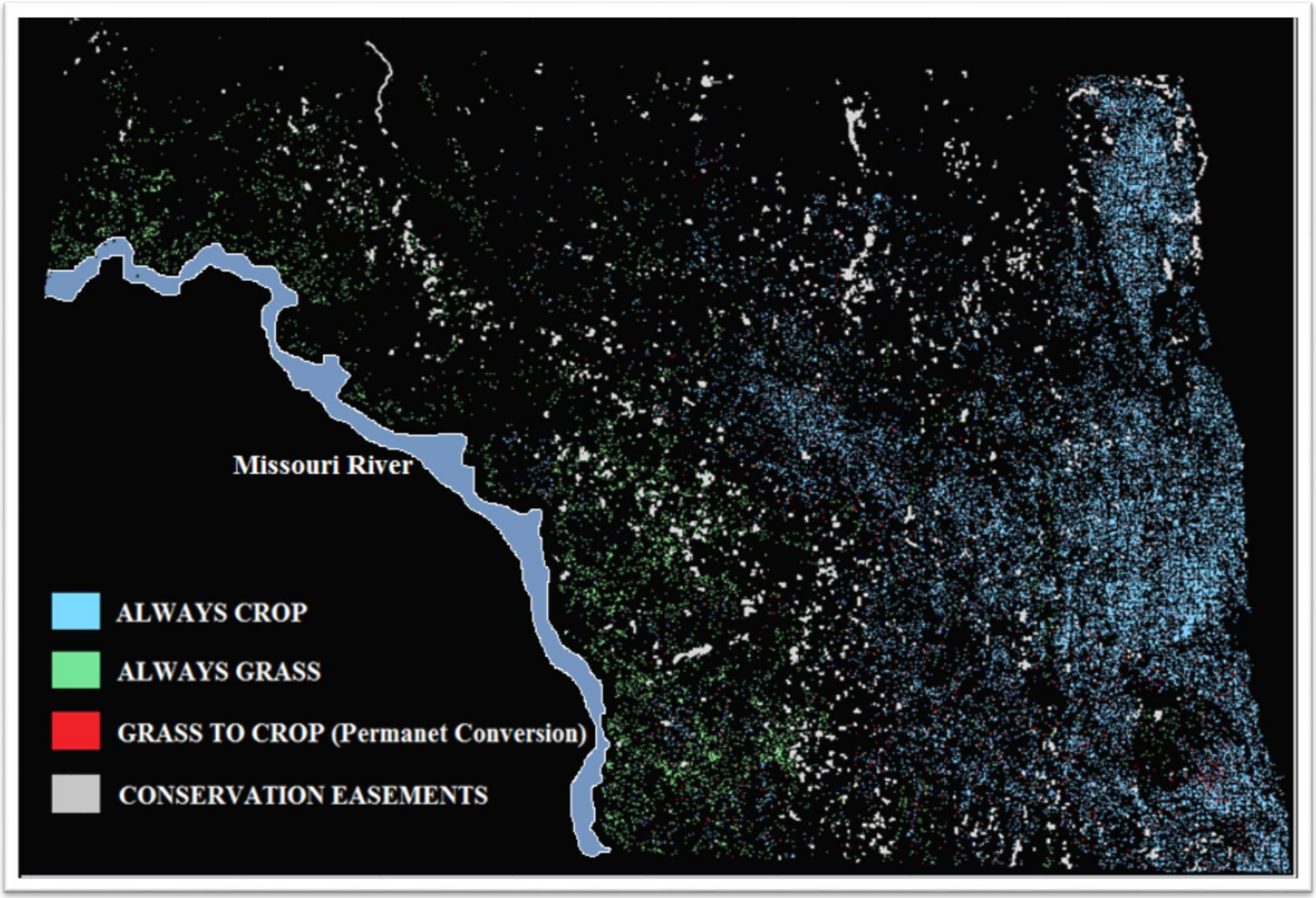

Figure 3. *Land use change combinations in eastern North Dakota and relative allocations of conservation easements.*

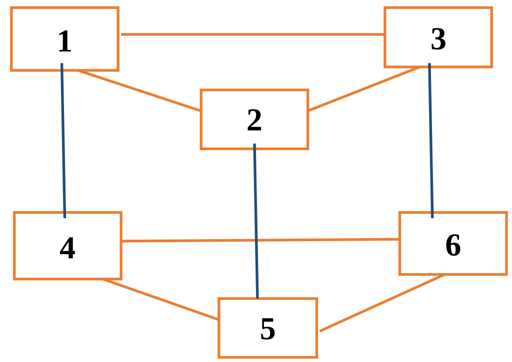

Figure 4. An example of inter-connected agents

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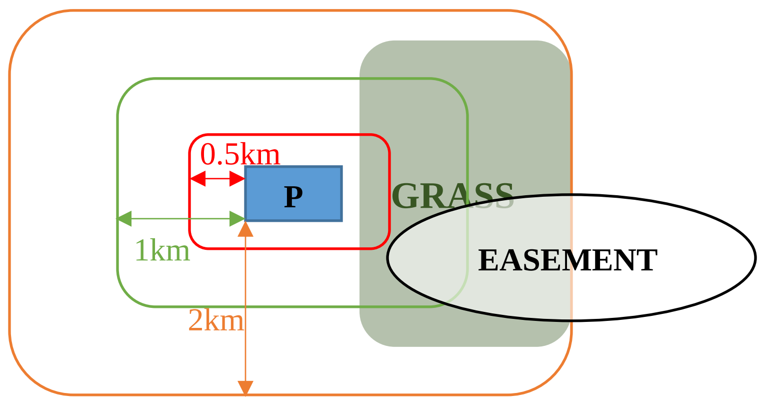
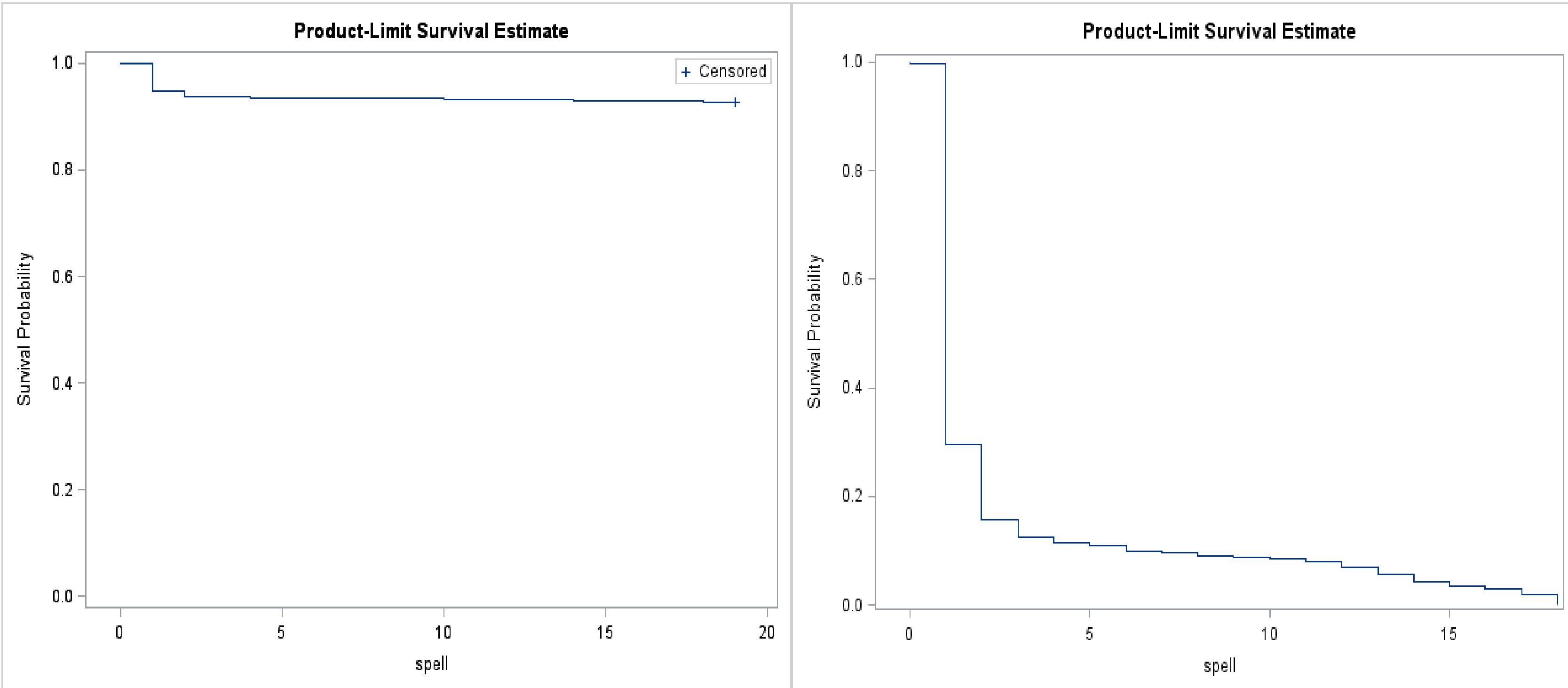
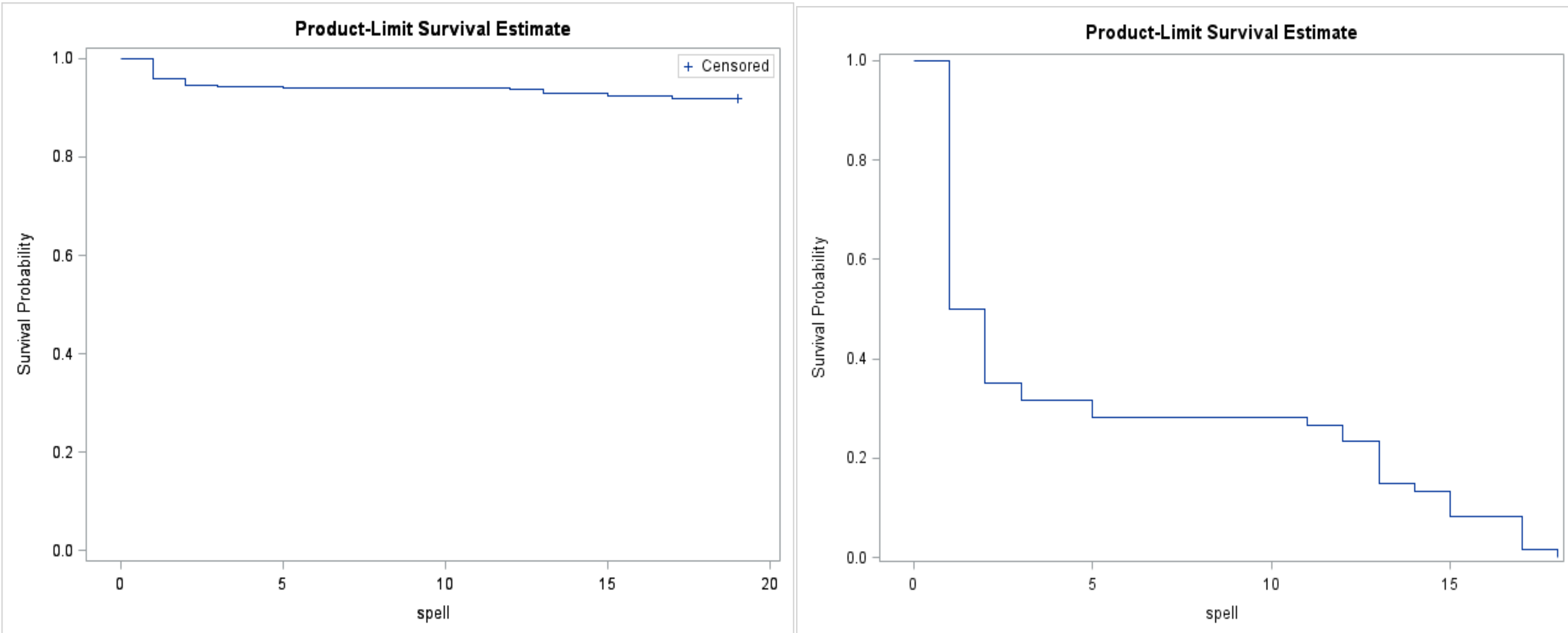


Figure 5. Spatial schematics of the neighborhood designations as outer-rings and easement allocations coverage for this study.



(a) (b)

Figure 6. 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.



(a) (b)

Figure 7. Kaplan-Meijer Survival Probability Estimates for ‘filtered’ parcels. Pane (a) is pooled data for G and GC categories; and Panel (b) zooms into the converted parcels or GC category in this filtered sample. The average mean survival time among the conversted parcels is now 5.2 years (almost double of what it was in the un-filtered sample in figure 6).

REFERENCES

Bikhchandani, S., Hirshleifer, D., Welch, I. 1992. " A theory of fads, fashions, custom and cultural change as informational cascade," *Journal of Political Economy,* 100(5): 992-1026.

Braza, M., 2017. "Effectiveness of conservation easements in agricultural regions," *Conservation Biology,* 31(4): 848-859.

Brock, W.A., Durlauf, S.N. 2001. "Discrete choice with social interactions," *Review of Economic Studies,* 68(2): 235-360.

Brock, W.A., Durlauf, S.N. 2007. "Identification of binary choice models with social interactions," *Journal of Econometrics,* 140(1): 52-75.

Drechsler, M., Watzold, F., Johst, K., Shogren, J.F. 2010. "An agglomeration payment for cost-effective biodiversity conservation in spatially structured landscapes," Resource and Energy Economics, 32(2): 261-275.

Durlauf, S.N. 1999. "How can statistical mechanics contribute to social science," *Proceedings of the National Academy of Sciences of the U.S.A.,* 96: 10582-10584.

Echenique, F. 2003. "Mixed equilibria in games of strategic complements," *Economic Theory,* 22(3): 33-44.

Edlin, A, Echenique, F. 2004. "Mixed equilibria are unstable in games of strategic complements," *Journal of Economic Theory,* 118(2004): 61-79.

Ellis, R. 1985. Entropy, large deviations and statistical mechanics, New York: Springer-Verlag, Ch. 4.

Greene W.H. 2003. Econometric analysis, 5th Ed., Ch. 22.5, pp. 791-801.

Harsanyi, J.C. 1995. "A new theory of equilibrium selection for games with complete information," *Games and Economic Behavior,* 10(2): 318-332.

Johnson, R.R., Granfors, D.A., Niemuth, N.D., Estey, M.E. Reynolds, R.E. 2010. "Delineating grassland bird conservation areas in the U.S. Prairie Pothole Region," *Journal of Fish & Wildlife Mgmt.,* 1(1): 38-42.

Kultti, K., Salonen, H. 1997. "Undominated equilibria in games with strategic complementarities," *Games and Economic Behavior,* 18(1): 98-115.

Manski, C.F. 1993. "Identification of endogenous social effects: the reflection problem," *Review of Economic Studies,* 60:531-42.

Mas-Collel, A., Whinston, M.D., Green, J. 1995. Microeconomic Theory. Oxford University Press, New York. Ch. 8.

Miao, R., Hennessy, D.A., Feng, H. 2016. “Grassland easement evaluation and acquisition: an integrated framework,” *Selected Paper for the Agricultural and Applied Economics Association Annual Meetings, Boston, M.A.* July 31-August 2, 2016.

Milgrom, P., Shannon, C. 1994. “Monotone comparative statics,” Econometrica, 62(1): 157-180.

Parkhurst, G.M., Shogren, J.F., Bastian, C., Kivi, P., Donner, J., Smith, R.B.W. 2002. “Agglomeration bonus: an incentive mechanism to reunite fragmented habitat for biodiversity conservation,” *Ecological Economics*, 41(2): 305-328.

Rashford B. S., Walker J. A., Bastian C. T. 2011. “Economics of grassland conversion to cropland in the Prairie Pothole Region,” *Conservation Biology*, 25(2): 276-84.

Stephens, S.E., Walker, J.A., Blunck, D.R., Jayaraman, A., Naugle, D.E., Ringelman, J.K., Smith A.J. 2008. “Predicting risk of habitat conversion in native temperate grasslands,” *Conservation Biology* 22(5):1320-30.

U.S. Fish and Wildlife Service. 2011. “Land Protection Plan-Dakota grassland conservation area, Lakewood, Colorado,” *Department of Interior, Fish and Wildlife Service, Mountain-Prairie Region*, 169 p. Available at:https://www.fws.gov/mountain-prairie/planning/lpp/nd/dkg/documents/dkg_lpp_final_all.pdf

U.S. Government Accountability Office. 2007. “At current pace of acquisitions, U.S. Fish and Wildlife Service is unlikely to achieve its habitat protection goals for migratory birds,” *Highlights of GAO-07-1093, a report to the Subcommittee on Interior, Environment, and Related Agencies, Committee on Appropriations, House of Representatives*.

Topkis, D.M. 1978. “Minimizing a submodular function on a lattice,” *Operations Research*, 26(2): 305-321.

Van Nouhuys, S. 2009. “Metapopulation ecology,” In Encyclopedia of Life Sciences, John Wiley & Sons.

Vives, X. 1990. “Nash equilibrium with strategic complementarities,” *Journal of Mathematical Economics* 19(3): 305-321.

Walker J, Rotella JJ, Loesch CR, Renner RW, Ringleman JK, Lindberg MS, Dell R, Doherty KE. 2013. “An integrated strategy for grassland easement acquisition in the Prairie Pothole Region, U.S.A.” *Journal of Fish & Wildlife Mgmt.*, 4(2): 267-279.

Wang, T., Luri, M., Janssen, L., Hennessy, D., Feng, H., Wimberly, M., Arora, G. 2016. “Farmers’ rankings of the determinants of land use decisions at the margins of the Corn Belt,” *Selected Paper for the Agricultural and Applied Economics Association Annual Meetings, Boston, M.A.* July 31-August 2, 2016.

Wright CK, Wimberly MC. 2013. “Recent land use change in the Western Corn Belt threatens grasslands and wetlands.” *Proceedings of the National Academy of Sciences of the U.S.A.*, 110: 4134-4139.

APPENDIX

A simple algorithm to find all of the game's Nash Equilibria:

Define the one-shot simultaneous move game as follows

- $i \in I$ = {1, 2, 3, 4, 5, 6} players.
- Individual action set, $a_i \in \{-1,1\}$ with $-1 \equiv$ 'stay in grass' and $1 \equiv$ 'convert to crop'. Hence, the overall strategy set of the game is $a = (a_1 \times a_2 \times a_3 \times a_4 \times a_5 \times a_6)$.
- Game's payoff function: $\pi(a) = (\pi_i(a_i, a_{-i}))_{i=1}^{6}$, where the individual player's payoff function is defined as $\pi_i(a_i, a_{-i}) = \pi_i^{a_i} + J\sum_{j \in N(i), j \neq i} a_i a_j$.

Steps to find all Nash Equilibria of the game:

1. Collect all unique strategy sets and compute their corresponding payoffs with neighbors as in figure 1.
2. ID each strategy profile, $s = 1, 2, ..., 64$, and designate the strategy profile and corresponding payoffs with a superscript: $a^s = (a_i^s)_{i=1}^{6}$; $\pi(a^s) = (\pi_i(a_i^s, a_{-i}^s))_{i=\mathbf{1}}^{\mathbf{6}}$.
3. Compare player 1's payoffs due to his/her strategy profile $a_1^s \in \{-1,1\}$ conditional on each unique strategy combination of players other than 1. Collect the strategy ID's where player 1's payoffs are maximized conditional on each unique a_{-1}^s and store them in set $s(1)$.
4. Repeat Step 3 for all players.
5. Collect the set of unique strategy IDs, $s(I) = \bigcap_{i=\{1,...,6\}} s(i)$.

The strategy sets $a_i^{s(I)}$ have the property that $\pi_i(a_i^{s(I)}, a_{-i}^{s(I)}) \geq \pi_i(a_i, a_{-i}^{s(I)})\ \forall\ i \,\&\, a_i \in a \setminus a_i^{s(I)}$, which is the definition of N.E.