Native Grassland Conversion: the Roles of Risk Intervention and Switching Costs

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Abstract

We develop a real option model of the irreversible native grassland conversion decision. Upon plowing, native grassland can be followed by either a permanent cropping system or a system in which land is put under cropping (respectively, grazing) whenever crop prices are high (respectively, low). Switching costs are incurred upon alternating between cropping and grazing. The effects of risk intervention in the form of crop insurance subsidies are studied, as are the effects of cropping innovations that reduce switching costs. We calibrate the model by using cropping return data for South Central North Dakota from 1989 to 2012. Simulations show that a risk intervention that offsets 20% of a cropping return shortfall increases the sod-busting cost threshold, below which native sod will be busted, by 41% (or $43.7/acre). Omitting cropping return risk across time underestimates this sod-busting cost threshold by 23% (or $24.35/acre), and hence underestimates the native sod conversion caused by crop production.

JEL Classification: Q18, Q38, H23

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Native Grassland Conversion: the Roles of Risk Intervention and Switching Costs

> "So when, to-day, on the homestead,
> We finished the virgin sod,
> Is it strange I almost regretted
> To have marred that work of God?"
> Rudolf Ruste, 1925, "The Last of the Virgin Sod."

In 1830 the U.S. prairie ecosystem was intact and extended from Indiana to the Rockies. Soils in the eastern tall grass prairie region are generally very fertile while the region's climate favors cropping. Westward expansion, together with the advent of the steel moldboard plow, tile drainage innovations and strong product demand ensured rapid conversion. By 1950, native grasslands in Illinois, Iowa, Southern Minnesota, and Northern Missouri had almost vanished, while much had also disappeared further west. Conversion continued in the western Prairie states over the latter half of the twentieth century, but the rate was not such as to attract widespread attention. Data are scarce but a variety of evidence suggests that the rate of native grassland conversion has increased markedly since the 1990s.

The prairie ecosystem is home to many species that are at risk to habitat loss. Much of the North American duck population nests in grasslands just east of the Missouri waterway, at the western fringe of the Corn Belt. Sprague's Pipit (*Anthus spragueii*) is a migratory songbird that nests primarily in northern plains native grasslands. It is a candidate for endangered species listing, and habitat loss has led to its disappearance from eastern parts of its historical breeding range. The Dakota Skipper butterfly (*Hesperia dacotae*) also has candidate status in the U.S. for listing as an endangered species. Presumed to have disappeared out of Illinois and Iowa it is one of many lepidopterans in the region that are of concern. It thrives best in non-shrubby post-fire prairie and so relocates and repopulates. In increasingly fragmented prairie, permanent disappearance from remaining tracts is likely as there is no amenable habitat to go to or return from upon prairie disturbance.

Stephens et al. (2008) calculated a 0.4% per year native grassland conversion rate in the period from 1989 to 2003 based on satellite data for parts of the 9,122 square mile Missouri Coteau portion of the Prairie Pothole Region (PPR). Farm Service Agency data for the Dakotas identified the cultivation of 450,000 acres of native grassland during 2002–2007. Rashford, Walker, and Bastian (2011) used National Resource Inventory data on non-cultivated land and cultivated land over 1979–80 through 1996–97. The study area is the 183 counties in the PPR stretching from Iowa and Minnesota through to Montana. Rashford, Walker, and Bastian anticipate that about 30 million acres of grassland (native or not) would be converted to cropping in the period from 2006 to 2011 given the market environment pertaining during that period. This conversion rate is slightly more than 1% per year. Johnston (2012) used remotely sensed National Land Cover Cropland Data Layer across the part of the PPR within the Dakotas. She found that 4,840 square miles of grassland (native or not) between 2001 and 2010 had been converted to cropping, representing 16.9% of grassland coverage in 2001. By using land-use data from the National Agricultural Statistics Service Cropland Data Layer, Wright and Wimberly (forthcoming) estimated that during 2006–2011 about 2 million acres of grassland had been converted to corn and soybean production in the western Corn Belt. If conversion from cropland to grassland is taken into account, then the net loss of grassland in this area was 1.3 million acres from 2006 to 2011.

Changes in the economic environment and available technology set may rationalize increased conversion. Regarding technology, drought tolerant corn and soybean varieties have removed one of the main obstacles to producing these crops in the western prairies (Yu and Babcock 2010; Tollefson 2011). Herbicide-tolerant and pest-resistant corn and soybean varieties have reduced chemical, labor, machine and management time requirements as well as allowing growers to expand the growing season by planting when conditions allow. For example the USDA’s estimate of usual planting dates for corn in North Dakota was given as

May 13–26 in 1997, but as May 2–28 in 2010; while the window for South Dakota was May 9–25 in 1997, but was May 2–27 in 2010 (USDA 1997, 2010). Badh et al. (2009) have found that the last frost to first frost growing season has increased by about one day per decade from 1879 to 2008 in North Dakota. Kucharik (2006, 2008) has confirmed a trend toward earlier average corn planting dates in the greater Corn Belt, and has ascribed a large fraction of trend yield growth to this shift toward earlier planting, increasing the attractiveness of crop production at any given price levels relative to grass-based production.

Other innovations of relevance include weed control that would reduce the costs of (*a*) converting native grassland, and (*b*) switching between crop production and grass-based farming subsequent to any conversion. Many soils in the Dakotas are prone to erosion and do not fare well under conventional tillage. The advent of atrazine, glyphosate and other herbicides since the 1960s has reduced the need for extensive cultivation when cropping (Triplett and Dick 2008), when rotating pasture with cropping, and when breaking virgin sod. Herbicide-resistant seed has further reduced the costs of cropping. In addition, these technologies likely have reduced the costs of compliance with the sodbuster provision introduced in the 1985 farm bill when a farmer contemplates converting highly erodible land.

United States farm-level prices for the major crops moved sharply above trend levels in 2006 and have remained 50% or more above the 1990–2006 average in the years 2007–2012. While the causes are in dispute, evidence suggests that renewable fuel use mandates put in place after the Energy Policy Act of 2005, coupled with strong emerging market demand for both energy and feedstock, are at least partly responsible (Enders and Holt 2012).

In the shorter-run, intensive margin responses to higher output prices are limited. For example, response to the most important non-seed input, nitrogen, is viewed as being concave with a plateau at nitrogen levels moderately above commercial applications (Setiyono et al. 2011). Expansion to meet demand needs to come from either long-run technical change or extensive margin adjustments. Growth in crop trend yield has not exceeded 2% for any of corn, wheat, or soybeans in the years 1960–2007, see Table S1 in Alston, Beddow, and Pardey (2009). Although high output prices increase the incentive to conduct yield improvement research, a meaningful trend yield growth response will likely take many years.

Both the market environment and aforementioned technical innovations suggest that much of the additional land for corn will come at the parched western fringe of the Corn Belt through converting grass and wheat land to a corn-soybean rotation in the Dakotas. Corn acres planted in South Dakota have increased from 4.5 million acres in 2006 to 5.2 million acres in 2011 while the corresponding figures in North Dakota are 1.69 million acres and 2.23 million acres, according to U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) data.

Our interest is in how U.S. commodity risk management policies might affect conversion. Since 1980, use of crop yield insurance, and more recently revenue insurance, has grown rapidly across all major U.S. crop sectors. The growth in use has been accompanied by increasingly generous premium, administrative cost, and underwriting subsidies that amounted to about $7 billion per year over the period 2005–2009 (Smith 2011). By 2012, maintaining and strengthening crop insurance policy was being viewed as among the U.S. farm lobby's main priorities (Glauber 2013). A prominent feature of the subsidies provided is that they are in proportion to premium. For example, if a grower elects to insure yield losses below 75% of reference yield then, as of 2012, the government pays 55% of the computed premium.

If the expected value of random yield y is $\bar{y}$ and coverage level is φ, then yield shortfall is given as $\max[\varphi\bar{y} - y, 0]$, a convex function of random yield. To the extent that the premium reflects the yield shortfall, a mean-preserving spread in yield will increase premium and so will increase the premium subsidy; that is, premium subsidy increases with yield riskiness. In light of poorer soils and aridity, production risk is generally viewed as greater on the Great Plains when compared with the Corn Belt (Shields 2010). Thus, a concern has long been that premium subsidies incentivize the decision to convert land from either virgin sod or previously cultivated grass-based agriculture to row crop production.

A recent effort to address the concern was the inclusion of the "Sodsaver" provision in the 2008 farm bill. This provision applies only to the Prairie Pothole states of Iowa, Minnesota, Montana, North Dakota, and South Dakota, and is implemented in a state only upon request by the state's governor. The provision disallows crop insurance coverage for land converted from native sod for the "first five years of planting," where coverage was typically proscribed for the first year in any case. Eligibility for the Supplemental Revenue Assistance Program (SURE) requires federal crop insurance uptake, so Sodsaver also precludes these program benefits. As of 2012, no state governor has sought to invoke the provision.

Many studies have examined the impacts of government payments on land use decisions. A few of these focused specifically on federal crop insurance programs (Young, Vandeveer, and Schnepf 2001; Goodwin, Vandeveer, and Deal 2004; Lubowski et al. 2006; Stubbs 2007; GAO 2007). Goodwin, Vandeveer, and Deal (2004) represents the consensus that while crop insurance subsidies do incentivize cropping, the effect is not large. These works referred to an environment in which lower subsidies were provided than those provided since 2000, while the level of analysis was aggregated. More recent work by Claassen, Cooper, and Carriazo (2011) sought to provide farm-level analysis of a wide suite of farm programs, while Claassen et al. (2011) has focused on the role of Sodsaver. It should be noted that, in addition to yield risk effects, the value of crop insurance subsidies increase in direct proportion to the overall output price level. Thus, a further distinction between these latter pair of studies and earlier work was treatment of the higher overall price environment since about 2006. Notwithstanding, the findings were similar—while insurance subsidies did have an impact the effect was not very large.

We too are interested in understanding the incentive to convert, especially in regard to any role of risk market policy interventions. Unlike all of the literature above, however, we will take a dynamic perspective. Further, our concern is not at all with how risk management policy interventions change the trade-off between high utility states of nature and low utility states of nature, although we do not deny that such benefits may motivate behavioral change. Our interest is in exploring a very different and, as far as we know, hitherto unmentioned channel through which crop insurance interventions could affect land use choices.

Specifically, we note that there are investment costs associated with both breaking native sod and converting between improved grassland and cropping. The magnitudes of these costs vary with the land at issue, but can be quite large. Technology has affected these conversion and switching costs. In addition, the incentive to incur these costs arises from the crop market environment. The more turbulent the returns the less inclined a grower should be to make costly investments that they might subsequently regret were cropping to suddenly become less profitable. Our intent is to build and simulate an asset valuation model that articulates incentives arising from cultivation innovations and changes in the crop production risk management policy environment.

Related literature exists on how incentives affect land quality dynamics. In a seminal paper, McConnell (1983) provided a capital valuation model of soil erosion dynamics. Hertzler (1990) developed this class of model for the study of how crops in rotation consume and restore fertility, but did not introduce switching costs. Willassen (2004) introduced a switching cost into a model of rotating through fallow and cropping. Doole and Hertzler (2011) introduced switching costs into a continuous time model in which crop input choice variables can also adjust over time subject to constraints on land quality dynamics. Hennessy (2006) introduced an essentially static model of crop rotation choice, where neither adjustment costs nor price randomness arise.

The present model is grounded in the real options line of models that seek to understand incentives for one-time capital investments in the presence of uncertainty about the level of returns they generate (Dixit 1989; Trigeorgis 1996). There are two states of market environment, namely high and low cropping returns. The owner of virgin sod must incur a one-time cost to convert, including deep cultivation, stone picking, removing brush, and applying herbicide treatments, and may do so if the crop market environment is sufficiently attractive relative to the grass-based agriculture market environment. Thereafter, the owner can choose to switch back and forth between cropping and grass-based agriculture, but these switches may also involve costs. If conversion or subsequent switching costs are large, then the owner seeking to maximize the expected net present value of profits may choose not to convert in the first place.

Crop insurance policy is relevant because a subsidized intervention pulls low cropping returns outcomes up toward high returns outcomes. This reduces the likelihood that a grower will find it optimal to switch at later time points, and so increases the expected profit from conversion. The owner foresees this and is all the more likely to convert. Technology innovations are also relevant to the extent that they reduce switching costs and will allow the operator to more readily switch upon conversion. When compared with the effects of a crop insurance subsidy intervention, the nature of the subsequent cropping behavior would differ under technology innovations. A more opportunistic alternating system would be supported rather than permanent cropping; however, both effects would increase the incentive to convert.

Our paper is presented consistent with the two-stage backward induction approach taken during analysis. In stage 2, which is presented first, the model is posed assuming that the land has been converted. Land valuations are developed for both a permanent cropping system and a cropping system in which switching occurs, and we consider when each system will be chosen. We then step back to stage 1 and ask whether land with given one-time conversion costs would be converted in light of the profit environment and system choices available were conversion to occur. The model is then calibrated with reference to available data on cropping opportunities in South Central North Dakota. The last section concludes.

Modeling Cropping System Choice

The setting is a two-stage decision game against nature. In the first stage the decision to convert land, or bust sod, is made. The second stage involves the choice among cropping systems. Both decisions are made with rational foresight over the future and necessitate modeling of crop profit environments.

The basic second-stage model setup involves the existence of crop profitability regimes, low, *l*, and high, *h*. State change occurs in a Markovian continuous time setting, see Section 3.2 in Hoel, Port, and Stone (1972). The constant hazard rate for transitioning from *l* to *h* is λa, while that for transitioning from *h* to *l* is $\lambda b.$ Here, $\lambda \geq 0$ is a scaling parameter to allow for increasing flux between the two states. The long-run equilibrium probability of being in states *l* and *h* are $b/(a+b)$ and $a/(a+b)$, respectively, and are unaffected by scaling parameter λ. However, λ should influence economic choices for two reasons. First, the present value of being in state *h* will be higher whenever λ is low, as the present regime can be viewed as being more persistent, and price persistence over time characterizes commodity markets (Deaton and Laroque 1992; Ghoshray 2013). Second, if there are opportunities to adjust to states by changing cropping choices, but at some adjustment cost, then a low value of λ will be preferred because it would reflect persistence in the decision environment—less need to adjust (i.e., incur switching costs), and so greater return on adjustment costs incurred.

Conversion and switching costs are as follows. There is a one-time sod-busting conversion cost of amount θ, which may differ across tracts of native grassland. The distribution is given by $F(\theta):[\underline{\theta},\overline{\theta}]\to[0,1]$, where $\underline{\theta}$ and $\overline{\theta}$ are the lower bound and upper bound of θ, respectively. For land that that has been cropped, the cost of switching from cropping to grazing is given by κ_{cg}, while that of switching from grazing to cropping is given by κ_{gc}. We assume that κ_{cg} and κ_{gc} are common across units.

In the second stage, the grower can choose an action between cropping and grazing under state *h* or state *l*. Let R_g denote the net revenues flow from grazing in both states *h* and *l*.[1] When the land has not been converted then returns are just R_g (i.e., we simplify in assuming that returns to grazing are the same under conversion as absent conversion). Let $R_{c,h}$ and $R_{c,l}$ denote net revenue flows from cropping in states *h* and *l*, respectively. To represent a lower net return in state *l*, we let $R_{c,l} = R_{c,h} - \delta$, where $\delta > 0$ is a constant. It is reasonable to assume that $R_{c,h} > R_g$. We also assume that $R_g > R_{c,l}$, and our rationale is as follows. Were $R_{c,l} \geq R_g$, then the grower would also prefer cropping in state *l*, and profits from cropping would dominate those from grass-based production in both states of nature. The policy concerns we are inquiring about regard marginal land rather than the fertile cropland where cropping is always profitable. The continuous time interest rate is given as r.

Based on the assumptions about the returns under each state and action, we can readily check that sod busting only occurs in state *h*. This is because with the option to bust native sod at any time, a landowner who busts sod under state *l* will receive a lower return than that from grazing, while also incurring a sod-busting cost. Moreover, were conversion profitable in state *l*, then the land would not be marginal for conversion and would have long since been cropped. We also show that once sod is busted the land owner will follow either a 'crop always' system or an 'alternate' system, where in the 'crop always' system the land owner crops under both states *h* and *l*; and in the 'alternate' system the land owner crops under state *h* but grazes under state *l*. The proof is presented in Item A of Supplemental Materials. In the remainder of this

[1]For simplicity, we assume that the net revenues flow from grazing in states *h* and *l* are the same. Relaxing this assumption will not extract extra insight from the article, but will complicate model exposition and analysis.

section we identify and compare returns from the two systems. For notational consistency, we denote native sod as the 'graze always' system.

'Crop always' System

We first establish the state-conditioned value of land when the land is cropped in all states. The valuation model is continuous-time with t as time, and present time given by $t=0$. Refer to the value of land under 'crop always' (or ca) when in states h and l as $\Phi(h;\text{ca})$ and $\Phi(l;\text{ca})$, respectively.

Appendix A shows that the system solves as

$$(1) \qquad \Phi(h;\text{ca}) = \frac{R_{c,h}}{r} - \frac{\lambda b\delta}{ru}; \qquad \Phi(l;\text{ca}) = \frac{R_{c,h}}{r} - \frac{(r+\lambda b)\delta}{ru}; \qquad u = r + \lambda a + \lambda b.$$

Observe that $\lim_{\lambda\to\infty}\Phi(h;\text{ca}) = \lim_{\lambda\to\infty}\Phi(l;\text{ca}) = R_{c,h}/r - b\delta/[r(a+b)]$. So, as state persistence vanishes, then the difference between state dependent values also vanishes:

$$(2) \qquad \Phi(h;\text{ca}) - \Phi(l;\text{ca}) = \frac{\delta}{u},$$

which is decreasing in the value of λ. The intuition is that the additional value of being in state h, rather than state l, decreases as the rate of flux increases.

Notice too that the long-run variance in profit is

$$(3) \qquad \frac{a}{a+b}\left\{R_{c,h} - \frac{aR_{c,h}}{a+b} - \frac{b(R_{c,h}-\delta)}{a+b}\right\}^2 + \frac{b}{a+b}\left\{R_{c,h} - \delta - \frac{aR_{c,h}}{a+b} - \frac{b(R_{c,h}-\delta)}{a+b}\right\}^2 = \frac{ab\delta^2}{(a+b)^2},$$

which is independent of λ. Persistence reduces short-run variability in profit but not long-run variability in profit.

'Alternate' System

If, instead of 'crop always,' the grower alternates over to grazing (i.e., puts land under pasture) whenever the state is low, then two modifications to the context occur. Returns to grazing replace returns to cropping while conversion costs are incurred. Upon analysis provided in Appendix B, we obtain

(4)
$$\Phi(h;\text{alt}) = \Phi(h;\text{ca}) - \frac{\lambda b(r+\lambda a)\kappa_{cg} + \lambda^2 ab\kappa_{gc} - \lambda b(R_g - R_{c,l})}{ru};$$
$$\Phi(l;\text{alt}) = \Phi(l;\text{ca}) - \frac{\lambda a(r+\lambda b)\kappa_{gc} + \lambda^2 ab\kappa_{cg} - (r+\lambda b)(R_g - R_{c,l})}{ru}.$$

Here state *h* revenue is reduced by amount $\lambda b\kappa_{cg}$ to reflect the expected cost of switching into grazing, while state *l* revenue is reduced by amount $\lambda a\kappa_{gc}$ for the same reason.

Observe that when the *l* state cropping returns and grazing returns are the same, or $R_g = R_{c,h} - \delta$, then

(5)
$$\Phi(l;\text{ca}) - \Phi(l;\text{alt}) = \frac{\lambda a\kappa_{gc}}{u} + \frac{ab\lambda^2(\kappa_{cg} + \kappa_{gc})}{ru};$$

or, in other words, the gap between the two depends only on the expected present value of pasture establishment and termination costs saved.

Which system?

It is the state *l* present value that matters when choosing between cropping systems in stage two. This is because only in state *l* do benefits from avoiding cropping at a loss arise under the 'alternate' system. When the exogenous environment state becomes *l* then the grower faces the choice between converting to grass or remaining in cropping, and so effectively the choice between the two systems. We define

(6)
$$\Delta^l_{\text{ca-alt}} \equiv \Phi(l;\text{ca}) - \Phi(l;\text{alt}) + \kappa_{cg}$$
$$= \frac{(r+\lambda b)(R_{c,h} - \delta - R_g)}{ru} + \frac{\lambda a\kappa_{gc}}{u} + \frac{ab\lambda^2(\kappa_{cg} + \kappa_{gc})}{ru} + \kappa_{cg}.$$

Whenever $\Delta^l_{\text{ca-alt}} > 0$, then in state *l* the grower remains in cropping. Why does the cost of switching from cropping to pasture, κ_{cg}, arise in the first line of eqn. (6)? This cost will be incurred in state *l* upon switching from the 'crop always' system to the 'alternate' system (i.e., from having value $\Phi(l;\text{ca})$ to having value $\Phi(l;\text{alt})$). Of course, the decision between the two systems tilts toward 'crop always' whenever any of the switching cost or state of flux parameters, λ, increase. Writing

$$\text{(7)} \qquad \hat{\delta} = R_{c,h} - R_g + \lambda a \kappa_{gc} + (r + \lambda a)\kappa_{cg},$$

as the breakeven δ satisfying $\Delta^{l}_{\text{ca-alt}} = 0,$ we can state that 'crop always' is preferred among the two choices whenever $\delta \le \hat{\delta}$.[2] From eqn. (7) it is immediate that an increase in any of $\{R_{c,h}, \lambda, a, \kappa_{gc}, \kappa_{cg}\}$ or a decrease in R_g, increases $\hat{\delta}$, and hence expands the set of circumstances under which 'crop always' is preferred over 'alternate,' given that sod has been busted.

Sod-busting Incentives

In our model, sod-busting occurs whenever the expected increase in net present value of profit to be had upon converting exceeds the conversion cost. This of course depends on the second-stage choice. It is state *h* present value that matters when making a non-trivial conversion decision because, as discussed in the previous section, sod-busting only occurs in state *h*. In this section we quantify sod-busting incentives and study factors that influence these incentives.

Under 'Crop Always' System

The native sod 'graze always' system has the value R_g / r. When $\delta \le \hat{\delta}$, then the choice facing the land owner contemplating irreversible conversion of native sod in state *h* will be between 'graze always' and 'crop always.' The difference between expected benefits and expected costs is given by

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[2] By eqn. (4) one can readily check that a comparison of $\Phi(h;\text{ca})$ with $\Phi(h;\text{alt})$ generates the same breakeven δ as in eqn. (7). This confirms that the optimal choice regarding cropping system to be made in state *h* is time-consistent.

(8) $$\Delta^{h}_{\text{ca-con}} = \Phi(h;\text{ca}) - \frac{R_g}{r} - \theta = \frac{R_{c,h} - R_g}{r} - \frac{\lambda b \delta}{ru} - \theta.$$

Define $\hat{\theta}^{\text{ca}}$ as the value of θ that sets $\Delta^{h}_{\text{ca-con}} = 0$. For $\theta < \hat{\theta}^{\text{ca}}$ then conversion occurs when 'crop always' is the preferred cropping system.

Notice that $\partial\hat{\theta}^{\text{ca}} / \partial\delta \,|_{\Delta^{h}_{\text{ca-con}}=0} = -\lambda b/(ru) < 0$, and also that

(9) $$\Delta^{h}_{\text{ca-con}} \,|_{\delta=\hat{\delta}} = \frac{(R_{c,h} - R_g)(r+\lambda a) - \lambda b[\lambda a \kappa_{gc} + (r+\lambda a)\kappa_{cg}]}{ru} - \theta.$$

The left part of Figure 1 characterizes equation set (8) and (9) in the (δ,θ) plane. As the value of δ increases the breakeven value of θ declines because the expected value of 'crop always' declines. Above line $\Delta^{h}_{\text{ca-con}} = 0$ the choice is to keep land in native sod, or graze always, and below the line the choice is the 'crop always' system.

Under 'Alternate' System

When $\delta > \hat{\delta}$ then the choice facing the land owner contemplating irreversible conversion of native sod in state *h* will be between 'graze always' and 'alternate.' The difference between values is given by

(10) $$\Delta^{h}_{\text{alt-con}} = \Phi(h;\text{alt}) - \frac{R_g}{r} - \theta = \frac{(r+\lambda a)(R_{c,h} - R_g - \lambda b \kappa_{cg}) - ab\lambda^2 \kappa_{gc}}{ru} - \theta,$$

where $\Phi(h;\text{alt})$ is provided in (B5) of the appendix. We write $\hat{\theta}^{\text{alt}}$ as the breakeven θ, such that $\Delta^{h}_{\text{alt-con}} = 0$. When $\theta \le \hat{\theta}^{\text{alt}}$ then conversion occurs. Here we see that $\hat{\theta}^{\text{alt}}$ does not depend on δ, as the 'alternate' system allows the farmer to avoid low revenue cropping environments.

We note for future reference that $d\Delta^{h}_{\text{alt-con}} / d\kappa_{cg} = -\lambda b u^{-1} - \lambda^2 ab/(ru) = -u^{-1} + d\Delta^{h}_{\text{alt-con}} / d\kappa_{gc} < d\Delta^{h}_{\text{alt-con}} / d\kappa_{gc} = -\lambda^2 ab/(ru) < 0$. The relationship will be useful when interpreting graphs.

We have already provided a graphical depiction of sod-busting decisions in $(\hat{\theta},\delta)$ space where eqn. (8) allows for a characterization of the critical value when $\delta \le \hat{\delta}$. Now we seek to learn how the critical value of $\hat{\theta}$ changes either side of $\delta = \hat{\delta}$. This will allow us to complete the characterization of optimal sod-busting choices in $(\hat{\theta},\delta)$ space, and so provide insights on how policies regarding δ affect conversion incentives.

When comparing the breakeven sod-busting cost θ in the two systems we obtain

$$\begin{aligned}\hat{\theta}^{\text{ca}}|_{\delta=\hat{\delta}} - \hat{\theta}^{\text{alt}} &= \frac{(R_{c,h}-R_g)(r+\lambda a) - \lambda b[\lambda a \kappa_{gc} + (r+\lambda a)\kappa_{cg}]}{ru} \\ &\quad - \frac{(r+\lambda a)(R_{c,h}-R_g-\lambda b \kappa_{cg}) - ab\lambda^2\kappa_{gc}}{ru} = 0.\end{aligned} \tag{11}$$

So for the δ at which there is indifference between second-stage cropping choices, then the breakeven sod-busting costs are equal in the 'crop always' system and in the 'alternate' system. This is quite intuitive in that whenever the land values under 'crop always' and 'alternate' systems are equal, then the magnitude of sod-busting costs that trigger grassland conversion under the two systems are also equal. Figure 1 depicts continuity along the boundary of the (δ,θ) set for which native sod is not broken, and eqn. (11) ensures that $\hat{\theta}^{\text{ca}}|_{\delta=\hat{\delta}} = \hat{\theta}^{\text{alt}}$. How the kink point in Figure 1, $(\hat{\delta},\hat{\theta}^{\text{ca}})$, changes with policy interventions will be discussed below.

Effects of Risk Intervention

Now suppose that the government agrees to absorb ("abs" for short) fraction $\phi \in (0,1)$ of crop revenue shortfall below $R_{c,h}$. It could do so through revenue insurance, for which subsidies are presently available on all the major field crops grown in the United States, see Shields (2010) for details. In that case $R_{c,l}^{abs} = R_{c,h} - (1-\phi)\delta$ while (7) and (8) are mapped as follows:

(12) $$\hat{\delta}^{abs} = \frac{R_{c,h} - R_g + \lambda a \kappa_{gc} + (r + \lambda a)\kappa_{cg}}{1-\phi} > \hat{\delta},$$

(13) $$\Delta^{h,\text{abs}}_{\text{ca-con}} = \frac{R_{c,h} - R_g}{r} - \frac{\lambda b(1-\phi)\delta}{ru} - \theta \geq \Delta^{h}_{\text{ca-con}}.$$

However $\Delta^{h}_{\text{alt-con}}$ is unaffected because δ does not arise in eqn. (10) or, perhaps stated more intuitively, because δ, does not appear in the 'alternate' system cropping return for state *l*. See (B5) in the Appendix.

Figure 2 depicts a risk intervention's impact on stage 1 conversion choices. When fraction ϕ of crop revenue shortfall δ is absorbed by a subsidized crop insurance program, then the $\Delta^{h}_{\text{ca-con}} = 0$ line will tilt upward, while the left end of the line remains fixed at point $(0, (R_{c,h} - R_g)/r)$ in (δ, θ) space. Since $\Delta^{h}_{\text{alt-con}}$ is unaffected by this reduction in revenue shortfall, the $\Delta^{h}_{\text{alt-con}} = 0$ line is not affected, except that its left-most point shifts rightward to $\delta = \hat{\delta}^{\text{abs}}$. For a given parcel of native sod, when $\delta \geq \hat{\delta}^{\text{abs}}$, then crop insurance subsidies do not affect sod busting. This is because when δ is very high then the converted land will be under the 'alternate' system and risk intervention does not matter. When $\delta < \hat{\delta}^{\text{abs}}$ then the risk intervention does increase sod busting (i.e., for that value of δ the set of θ values under native sod contracts). The extent of the impact is given by the probability measure, according to $F(\theta)$, of the vertical difference between the solid line and the dotted line valued at δ.

Suppose now that we extend native sod's distribution into two dimensions to include both sod-busting costs and cropping return shortfalls (i.e., $F(\delta, \theta): [\underline{\delta}, \overline{\delta}] \times [\underline{\theta}, \overline{\theta}] \rightarrow [0,1]$). Then the impact of the risk management policy is given in Figure 2 and land tracts amounting to the probability measures of areas A and B become open to conversion; that is, land tracts with higher conversion costs become open to conversion. All of these tracts convert to 'crop always,' where wedge A converts from native sod. Observe here that the area of triangle A scales up in proportion to the value of $\hat{\delta}^{\text{abs}} - \hat{\delta}$, its base. In addition, from

(14) $$\hat{\delta}^{\text{abs}} - \hat{\delta} = \frac{\phi\hat{\delta}}{1-\phi},$$

together with the calculation $d^2[\phi/(1-\phi)]/d\phi^2 = 2(1-\phi)^{-3} > 0$, it is clear that area A is convex in subsidy parameter ϕ. Consider when $\phi = 0.3$ so that $\phi/(1-\phi) = 3/7$. If scaling parameter ϕ doubles to 0.6, which is typical for U.S. revenue insurance subsidies, then $\phi/(1-\phi) = 1.5$. So a doubling of the risk intervention increases area A by factor $1.5/(3/7) = 3.5$, or by 250%.

Area B in parameter space (δ, θ) converts from 'alternate' to 'crop always.' This area is also proportional to $\hat{\delta}^{\text{abs}} - \hat{\delta}$, and so convex in subsidy parameter ϕ. This simple arithmetic on how sensitive conversion incentives for native sod and other grasslands can be to a change in crop insurance subsidies should underline the gravity of the need for empirical inquiry into the issue.

Effects of a Change in Switching Costs

Market events and technological innovations have reduced the costs of switching land in recent times. In particular broad-spectrum herbicide Roundup® (glyphosate) was first marketed in 1976. Glyphosate kills most growing plants upon contact and so reduces the need for costly mechanical cultivation as a means of weed control. It has been off-patent since 2000 and its price declined by about 40% in the United States during patent protection phase-out (Nail, Young, and Schillinger 2007; Duke and Powles 2009). The chemical's increasing availability can be interpreted as reducing the values of κ_{gc} and κ_{cg} in our model. We inquire into how our model suggests this would affect the nature of equilibrium cropping choices.

Let the switching cost of converting from cropping to grass (i.e., κ_{cg}) decrease.[3] Then eqn. (8) shows that the value of $\Delta^{h}_{\text{ca-con}}$ is unaffected, as neither of the systems being compared

[3] Qualitatively the effect of a change in κ_{gc} would be similar.

involves the possibility of switching crops at a later date. However, from eqn. (7), value $\hat{\delta}$ at which there is indifference between 'crop always' and 'alternate' systems decreases. This is because switching costs would be avoided under permanent cropping but would not be avoided under the 'alternate' system. So 'alternate' becomes more attractive under the lower switching costs. From eqn. (10), line $\Delta^{h}_{\text{alt-con}} = 0$ shifts up in (δ, θ) space as converting to the 'alternate' system has become more attractive relative to keeping the land in native sod.

Figure 3 depicts how a decrease in κ_{cg} to a value κ'_{cg}, that shifts the value of $\hat{\delta}$ down to $\hat{\delta}'$ in compliance with eqn. (7), affects the critical parameters at which one would be indifferent between the three systems. As κ_{cg} decreases, line $\Delta^{h}_{\text{alt-con}} = 0$ shifts upward and intersects with line $\Delta^{h}_{\text{ca-con}} = 0$ at $\delta = \hat{\delta}'$, where $\hat{\delta}'$ is the value of δ at which the landowner is indifferent between 'crop always' and 'alternate' systems under κ'_{cg}, and $\theta^{\text{alt}\prime}$ is such that $\Delta^{h}_{\text{alt-con}} = 0$ for land tracts with $\theta \in (\theta^{\text{alt}}, \theta^{\text{alt}\prime}]$. From area D in Figure 3, we can see that land tracts under native sod with $\delta > \hat{\delta}'$ will be busted and placed in the 'alternate' system. The magnitude of this extra native sod busted is the probability measure of the vertical difference between the solid line and the dotted line valued at δ. If $\delta \le \hat{\delta}'$, however, a decrease in κ_{cg} does not affect land conversion. This is because when $\delta \le \hat{\delta}'$ converted land is under 'crop always,' and κ_{cg}, the switching cost from cropping to grazing, does not affect either the value of land under 'crop always' or the value of native sod. Lower switching costs will also induce some land to convert from 'crop always' to 'alternate' because the friction costs of alternating have fallen. These land tracts are represented by area C in Figure 3.

However, one might expect that a technology that decreases switching costs between cropping and grazing would also reduce the one-time sod-busting cost, θ. For example, as mentioned at this sub-section's outset, broad-spectrum herbicide glyphosate reduces the need for costly mechanical cultivation when busting native sod. If the one-time sod-busting cost falls reduced across all land units, then more native sod will be converted because more native sod has conversion cost less than the threshold sodbusting cost. Stated differently, innovations such as glyphosate are likely to have effects beyond those in Figure 3. They are likely to shift the distribution of $F(\theta)$ lower such that it is less costly to convert land of any given δ value and so a larger mass of land tracts will fall in the 'crop always' and 'alternate' regions.

A Numerical Example

In this section, we utilize a numerical example to illustrate the intuition obtained from the above qualitative analysis. Model parameters can be separated into four sets. These are the returns parameter set $\mathcal{R} = \{R_{c,h}, R_{c,l}, R_g\}$, dynamics parameter set $\mathcal{D} = \{a, b, \lambda, r\}$, friction parameter set $\mathcal{F} = \{\kappa_{gc}, \kappa_{cg}, \theta\}$, and the single-element policy parameter set $\mathcal{P} = \{\phi\}$. We discuss our choices of each in turn. Table 1 summarizes values of these parameters in the baseline scenario where there is no policy intervention (i.e., $\phi = 0$). Since crop prices increased dramatically in 2007 and thereafter, for returns parameters we calibrate two sets of values. One is for the period before 2007 and the other is for the period 2007–2012.

Profitability Level Parameters

Returns from cropping (i.e., $R_{c,h}$ and $R_{c,l}$) in the period 1989–2006 are calibrated by use of North Dakota State University Extension annual crop budgets for the South Central North Dakota (SCND) region.[4] The SCND region contains 11 counties: Barnes, Dickey, Eddy, Foster, Griggs, Kidder, LaMoure, Logan, McIntosh, Stutsman, and Wells (see the map in

[4] Paulann Haakenson at North Dakota State University Extension Service generously shared the historical crop budgets with us.

Figure SM1 of the Supplement Materials).[5] We also calibrate a second set of cropping returns for the 2007–2012 period, as returns on cropping starting from 2007 were so high that the cropping profitability clearly had entered in a new regime. From the crop budgets we collect returns to land, labor, and management from growing corn, soybean, and wheat in each year. Then we calculate a weighted average return for each year by using harvested acres in the South Central North Dakota region as weights. The U.S. GDP implicit price deflator is used to translate the returns into 2006 dollars. Returns in this article are all in 2006 dollars unless stated otherwise. Figure 4 depicts the weighted average returns over 1989–2012.

Since there is no clear upward trend in returns over 1989–2006, we use the sample mean of the weighted average returns (i.e., \$27.55/acre) as a threshold to differentiate returns in state h and returns in state l.[6] That is, if in a year the return is higher (respectively, lower) than the sample mean, then we assume that state h (respectively, l) occurs in that year. By doing so we transform the return process over 1989–2006 to a two-state process. If we label state h as 1 and state l as 0, then the Dickey-Fuller test (performed by Stata command "dfgls") rejects the null hypothesis that the two-state process is a unit root.[7] Moreover, the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test on the two-state process does not reject the hypothesis that the process is stationary at any reasonable significance level. We perform the same tests on the original return process and the test results do not reject the stationarity hypothesis either. We then define the simple average of returns in state h to be $R_{c,h}$, which is \$42.80/acre. Similarly, we define average returns in state l to be $R_{c,l}$, which is \$17.85/acre. In the 2007–2012 regime, the cropping returns in states h and l are \$85.73/acre and \$45.49/acre, respectively.

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[5] In 2005 and after, the SCND was redefined to contain only 6 counties: Burleigh, Emmons, Kidder, Logan, McIntosh and Sheridan counties. Since *a*) the newly defined SCND is geographically similar to the previously defined SCND; and *b*) the redefinition occurred at the very end of our 1989-2006 regime, we assume that this regional redefinition does not affect the underlying data generating mechanism to the parameters.

[6] A simple ordinary least square regression of the weighted average returns on year shows that the coefficient on year is insignificant (with p-value at 0.28).

[7] The same results are obtained when we perform the Phillips-Perron unit-root test by using Stata command "pperron" and when we perform the augmented Dickey-Fuller unit-root test by using Stata command "dfuller."

Returns from grazing, R_g, are calculated by using pasture cash rent in North Central South Dakota over 1991–2006 because pasture cash rent data in South Central North Dakota are not available to us.[8] We first translate the cash rent into 2006 dollars and then let the returns from grazing, R_g, equal the cash rent average, or \$19.99/acre. In the 2007–2012 regime, returns from grazing equal \$30.95/acre.

Dynamic Parameters

We apply maximum likelihood methods to estimate the transition probabilities between state *h* and state *l* based on the two-state cropping return process we have discussed above. We refer readers to Craig and Sendi (2002) for details about the methodology. Here we only outline the formula used to obtain the estimates. Suppose n_{ij} is the number of times that state *i* is followed by state *j* in the two-state return process, where $i, j \in \{h, l\}$. Then the estimated probability of state *i* being followed by state *j* is:

$$(15) \qquad \hat{p}_{ij} = \frac{n_{ij}}{\sum_{j \in \{h,l\}} n_{ij}}, \quad i, j \in \{h, l\}.$$

Based on the data we calculate $\hat{p}_{lh} \approx 0.2$ and $\hat{p}_{hl} \approx 0.43$; therefore, the estimated values for λa and λb are 0.2 and 0.43, respectively. So the long-run equilibrium probability of being in states *l* and *h* are $b/(a+b) \approx 0.68$ and $a/(a+b) \approx 0.32$, respectively. Based on our sample, the empirical probability that state *l* occurs is $11/18 \approx 0.61$, which is close to the long-run equilibrium probability. Following Claassen, Cooper, and Carriazo (2011), the interest rate is assumed to be $r = 0.07$.

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[8] The counties in the North Central South Dakota area are Brown, Campbell, Edmunds, Faulk, McPherson, Potter, Spink, and Walworth (see the map in Figure SM1 of the Supplemental Materials).

Friction Parameters

The cost of sodbusting varies greatly, depending on the land at issue. It can be as low as just the cost of making a few herbicide application runs (Faulstich 2011), or less than $30/acre if the land is ideally suited. An intermediate case between bringing native sod into production and converting pasture to crop production is that of bringing formerly cropped Conservation Reserve Program land back into production. This land has typically been out of production and largely unmanaged for 10 years or more. Rock removal, extensive land shaping, and drainage would not be major issues as such land tracts would have formerly been in crop production. However, heavy scrub and gopher mounds may be issues, and Ransom et al. (2008) suggest costs in the order of $55/acre for North Dakota land, where costs are approximately equally divided between chemical treatment and mechanical cultivation.

Costs may reach well beyond $100/acre when the land is new to cropping (Renner 2011). In addition to rock, scrub and perhaps fence removal, gulleys and gopher holes may need to be filled. Labor may be a significant component of cost. In this article we focus on how risk interventions and switching cost reductions can affect the critical value of θ at which land value is unaffected by the sod-busting decision. Since we have very limited information on the distribution of θ, we utilize the change in the critical value of θ to roughly measure the grassland-conversion impact of risk interventions and switching cost reductions.

The cost of switching from well-maintained pasture to cropping is typically not large, where tilling and herbicide are the most prominent parts. Therefore, we assume that $\kappa_{gc} = \$15/\text{acre}$. The cost of establishing a pasture is typically much larger. For Iowa, Barnhart and Duffy (2012) assert a cost of about $200/acre depending on cultivation, weed management, seeding and fertilization choices. For North Dakota, with generally less productive land, growers are not likely to pay that much, and we assume a cost of $\kappa_{cg} = \$120/\text{acre}$ for conversion.

Policy Parameter

Table 2 provides premium subsidy rates that were available on the most popular government yield and revenue insurance contracts in 2012. Catastrophic insurance is provided free for losses beyond 50% of expected yield or revenue, where yield expectations are computed from historical yield data. Typical coverage levels chosen vary with crop and location but are broadly about 70% or more, such that subsidies are in the range of 38–59%. In the simulation we calibrate ϕ as the ratio of crop insurance subsidy over cropping return shortfall, δ. Since an actuarially fair insurance does not affect expected net returns, it is the crop insurance subsidy that matters for land-owners' expected returns.

The crop insurance subsidy is calculated as the average of per acre subsidy in North Dakota over 1989–2006, which is $4.90/acre. The state-level of crop insurance subsidy and insured acres over 1989–2006 is obtained from Summary of Business Reports and Data of Risk Management Agency (RMA) at USDA.[9] We calculate that over the 1989–2006 regime $\phi = 4.9/24.95 \approx 0.2$. In the simulation, to check sensitivity we also vary the value of ϕ from 0.2. In the 2007–2012 regime, the subsidy over cropping returns shortfall ratio is about 0.5. In the baseline scenario where there is no policy intervention we let $\phi = 0$.

Simulations

We are interested in examining how (*a*) implementation of a policy that directly modifies the cropping return shortfall, δ, and (*b*) technology advances that reduce switching cost between cropping and grazing (i.e., κ_{cg} and κ_{gc}) would affect land use. Therefore, we need to identify how the critical values of cropping return shortfall, δ, and the one-time sod-busting cost, θ, are affected by the risk intervention policy and technology advances. Table 1 lists these critical

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[9] *Link: http://www.rma.usda.gov/data/sob.html.*

values in the baseline scenario under which there is no policy intervention (i.e., $\phi = 0$). From eqn. (7), $\hat{\delta} = \$58.21/\text{acre}$ over the 1989–2006 regime, while $\hat{\delta} = \$90.17/\text{acre}$ over the 2007–2012 regime. Since the baseline scenario δ is \$24.95/acre (respectively, \$40.23/acre) under the 1989–2006 (respectively, 2007–2012) regime, we know that were a parcel of native sod converted then it would be under 'crop always' rather than 'alternate'.

In the baseline scenario, the critical value for the one-time sod-busting cost in 1989–2006 is \$107.17/acre (Table 1), implying that native sod with one-time conversion cost lower than \$107.17/acre will be converted into the 'crop always' system. In the 2007–2012 regime the critical value becomes \$429.86/acre in the baseline scenario (Table 1). We can see that in the 2007–2012 regime under the baseline scenario, the critical value of θ is about four times as large as that in the 1989–2006 regime, which means that higher cropping returns in the 2007–2012 regime significantly increases the critical values of sod-busting cost at which landowners are indifferent between converting and not converting. In both regimes, the critical values of θ under 'alternate' are negative, which means that were $\delta > \hat{\delta}$, then native sod would not be converted even if the sod-busting cost were zero.

Tables 3 and 4 present simulation results of critical values of δ and θ upon risk intervention and decreasing switching costs in the 1989–2006 and 2007–2012 regimes, respectively. There are three panels in each of Tables 3 and 4. The first column in each panel includes the critical values of δ and θ in the baseline scenario (i.e., $\phi = 0$, $\kappa_{gc} = 15$, and $\kappa_{cg} = 120$). In both regimes, a risk intervention significantly increases the critical values of sod-busting cost. For example, consider the 1989–2006 regime. When the reduction in cropping returns shortfall is 20% (i.e., $\phi = 0.2$, the calibrated value) then, compared with the baseline scenario, the critical value of sod-busting cost (i.e., $\hat{\theta}^{\text{ca}}$) will increase from \$107.17/acre to \$150.91/acre—a 41% increase (see Panel A of Table 3). Even a 10% reduction in shortfall (i.e., $\phi = 0.1$) will increase $\hat{\theta}^{\text{ca}}$ by 20%. The critical values of return shortfall, $\hat{\delta}$, are increased by risk intervention as well. When $\phi = 0.2$ and when compared with the value in the baseline scenario, then $\hat{\delta}^{\text{abs}}$ increases from $58.21/acre to $72.76/acre, a 25% increase (see Panel B of Table 3). So the crop insurance subsidy makes it more likely that native sod will be converted into ‘crop always.’

In the 2007–2012 regime, the calibrated risk intervention parameter (i.e., $\phi = 0.5$) is much higher than that in regime 1989–2006. When $\phi = 0.5$ then the absolute increase in $\hat{\theta}^{\text{ca}}$ is as large as $176/acre (calculated by using $606.17 - 429.86$ from Panel A of Table 4). However, in the 2007–2012 regime the calibrated risk intervention (i.e., $\phi = 0.5$) increases $\hat{\delta}^{\text{abs}}$ by 100% when compared with the baseline scenario, which makes the converted native sod more likely under ‘crop always’ system (see Panel A of Table 4).

On the other hand the effects of a decrease in switching costs, κ_{cg} or κ_{gc}, are much smaller in magnitude than the effects of a risk policy adjustment. In the 1989–2006 regime, we can see that when the switching cost from grazing to cropping (i.e., κ_{gc}) decreases from $15/acre to $3/acre then (*a*) $\hat{\delta}^{\text{abs}}$ only decreased by $2.4/acre, and (*b*) the critical value of sod-busting cost under the ‘alternate’ system, $\hat{\theta}^{\text{alt}}$, remains negative (see Panel B of Table 3). Regarding the impacts of a decrease in the cost of switching from cropping to grazing (i.e., κ_{cg}), similar conclusions can be made except that when κ_{cg} reaches $40/acre, then $\hat{\theta}^{\text{alt}}$ becomes positive (see Panel C of Table 3). In the 2007–2012 regime the effects of decreasing switching costs are not significant either. When switching costs are zero (i.e., $\kappa_{gc} = \kappa_{cg} = 0$), however, then native sod will be converted into the ‘alternate' system under the 1989–2006 regime and into the ‘crop always’ system under the 2007–2012 regime (upper rows in Table 5).

One may be interested in the critical values of sod-busting costs when the landowner omits risks in cropping returns. That is, the landowner converts native sod whenever the net present value of long-run equilibrium expected cropping returns is greater than the sum of conversion cost and the net present value of grazing returns. This is of interest because studies on grassland conversion typically base their methodologies on this idea. Examples include Claassen, Cooper, and Carriazo (2011), Claassen et al. (2011), and Rashford, Walker, and Bastian (2011).

The lower rows in table 5 show that in the 1989–2006 regime $\hat{\theta}^{\text{ca}} = 82.82$ when $R_{c,h}$ and $R_{c,l}$ are set to equal \$25.79/acre, the long-run equilibrium expected cropping returns over the period. Clearly here the value of $\hat{\theta}^{\text{ca}}$ is 23% (or \$24.35/acre) smaller than that in the baseline scenario, which is \$107.17/acre. In other words, omission of cropping return risk across periods will lead to an underestimation of the magnitude of grassland conversions. The reason is as follows. Sod-busting always occurs in state *h*. Moreover, state *h* will persist at time *t* with approximate probability $1-\lambda bt$. Therefore, if the interest rate is greater than 0 (i.e., the discount factor is less than 1), then the present value of long-run equilibrium expected returns is less than the present value of land under the 'crop always' system. That is, omission of risk across periods will underestimate expected net returns from cropping, and hence underestimate the magnitude of grass conversions. Of course, if the interest rate is 0 (i.e., the discount factor equals 1) then the present value of long-run equilibrium expected returns is equal to the present value of the 'crop always' system.

Conclusion

Under a two-point Markov random return process, we have developed and simulated a real option model that articulates incentives arising from cultivation innovations and changes in the risk management subsidy policy environment surrounding crop production. We have shown that, upon plowing, native sod is followed by either (*a*) a ‘crop always’ (i.e., permanent cropping) system, or (*b*) an ‘alternate’ system, in which land is put under cropping (respectively, grazing) whenever crop prices are high (respectively, low). We then compared the value of land under these two systems with the value of land under native sod having accounted for the switching costs incurred upon alternating between cropping and grazing. In this comparison we studied how (*a*) risk interventions, and (*b*) cropping innovations that reduce switching costs affect a landowner’s sod-busting decision. Our findings were that the presence of risk intervention likely converts marginal native sod to a ‘crop always’ rather than an ‘alternating’ production system. For land that has already been converted, a risk management intervention would increase the fraction of land tracts under a ‘crop always’ system while decreasing the fraction under an ‘alternate’ system. Theoretically, cropping innovations that reduce switching costs will reduce the extent of native sod land tracts and land originally under a ‘crop always’ system and increase the extent of land under an ‘alternate’ system.

Based on data from South Central North Dakota, the calibrated model shows that risk policy interventions would likely have more significant effects on native sod conversion than would innovations in switching costs. Consider a risk intervention that causes a 20% reduction in the extent to which cropping returns fall short of their potential. This intervention would increase the maximum (or threshold) value of the one-time sod-busting cost that an asset value maximizing land owner would pay by 41%, or $43.7/acre, under the 1989–2006 regime. Although we cannot quantify the magnitude of native sod that would be affected by this increase in threshold value without knowing the distribution of sod-busting costs, we believe that the 41% increase indicates a significant change in motivation for native sod conversion. Our simulation also shows that omitting cropping returns risk across time underestimates the threshold value of sod-busting cost by 23%, and hence underestimates the incentive for native sod conversion to crop production.

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Appendix A

In this appendix we derive equation system (1). Following standard Bellman equation statistical methods, if one commences in state *h* then

(A1) $\Phi(h;\text{ca}) \approx R_{c,h}t + (1-rt)E_t[\Phi \,|\, h]$,

where $R_{c,h}t$ is income over a small immediate time interval, $1-rt$ is the locally valid approximation of the time discount factor, and $E_t[\Phi \,|\, h]$ is the present time expectation of value after time increment t given that the initial state is *h*.

In turn,

(A2) $E_t[\Phi \,|\, h] = \lambda bt\Phi(l;\text{ca}) + (1-\lambda bt)\Phi(h;\text{ca})$

where (*a*) $\lambda bt\Phi(l;\text{ca})$ is the product of the approximate probability of state change and value under the state change, while (*b*) $(1-\lambda bt)\Phi(h;\text{ca})$ is the product of the approximate probability of state continuance and value under continuance. Insert (A2) into (A1) to obtain

(A3) $\Phi(h;\text{ca}) \approx R_{c,h}t + (1-rt)\{\lambda bt\Phi(l;\text{ca}) + (1-\lambda bt)\Phi(h;\text{ca})\}$,

and so, upon some housekeeping,

(A4) $\Phi(h;\text{ca}) \approx \dfrac{R_{c,h} + (1-rt)\lambda b\Phi(l;\text{ca})}{r + \lambda b - r\lambda bt}$.

Taking the infinitesimal limit, so that the approximation converges to equality, we have

(A5) $\text{Lim}_{t\downarrow 0} \dfrac{R_{c,h} + (1-rt)\lambda b\Phi(l;\text{ca})}{r + \lambda b - r\lambda bt} = \dfrac{R_{c,h} + \lambda b\Phi(l;\text{ca})}{r + \lambda b}$,

so that $\Phi(h;\text{ca}) = [R_{c,h} + \lambda b\Phi(l;\text{ca})]/(r+\lambda b)$, and

(A6) $r\Phi(h;\text{ca}) = R_{c,h} + \lambda b[\Phi(l;\text{ca}) - \Phi(h;\text{ca})]$.

A similar argument can be used to establish that, upon commencing in state *l*, then

(A7) $r\Phi(l;\text{ca}) = R_{c,h} - \delta + \lambda a[\Phi(h;\text{ca}) - \Phi(l;\text{ca})]$.

Now write out system (A6)-(A7) as

(A8) $$\begin{pmatrix} -\lambda b & r+\lambda b \\ r+\lambda a & -\lambda a \end{pmatrix} \begin{pmatrix} \Phi(l;\mathrm{ca}) \\ \Phi(h;\mathrm{ca}) \end{pmatrix} = \begin{pmatrix} R_{c,h} \\ R_{c,h}-\delta \end{pmatrix}.$$

Invert to obtain system (1).

Appendix B

In this appendix we derive equation system (4). Instead of equation (A3) and the corresponding equation for the *l* state, the state equations are

$$\text{(B1)}\quad \begin{aligned} &\Phi(h;\text{alt}) \approx R_{c,h}t + (1-rt)\left\{\lambda bt[\Phi(l;\text{alt}) - \kappa_{cg}] + (1-\lambda bt)\Phi(h;\text{alt})\right\};\\ &\Phi(l;\text{alt}) \approx R_{g}t + (1-rt)\left\{\lambda at[\Phi(h;\text{alt}) - \kappa_{gc}] + (1-\lambda at)\Phi(l;\text{alt})\right\}. \end{aligned}$$

Here the state *h* value factors in $\Phi(l;\text{alt}) - \kappa_{cg}$, because this is the value upon incurring pasture establishment cost κ_{cg} under state transition from *h* to *l*. The state *l* value factors in $\Phi(h;\text{alt}) - \kappa_{gc}$, because the state transition from *l* to *h* involves incurring the pasture termination cost κ_{gc}. Upon some housekeeping, we have

$$\text{(B2)}\quad \begin{aligned} &\Phi(h;\text{alt}) \approx \frac{R_{c,h} + (1-rt)\lambda b[\Phi(l;\text{alt}) - \kappa_{cg}]}{r + \lambda b - r\lambda bt};\\ &\Phi(l;\text{alt}) \approx \frac{R_{g} + (1-rt)\lambda a[\Phi(h;\text{alt}) - \kappa_{gc}]}{r + \lambda a - rt\lambda a}. \end{aligned}$$

Taking the infinitesimal limit in each case allows us to arrive at

$$\text{(B3)}\quad \begin{aligned} &\text{Lim}_{t\downarrow 0} \frac{R_{c,h} + (1-rt)\lambda b[\Phi(l;\text{alt}) - \kappa_{cg}]}{r + \lambda b - r\lambda bt} = \frac{R_{c,h} + \lambda b[\Phi(l;\text{alt}) - \kappa_{cg}]}{r + \lambda b} = \Phi(h;\text{alt});\\ &\text{Lim}_{t\downarrow 0} \frac{R_{g} + (1-rt)\lambda a[\Phi(h;\text{alt}) - \kappa_{gc}]}{r + \lambda a - rt\lambda a} = \frac{R_{g} + \lambda a[\Phi(h;\text{alt}) - \kappa_{gc}]}{r + \lambda a} = \Phi(l;\text{alt}). \end{aligned}$$

Now write out system (B3) as

$$\text{(B4)}\quad \begin{pmatrix} -\lambda b & r+\lambda b \\ r+\lambda a & -\lambda a \end{pmatrix} \begin{pmatrix} \Phi(l;\text{alt}) \\ \Phi(h;\text{alt}) \end{pmatrix} = \begin{pmatrix} R_{c,h} - \lambda b\kappa_{cg} \\ R_{g} - \lambda a\kappa_{gc} \end{pmatrix},$$

and invert:

$$\text{(B5)}\quad \begin{aligned} &\Phi(l;\text{alt}) = \frac{\lambda a(R_{c,h} - \lambda b\kappa_{cg}) + (r+\lambda b)(R_g - \lambda a\kappa_{gc})}{r(r+\lambda a+\lambda b)};\\ &\Phi(h;\text{alt}) = \frac{(r+\lambda a)(R_{c,h} - \lambda b\kappa_{cg}) + \lambda b(R_g - \lambda a\kappa_{gc})}{r(r+\lambda a+\lambda b)}. \end{aligned}$$

Then utilize equation system (1), to obtain system (4).

Table 1. Baseline Parameters and Critical Values in the Numerical Example

	Symbol	Explanation	Values (1989–2006)	Values (2007–2012)
Calibrated parameters	$R_{c,h}$	Cropping returns in state *h* (\$/acre)	42.80	85.73
	$R_{c,l}$	Cropping returns in state *l* (\$/acre)	17.85	45.49
	δ	Difference, $R_{c,h} - R_{c,l}$ in (\$/acre)	24.95	40.23
	R_g	Grazing returns (\$/acre)	19.99	30.95
	r	Interest rate	0.07	
	$a\lambda$	Probability of transition from state *l* to state *h*	0.20	
	$b\lambda$	Probability of transition from state *h* to state *l*	0.43	
	κ_{gc}	Switching cost, grazing to cropping (\$/acre)	15.0	
	κ_{cg}	Switching cost, cropping to grazing (\$/acre)	120	
	ϕ	Risk policy parameter, measuring fall in δ	0.0	
Critical values	$\hat{\delta}$	Threshold value of δ	58.21	90.17
	$\hat{\theta}^{ca}$	Threshold value of θ under cropping always	107.17	429.86
	$\hat{\theta}^{alt}$	Threshold value of θ under alternating system	-184.31	-7.82

Table 2. Government Premium Subsidy Rate on Yield- and Revenue-Based Products (portion of premium that is paid by government)

Coverage level	Catastrophic	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85
Subsidy rate	1.0	0.67	0.64	0.64	0.59	0.59	0.55	0.48	0.38

Source: Table 1 of Shields (2010).

Table 3. Critical Values of δ and θ under Risk Interventions or under Changes in Switching Costs (1989–2006 Regime)

	Panel A: critical values of δ and θ when ϕ increases				
	$\phi = 0$ (baseline)	$\phi = 0.1$	$\phi = 0.15$	$\phi = 0.2$	$\phi = 0.25$
$\hat{\delta}^{\text{abs}}$	58.21	64.68	68.48	72.76	77.61
$\hat{\theta}^{\text{ca}}$	107.17	129.04	139.97	150.91	161.84
$\hat{\theta}^{\text{alt}}$	-184.31	-184.31	-184.31	-184.31	-184.31
	Panel B: critical values of δ and θ when κ_{gc} decreases				
	$\kappa_{gc} = 15$ (baseline)	$\kappa_{gc} = 12$	$\kappa_{gc} = 9$	$\kappa_{gc} = 6$	$\kappa_{gc} = 3$
$\hat{\delta}^{\text{abs}}$	58.21	57.60	57.00	56.40	55.80
$\hat{\theta}^{\text{ca}}$	107.17	107.06	107.06	107.06	107.06
$\hat{\theta}^{\text{alt}}$	-184.31	-179.09	-173.84	-168.58	-163.32
	Panel C: critical values of δ and θ when κ_{cg} decreases				
	$\kappa_{cg} = 120$ (baseline)	$\kappa_{cg} = 100$	$\kappa_{cg} = 80$	$\kappa_{cg} = 60$	$\kappa_{cg} = 40$
$\hat{\delta}^{\text{abs}}$	58.21	52.80	47.40	42.00	36.60
$\hat{\theta}^{\text{ca}}$	107.17	107.06	107.06	107.06	107.06
$\hat{\theta}^{\text{alt}}$	-184.31	-137.03	-89.70	-42.37	4.95

Table 4. Dollar Critical Values of δ and θ under Risk Interventions or under Changes in Switching Costs (2007–2012 Regime)

	Panel A: critical values of δ and θ when ϕ increases				
	$\phi = 0$ (baseline)	$\phi = 0.45$	$\phi = 0.50$	$\phi = 0.55$	$\phi = 0.60$
$\hat{\delta}^{\text{abs}}$	90.17	163.95	180.35	200.39	225.43
$\hat{\theta}^{\text{ca}}$	429.86	588.54	606.17	623.80	641.43
$\hat{\theta}^{\text{alt}}$	-7.82	-7.82	-7.82	-7.82	-7.82
	Panel B: critical values of δ and θ when κ_{gc} decreases				
	$\kappa_{gc} = 15$ (baseline)	$\kappa_{gc} = 12$	$\kappa_{gc} = 9$	$\kappa_{gc} = 6$	$\kappa_{gc} = 3$
$\hat{\delta}^{\text{abs}}$	90.17	89.57	88.97	88.37	87.77
$\hat{\theta}^{\text{ca}}$	429.86	429.86	429.86	429.86	429.86
$\hat{\theta}^{\text{alt}}$	-7.82	-2.56	2.70	7.95	13.21
	Panel C: critical values of δ and θ when κ_{cg} decreases				
	$\kappa_{cg} = 120$ (baseline)	$\kappa_{cg} = 100$	$\kappa_{cg} = 80$	$\kappa_{cg} = 60$	$\kappa_{cg} = 40$
$\hat{\delta}^{\text{abs}}$	90.17	84.77	79.37	73.97	68.57
$\hat{\theta}^{\text{ca}}$	429.86	429.86	429.86	429.86	429.86
$\hat{\theta}^{\text{alt}}$	-7.82	39.51	86.83	134.16	181.49

Table 5. Dollar Critical Values of δ and θ under No Risk (i.e., $R_{c,h} = R_{c,l}$) or under Zero Switching Costs (i.e., $\kappa_{gc} = \kappa_{cg} = 0$)

	Regime	$R_{c,h}$	$R_{c,l}$	R_g	$\hat{\delta}^{\text{abs}}$	$\hat{\theta}^{\text{ca}}$	$\hat{\theta}^{\text{alt}}$
No switching	1989-2006	42.80	17.85	19.99	22.81	107.17	125.94
cost	2007-2012	85.73	45.49	30.95	54.77	429.86	302.43
No risk in	1989-2006	25.79	25.79	19.99	41.20	82.82	-278.24
Returns	2007-2012	58.29	58.29	30.95	62.74	390.59	-159.29

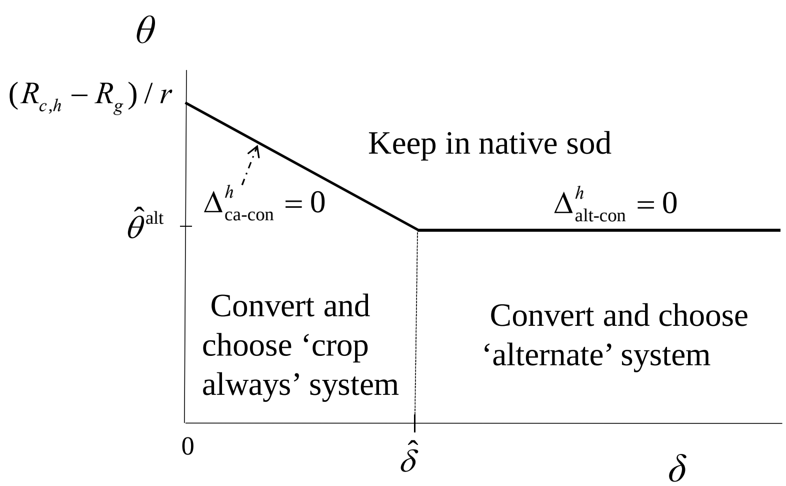

Figure 1. Sodbusting choices in (δ, θ) space

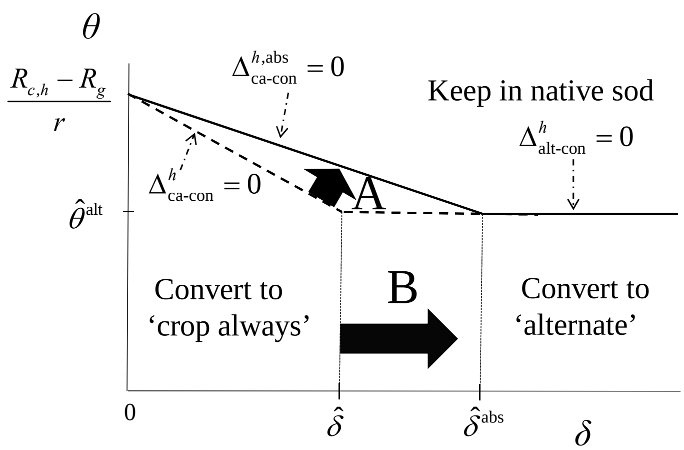

Figure 2. Effect of risk intervention on sodbusting choices in (δ, θ) space

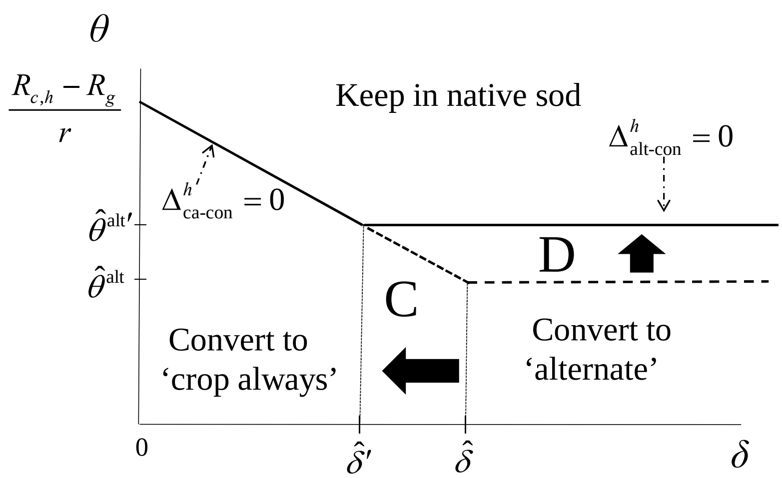

Figure 3. Effect of lower grass to crop conversion cost on sodbusting choices in (δ, θ) space

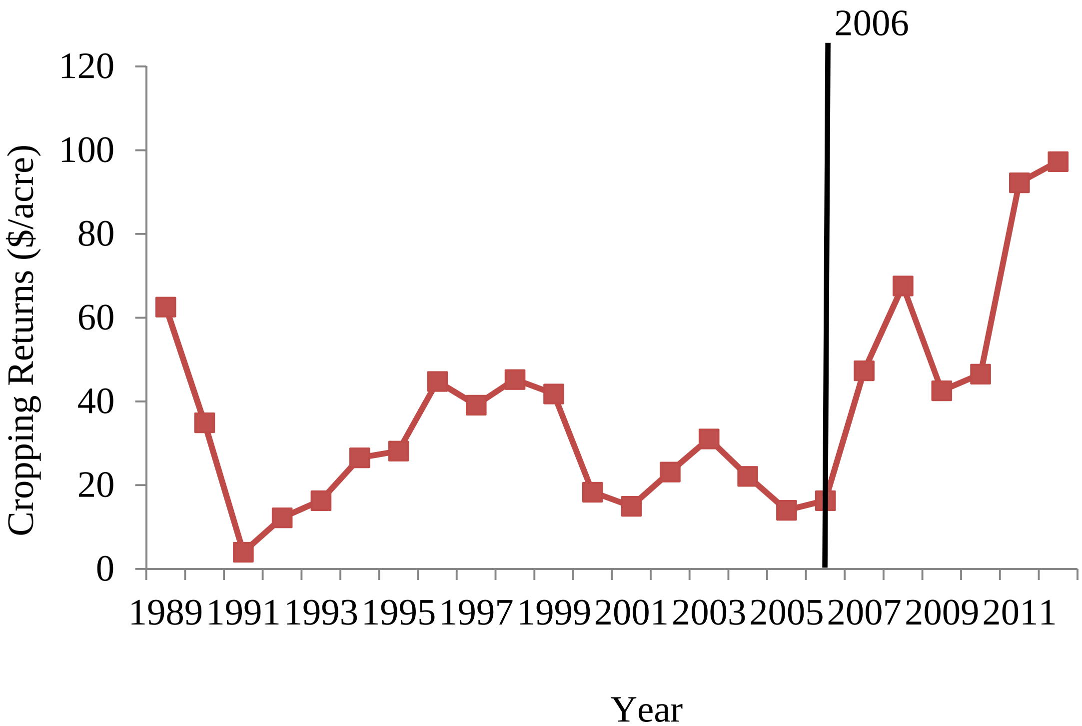

Figure 4. Cropping Returns over 1989–2012 in South Central North Dakota (in 2006 dollars)

Supplemental Materials

Item A

In this item we show that once sod is busted then the land owner will either 'crop always' or 'alternate.' In 'crop always' the land owner always crops regardless of the state of nature. In the 'alternate' system the land owner crops under state *h* but grazes under state *l*.

Let the moment when native sod is busted be denoted as time 0. At each time $t > 0$ the landowner considers whether to take action 'crop' (labeled as *c*) or 'graze' (labeled as *g*), based on (*a*) the current state of nature (i.e., *h* and *l*), and (*b*) the current state of land use (i.e., cropping or grazing). The current state of land use at time *t* should be taken into account when choosing an action at time *t* because a switching cost will be incurred whenever the landowner switches land use from one type to the other. Since nature's state change occurs in a Markovian continuous time setting, only the current state matters for the time *t* decision. Therefore, the landowner has sixteen strategies for choosing a land-use type at time *t*. Let "$(i, j) \rightarrow k$" stand for "if nature's state is $i \in \{h, l\}$ and if the land is currently under land-use type $j \in \{c, g\}$, then the landowner chooses land-use type $k \in \{c, g\}$ at time *t*."

The sixteen strategies can be written as:

1) $(h, c) \rightarrow c$, $(h, g) \rightarrow c$, $(l, c) \rightarrow c$, $(l, g) \rightarrow c$;
2) $(h, c) \rightarrow c$, $(h, g) \rightarrow c$, $(l, c) \rightarrow c$, $(l, g) \rightarrow g$;
3) $(h, c) \rightarrow c$, $(h, g) \rightarrow c$, $(l, c) \rightarrow g$, $(l, g) \rightarrow c$;
4) $(h, c) \rightarrow c$, $(h, g) \rightarrow c$, $(l, c) \rightarrow g$, $(l, g) \rightarrow g$;

5) $(h, c) \rightarrow c$, $(h, g) \rightarrow g$, $(l, c) \rightarrow c$, $(l, g) \rightarrow c$;
6) $(h, c) \rightarrow c$, $(h, g) \rightarrow g$, $(l, c) \rightarrow c$, $(l, g) \rightarrow g$;
7) $(h, c) \rightarrow c$, $(h, g) \rightarrow g$, $(l, c) \rightarrow g$, $(l, g) \rightarrow c$;
8) $(h, c) \rightarrow c$, $(h, g) \rightarrow g$, $(l, c) \rightarrow g$, $(l, g) \rightarrow g$;

9) $(h, c) \rightarrow g$, $(h, g) \rightarrow c$, $(l, c) \rightarrow c$, $(l, g) \rightarrow c$;
10) $(h, c) \rightarrow g$, $(h, g) \rightarrow c$, $(l, c) \rightarrow c$, $(l, g) \rightarrow g$;
11) $(h, c) \rightarrow g$, $(h, g) \rightarrow c$, $(l, c) \rightarrow g$, $(l, g) \rightarrow c$;
12) $(h, c) \rightarrow g$, $(h, g) \rightarrow c$, $(l, c) \rightarrow g$, $(l, g) \rightarrow g$;

13) (h, c) → g, (h, g) → g, (l, c) → c, (l, g) → c;
14) (h, c) → g, (h, g) → g, (l, c) → c, (l, g) → g;
15) (h, c) → g, (h, g) → g, (l, c) → g, (l, g) → c;
16) (h, c) → g, (h, g) → g, (l, c) → g, (l, g) → g.

Strategy 1) can be interpreted as "at time t the land owner will always put land under cropping, regardless of nature's state and the current land-use type." Strategy 2) can be interpreted as "If nature's state is l and if the land is currently under grazing, then at time t the land owner will put the land under grazing. The land will be put under cropping under any other scenarios." Other strategies can be interpreted similarly. One can readily check that strategies 9) through 16) are strictly dominated by the matched strategy among 1) through 8) where matching is in sequential order.

For example, the only difference between strategies 1) and 9) is the action taken when facing (h, c). In strategy 1), when (h, c) occurs in period t then the grower takes action 'crop'. In strategy 9), when (h, c) occurs in period t then the grower takes action 'graze', which will induce the switching cost from cropping to grazing, κ_{cg} , and revenue loss from giving up cropping, $R_{c,h} - R_g$. Moreover, taking the action 'graze' when facing (h, c) cannot improve future income. This is because the option to switch land use is always open. Therefore, in strategy 9), converting from cropping to grazing when facing (h, c) cannot improve future income but incurs both a cost and a loss in revenue in the present state. So strategy 9) is strictly dominated by strategy 1). By the same argument one can show that strategy 10) is strictly dominated by strategy 2) and generally strategy k is dominated by strategy k-8, $k \in \{9,10, ... ,16\}$. Also, one can show that strategy 3) is strictly dominated by strategy 4), and that strategy 7) is strictly dominated by strategy 8). Moreover, it is readily checked that the strategy 16) is dominated by the action of not sod-busting in the first place.

Therefore, we only need to consider strategies 1), 2), 4), 5), 6), and 8). Strategies 1), 2), 5), and 6) are equivalent to the 'crop always' system. This is because sod-busting only occurs under state *h* and whenever the sod is busted then it is converted to cropland; that is, at time $t = 0$ we have (*h*, *c*). Therefore, starting from time $t = 0$, if the landowner follows strategies 1), 2), 5), and 6), then 'grazing' will never occur in the system, which implies the 'crop always' system.

Similarly, starting from time $t = 0$ if the landowner follows strategy 4), then the land will be under cropping (respectively, grazing) whenever the state is *h* (respectively, *l*), which implies the 'alternate' system. Were the native sod busted, then strategy 8) would never be optimal. The reason is as follows. If the native sod is busted, then busting is profitable when nature's state is *h*. Suppose strategy 8) is followed after the sod is busted and suppose the system evolves to (*h*, *g*), or the situation in which nature's state is *h* and the current land use is grazing. In this situation, deviating from strategy 8) (i.e., putting land under cropping) will be more profitable than following strategy 8) because under state *h* busting native sod has been profitable. Recall that the one-time sod-busting cost, θ, is higher than the switching cost from grazing to cropping, κ_{gc}.

In sum, once native sod has been converted then we only need to consider the 'crop always' and 'alternate' systems. At no loss we may represent 'crop always' and 'alternate' by strategies 1) and 4), respectively.

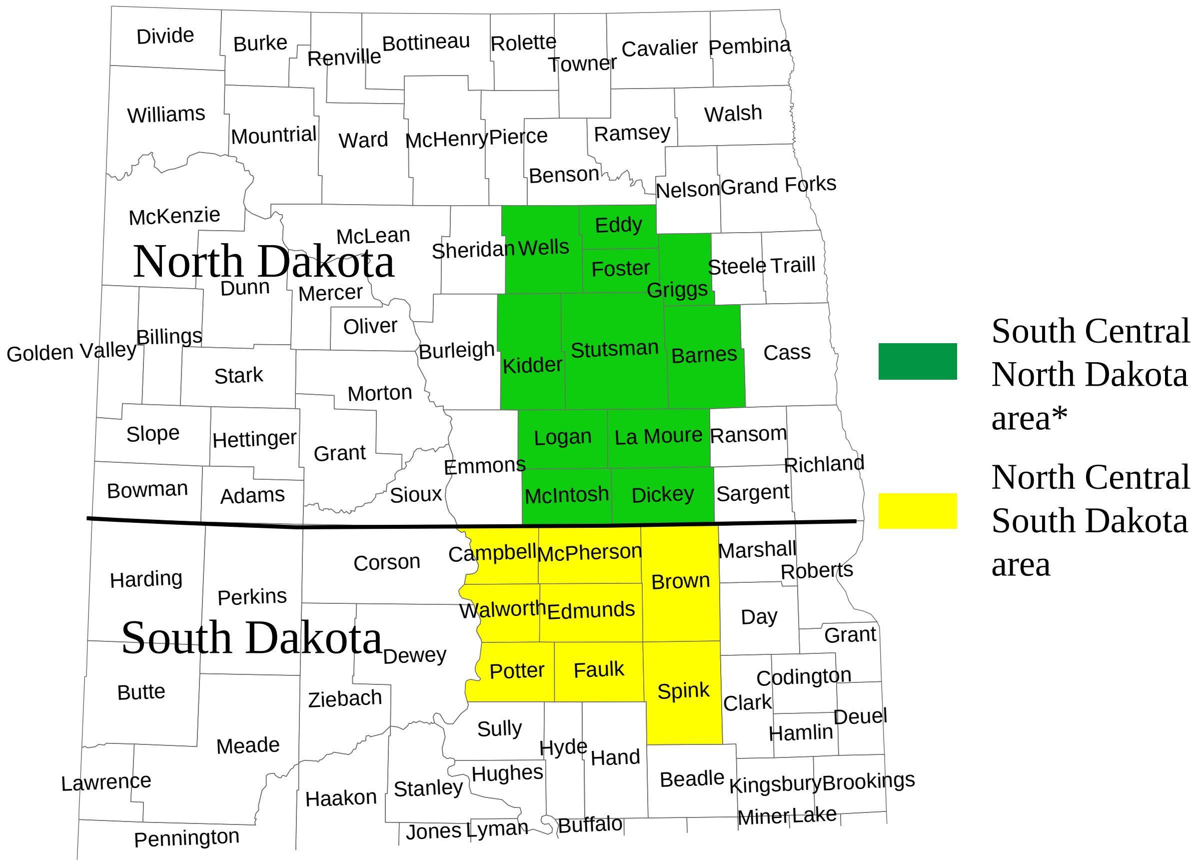

Figure SM1. South Central North Dakota (SCND) area and North Central South Dakota (NCSD) area

Note: * In 2005 and after, the SCND area was redefined to contain only 6 counties: Burleigh, Emmons, Kidder, Logan, McIntosh and Sheridan counties.)