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Exploring agent-level calculations of risk and returns in relation to observed land-use changes in the US Great Plains, 1870–1940

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Abstract

Land-use change in the U.S. Great Plains since agricultural settlement in the second half of the nineteenth century has been well documented. While aggregate historical trends are easily tracked, the decision-making of individual farmers is difficult to reconstruct. We use an agent-based model to tell the history of the settlement of the West by simulating farm-level agricultural decision making based on historical data about prices, yields, farming costs, and environmental conditions. The empirical setting for the model is the period between 1875 and 1940 in two townships in Kansas, one in the shortgrass region and the other in the mixed grass region. Annual historical data on yields and prices determine profitability of various land uses and thereby inform decision-making, in conjunction with the farmer's previous experience and randomly assigned levels of risk aversion. Results illustrating the level of agreement between model output and unique and detailed household-level records of historical land use and farm size suggest that economic behavior and natural endowments account for land change processes to some degree, but are incomplete. Discrepancies are examined to identify missing processes through model experiments, in which we adjust input and output prices, crop yields, agent memory, and risk aversion. These analyses demonstrate how agent-based modeling can be a useful laboratory for thinking about social and economic behavior in the past.

Keywords

agent-based model; settlement; land-use; behavior; simulation; risk aversion; Great Plains

Introduction

The rate and pattern of land-use change during the period of agricultural settlement of the U.S. Great Plains (mid-19th to mid-20th centuries) had significant environmental impacts on the region, including soil erosion affecting surface water quality, declines in native grassland

diversity, and releases of carbon from the soil to the atmosphere (Hartman et al. 2011). While the processes of settlement and land-use change during this period were facilitated by state, local, and federal policies (Homestead Act, railroad subsidies, etc.), they were ultimately carried out by farmers who made decisions about the purchase and sale of land and about specific cropping practices with remarkably few constraints. Access to land ownership was widespread among the early settlement populations and government land policy assured an initially equal distribution of land. Most locations had access to transportation within a few years of initial settlement, and opportunities for market specialization were considerable. In previous work we have demonstrated that farmers in the plains were careful stewards of the land who recognized environmental constraints (Sylvester & Rupley 2012), diversified rather than specialized production over time (Sylvester & Cunfer 2009), and were influenced by demographic priorities in finding the appropriate mix of land use over the family life cycle (Leonard, Gutmann & Deane 2011). Whether or not settlers in the Great Plains pursued a logic that prioritized economic gain, and the degree to which their decisions deviated from profit maximization, represents an important open question about their behavior and its effects on the environment of the plains.

Understanding the processes by which farming households made their land-use decisions is challenging because of the complexity of interactions between people and the places in which they lived and worked, and the often insufficient resolution of observed information. Complexity characterizes land-use processes because observed historical behaviors often represent accumulated decisions of heterogeneous actors who were affected by a wide range of environmental and human factors, and by specific social and spatial interactions. Given these limitations, strictly empirical approaches, based on inductive reasoning or statistical estimation, generally impose population-averaged estimates, and are therefore not likely to directly address the actual underlying mechanisms of individual-level and heterogeneous decision making that drive change in the overall landscape (Entwistle 2007). Instead a more deductive approach that builds behavioral explanations from the bottom up and tests their efficacy against this historical record has potential to add to our understanding of historical land-change processes. Epstein (2006) suggests that causal explanations in the social sciences can be most persuasive when the arguments are supported by a model that generates observed aggregate outcomes on the basis of posited mechanisms at the micro level, in an approach he terms ‘generative social science.’

Agent-based models are a critical tool for developing such mechanistic explanations for the behavior of land-use systems, in which heterogeneous, intelligent actors, or agents, interact to produce land-use outcomes (Parker et al. 2003). An agent-based model can be construed as a hypothesis for the mechanisms generating some observed pattern in the real world (e.g., spatial-temporal patterns of land-use change), and those modeled patterns can be compared with observations. Such models can be constrained by available data, but also developed with rules or algorithms that represent the judgments of the analysts where data are unavailable. This bottom-up approach to social explanation is shared with, though implemented through less quantitative means, both the moral economy and rational peasant theoretical approaches, the logic of which proceeds from micro-level behavior to macro-level outcomes and represents the most promising avenue for exploration of the diverse

conditions under which similar aggregate outcomes emerge and examination of the common human behaviors that underwrite seemingly distinct historical experiences (Little 1989). Within the ecological sciences, Volker Grimm and colleagues (2005) set out logics for testing model-based explanations, referred to as ‘pattern-oriented modeling.’ In pattern-oriented modeling, outputs are compared with observations not only of the patterns the model is meant to explain (e.g., trends in land use over time), but also of secondary patterns generated by the model (e.g., distributions of farm sizes), which can be used to support the validity of the structure of the model. Evaluating the degree of match between the outputs of a model of a system and empirical observations of an actual system across multiple dimensions not only provides a means of understanding how well a model does in explaining the behavior of that system, but also provides opportunities to learn why the model might not do as well as it could.

We developed an agent-based model to understand land-use change between 1875 and 1940 in two townships in the U.S. Great Plains – Washington Township in eastern Kansas and Wheatland Township in western Kansas. Inputs to the model are based on the best available data on demographic, economic (especially prices for farm inputs and outputs), and environmental changes over that period, and outputs describe the numbers and sizes of farms, the amount of land cropped by crop type, and the amount of land used for pasture. The agents of the model follow a profit-driven rationale for their decisions to undertake various agricultural activities. We compare the performance of this earnings-centered model, measured with reference to the historical record, on numbers and sizes of farms and distributions of land across land-use activities, with the performance of versions of the model in which we impose constraints on environmental, cognitive, and risk-taking aspects of agent decision making. These model-based experiments were aimed at answering two key questions: (1) how well does a profit-maximizing model explain observed land-use patterns?; and (2) what kinds of constraints might have limited the match between expected outcomes from a profit-based model and the historical record? We tested two competing hypotheses: (a) farmers’ land-use decisions were based on the logic of profit maximization; and (b) farmers’ economic logic was constrained by environmental, cognitive, and risk-taking considerations. We use the pattern-oriented modeling approach to evaluate the explanatory power of alternative model formulations, learn about how and where model output diverges from the historical record, and draw conclusions about both the limitations of our model and the relative value of alternative explanations of historical land-use decision making on the Great Plains.

Background

The debate about whether small farmers act as profit maximizers has a long tradition in the social sciences. In several literatures, the generally long period of innovation required for family farms to adopt new technologies and raise productivity has always inspired theorizing about the limits of profit maximization. Two largely disparate theoretical frameworks have emerged to explain the relatively slow transitions out of traditional agriculture. One theoretical framework has argued that traditional farm communities were always shaped by more than the autonomous behavior of farm households. James Scott (1976), Clifford Geertz (1983), and other scholars have emphasized that agrarian

communities change only gradually because members of tight-knit village societies judge the value of new production strategies in terms of shared values – moral, religious and political. Village society places more emphasis on reciprocity and cooperation than on innovation and future earnings. In the American literature, these debates have generally been confined to discussions of communities in the colonial era, where the need for various forms of collective action were apparent in settler society, but tended to fade from the discussion after the Jacksonian period, as domestic markets expanded and the physical isolation of rural society diminished (e.g., Henretta 1991, Clark 1990, Rothenberg 1992, Lamoureaux 2003, Donahue 2004).

The second theoretical framework, which cuts across each of these literatures, takes as its starting point the idea that the farmer is a rational actor, and the factors standing in the way of market or technological change are often institutional in nature, and are related to patterns of inequality and exploitation in traditional society. Samuel Popkin (1979) and Tracy Dennison (2011) argue that moral values or market-aversion were not decisive in traditional societies like Vietnam and Russia. Popkin and Dennison both argue that collective outcomes are best explained as the aggregates of varied circumstances of welfare-maximizing individuals, but that those individual interests were served better in some settings than others. From this political economy perspective, self-interest still drives the patterns of market activity that are visible and the commitment to traditional practice is shaped more by the patterns of rent extraction or institutional constraints exercised by the powerful.

Much of postwar economics has accepted the profit maximization model as an elegant (powerful but simple) explanation of individual motivations. Wherever traditional producers remained fearful of change, Theodore Schultz (1964) and other members of the Chicago School argued that the example of U.S. investment in human capital, with its land-grant universities and extension system, was a model of how to foster agricultural and market innovation around the globe. But poor and small farmers have remained attached to existing production patterns and forms of organization in many developing countries, as a way to diversify livelihoods and smooth consumption (Netting 1993; Ellis 2000; Harwood 2012). Even with the greater awareness of institutional barriers to change, the slow adoption of new techniques continues to be portrayed in the economics literature as a kind of ‘behavioral bias.’ Esther Duflo and colleagues (2011), for instance, argue for more targeted subsidies in eastern Kenya because too many small maize producers defer the costs of fertilizer purchase until late in the season. In other words, unearthing the rational economic actor is a matter of recognizing which small farmers will respond to meaningful economic signals.

In the United States, the plow-up of the Great Plains is generally portrayed as a signature example of 20th century market formation and some of its environmental consequences. Settlers moved onto the plains and were encouraged to plow native grassland by land grants, farm mechanization, and a commodity boom leading up to the First World War. The ecological and environmental disaster of the Dust Bowl is frequently attributed, at least in part, to homestead policy and the discounting of scientific advice that warned that the semi-arid west was too dry to support small farmers (Worster 2001). It is hard to imagine more favorable circumstances for market formation – widespread individual land ownership, well-developed rail transportation networks, and growing credit markets. But with so few

impediments, short-term economic gain is seen as the main ingredient in the mix of historical factors that shaped western expansion and motivated the behavior of small farmers (Steinberg 2002, Worster 1979). Some historians argue that a new kind of gigantism, of large private and corporate farms, reinforced the short-term orientation (Egan 2006, Fitzgerald 2003). According to this perspective, the result was an excessive expansion of cropland and wheat monoculture in the driest part of the region.

At the same time, some of the literature identifies a different trend in American agriculture as a whole, which experienced a relatively slow adoption of new technology in the years leading up to the Great Depression (Danbom 1979, 2006). Sally Clarke (1994) has argued that productivity gains coincided instead with the introduction of New Deal regulations in 1935, when investments in new machinery were underwritten by a combination of new credit and subsidized prices. With our agent-based model, we examine a related feature of the settlement process – the degree to which land use specialized in response to market change. We identify a lack of market responsiveness in the unwillingness of the historical actors to pursue the returns available in the most profitable land uses.

Methods

We use the same framework to model land-use decision-making in each of the townships, and then vary the model inputs to represent the environmental and economic features that distinguished the townships from one another. Each township is made up of *Parcels* of land that are bought, sold, and managed by *Farmers*. The model operates at one-year time steps, beginning in 1875 and ending in 1940. At each time step, new Farmers are introduced to the model, Farmers have the opportunity to sell and buy Parcels, Farmers use a profit-maximizing rationale to decide what to do with the Parcels they own, and a determination is made about whether each Farmer will remain in the model for the next time step.

The model was written in Java, and run in Eclipse and Repast Symphony. Results were summarized and analyzed using SAS. In this section we outline the operation of the model, with details following the ODD protocol for model description provided in an appendix (Grimm et al. 2010).

Creating Land Parcels

Initializing the model creates a set of 40-acre Parcels for ownership and use in each township. In Washington Township, in Nemaha County, the land area represents a total of 576 parcels or 23,000 acres – a single public land survey township. In the western part of the state, Wheatland Township, in Ford County, is twice the size of its eastern counterpart, with 1152 parcels. In the model, the parcels are not assigned any spatial locations, but are characterized by the distribution of two very specific environmental attributes: soil quality (high, medium, or low) and an indication (yes or no) of land capability for agriculture, or arability. In the model, the latter measure determines the likelihood that a parcel will initially be plowed for cultivation, while soil quality influences the price of the parcel and crop yields on cultivated parcels. Values of these attributes are assigned from the actual distributions in the two townships measured in the current digital soil surveys (Soil Survey Geographic Database, 2004), and summarized according to the township boundaries. The

soil surveys indicate that 55% of land in Washington is suitable for arable production; 27.4% has high quality soil, 22.2% has medium quality soil, and the remaining 50.4% has low quality soil. In Wheatland Township, 94% of land is designated as suitable for arable production; 87.7% has high quality soil, 5.7% has medium quality soil, and the remaining 6.6% has low quality soil. In the model, all Parcels begin in native grassland and under government ownership. Half of the Parcels in each township are available to farmers (in sets of four Parcels) at no cost under the 1862 Homestead Act, and the remaining half are available for sale at contemporary market prices. Soil quality and arability are independent of whether the Parcels are distributed for free or at cost, though these characteristics affect the price of those that are sold through a set rule.

Creating New Farmers

The number of Farmers entering the model in each year is derived from a historical dataset compiled from household-level agricultural censuses conducted by the state of Kansas between 1870 and 1940, for the years when they could be matched to population censuses (generally every 5 years) (Sylvester et al 2002). The number of Farmers introduced to the model at each time step is the number of ‘new’ farmers in a given township at each historical census, smoothed over the intercensal period. ‘New’ farmers are those who were not listed in the previous agricultural census. Farmers in the model have two attributes: *risk aversion*, assigned randomly from a uniform distribution and taking a value between 0 and 1, and *initial cash*, assigned randomly from a log-normal distribution based on the historical record of land, livestock, equipment, and fencing in the 1875 census in Washington and the 1885 census in Wheatland, and adjusted for change over time. We use the value of these resources as a proxy for the distribution of farm-making capital. Historically, the household-level reporting in Kansas suggests that these costs rose until about 1920 and then leveled off as agricultural prices and land values fell (for full details, see the ODD Appendix). In the model, Farmers entering the townships before all free parcels have been distributed receive four randomly-assigned parcels (representing a 160-acre homestead) at no cost. Farmers entering later must purchase between two and four parcels when they are introduced to the model; those who cannot afford to do so cannot enter the model.

The level of risk aversion assigned to a new Farmer will affect nearly all of his decisions. Being more risk averse will make a Farmer less likely to buy additional parcels, much less likely to plow grass parcels (Farmers with risk aversion of 0.5 or higher will not plow non-arable parcels), and less likely to change the land use he has chosen for any given parcel. Risk aversion is only indirectly related to a Farmer’s decision to sell a parcel (which relies mainly on annual earnings) and not related to the decision to exit the model (which is based on random adult death and a fixed retirement). Because we have no data on which to draw in assigning risk aversion to Farmers, we simply assume (as stated above) that it is variable and uniformly distributed. Subsequent experiments examine the implications of changing this distribution.

Selling and Buying Parcels

The decisions Farmers make to buy, sell, and plow Parcels are represented by simple heuristics grounded in economic rationale, in order to account for the costs and benefits of

the decision and the constraints on farmer decision making, and to focus the model on economic decisions associated with land-use choices. Farmers may buy and sell Parcels if they have been in the model for at least a year. The price of Parcels is based on an annual series of land prices reported in Michael Haines' county-level U.S. census dataset, *Historical, Demographic and Social Data of the United States* (Haines and ICPSR 2010), interpolated linearly between decadal and quinquennial values and adjusted for soil quality. Two conditions can trigger a Farmer's decision to sell. First, if a Farmer is not making money, defined as currently having less cash than in his most distant memory (maximum is five years), and owns fewer than four Parcels, he will decide to exit the model. He does this by putting all of his Parcels up for sale but he does not leave the model until all his Parcels are purchased by other Farmers. The second assessment of earnings is determined by the Farmer's Operating Debt Limit (ODL), which is defined as a measure of the short-term loss that the agent could absorb or carry before making the decision to exit. We debated various forms of operating capital that might serve as the threshold, and decided to use machinery or implement values as the benchmark against which to measure the short-term capital available to the agent. These data were drawn from county-level estimates reported in the federal census of agriculture, reported on a decennial basis until 1920 and then every five years.

If a Farmer owes more than half of the value of his machinery – a very cautious standard – he has exceeded his ODL, and must sell land in order to rebalance his finances. He begins by putting his worst-quality Parcel up for sale. Farmers may also make the decision to sell land if a sale represents a profit-maximizing decision. A Farmer who does not owe more than his ODL will sell all Parcels he has owned for at least five years and for which the expected profit over the next five years is less than the current market price for the Parcel. In the model, Farmers continue to own Parcels they have decided to sell until they are purchased by another Farmer. While they are for sale, the Parcels are kept in the land use practiced at the time the decision to sell is made. Exiting Farmers continue to earn (or lose) money, but cannot reverse the decision to exit.

A Farmer will only consider buying the best Parcel currently on the market, defined in terms of soil quality and agricultural suitability. If he cannot afford that Parcel (i.e., if buying it would put him over his ODL), he does not buy. If he can afford the Parcel, whether he buys or not is based on his level of risk aversion and whether he is making money. Farmers with lower levels of risk aversion are more likely to buy, as are Farmers who are making money. If the Farmer can afford to buy the best Parcel on the market and is making money, his probability of doing so is calculated as: $1 - \text{RiskAversion}/2$. If he can afford to buy the best Parcel on the market but is not making money, his probability of doing so is $1 - \text{RiskAversion}$.

More complete representations of land market interactions are recent developments in the agent-based models of land use (Filatova et al. 2009; (Parker 2008; Magliocca, Safirova et al. 2011)), and incorporating them into this model would introduce a level of complexity that we fear would obscure our ability to analyze land-use distributions and may not be necessary. A future direction for model development is to test more explicitly profit-

motivated representations of these buy/sell decisions, as well as the plowing decisions described next.

Plowing Grass Parcels

All Parcels begin in native grassland, and a Farmer can choose to plow one of his grass Parcels each year. Unplowed Parcels can remain idle or can be used to graze cattle; if a Farmer has only idle Parcels, he is assumed to be working for a wage off the farm. Wages are assigned uniformly for all agents in both townships in a given year based on USDA publications (for 1875–1892, USDA 1892; for 1891–1909, Holmes 1912; for 1910–1929, USDA 1945; for 1930–1940 USDA 1930–1940). Once a Parcel has been plowed, it cannot revert to native grassland and must be planted in corn, wheat, or hay (for cattle). A Farmer will plow all of his arable Parcels before plowing any non-arable Parcels. Plowing is a stochastic decision, the probability of which is based on risk aversion, arability, and township. The farmer must have a risk aversion lower than 0.5 in order to plow a non-arable Parcel.¹ In Washington, the probability of plowing an arable Parcel is $1 - \text{RiskAversion}$, and the probability of plowing a non-arable Parcel is $1 - \text{RiskAversion} * 2$. Farmers in Wheatland always have $2/3$ the probability of plowing as Farmers in Washington because Wheatland has $2/3$ as much precipitation. In both townships, and through the whole period, we assume that it costs a farmer \$100 to plow a Parcel, and that the process takes one year, so he will not choose a land use for a Parcel he decides to plow until the following year.

Choosing Land Use

Each year, Farmers make land-use decisions for new Parcels and newly-plowed Parcels, and review the land use of all Parcels that have been in the same land use category for at least five years. Farmers calculate the profit that each land-use category would have made on each Parcel within the span of their memory (maximum = five years), and choose the ideal land use on the basis of that memory and their risk aversion. Profit is calculated by multiplying realized yield of each agricultural product (i.e., corn, wheat, and beef products) by the price for those products on the market, and subtracting costs. Yields are based on annual county-level historical yields reported by the Kansas State Board of Agriculture, and compiled by Parker, Decanio, and Trojanowski (2000). Variations in yields are reflective of changes in both weather (especially precipitation) and technology (e.g., seed varieties). The county-level average yields are adjusted in the agent-based model by the soil quality of the parcels controlled by each individual agent (Soil Survey Staff 2004). The prices and costs of agricultural commodities are based on annual price series reported in the *Historical Statistics of the United States* and current online USDA historical datasets. These are national price series and we drew on nominal price series for wheat, corn and beef available from 1870 to 1940 (See Census Bureau, 1975, USDA, 2005 and 2011).

Farmers with low risk aversion choose the land use that was most lucrative under the best circumstances observed over the memory period (i.e., the year with maximum yield for each product), those with medium risk aversion choose the land use that was most lucrative under

¹In the current version of the model the decision to plow a non-arable parcel is based on a randomized distribution of risk aversion in the agent population. The plowing decision might also have been based on some calculation of expected future earnings or a more clustered distribution of risk aversion. These are both areas for further exploration.

average conditions, and those with high risk aversion choose the land use that was most lucrative under poor conditions (i.e., based on the year with lowest yield for each product). If the Parcel is not already in the chosen land use, and if the Farmer can afford to change land use (including the purchasing of equipment for wheat or corn if the Farmer has not previously pursued wheat or corn) without going over his ODL, the Farmer makes a stochastic decision to purchase with a probability of making the switch depending on his risk aversion. The lower the Farmer's risk aversion, the more likely he is to change land use. If the Farmer cannot afford to change, he continues with his current land use.

Updating

At the end of each year, each Farmer's cash is incremented by the profit earned on each of his Parcels and his memory is updated with his current cash level and the profits generated over the past year. A random exit function is applied to simulate death and retirement. The probability of a Farmer exiting increases exponentially with time in the model, reaching 0.05 at 30 years and 1 at 60 years. Once it is decided that a Farmer will exit (either as a result of this function or because he was not making money, as described above), he will remain in the model until other Farmers purchase all of his Parcels, but he will not buy additional Parcels or make further land use decisions. These heuristics simplify the demographic characteristics of the household, and representing these with somewhat more fidelity is an alternative direction for future model development.

Model Experiments

With these assumptions in place, the base model is intended as a common representation of the effects of profit-maximizing behavior in the simulated communities. Because of the many random starting conditions and choice heuristics, simulation results were summarized over 100 runs and expressed in terms of the means and standard deviations of the outcome variables. We developed several measures of correspondence over time between the simulated farm communities and the actual historical record of land use in the census townships. The first calculates the sum of the squared differences in proportion of land in each use at each point in time, producing a measure of departure from sameness known as the Multi-Dimensional Euclidean Distance (MDED). Because the categories used in the historical record do not correspond exactly to the categories of the model, we equated land out of farms and land in pasture in the historical record with grass and beef grass in the model, and equated crops other than wheat and corn in the historical record (hay, sorghum, rye, oats, and barley) with hay in the model. Using those simplified categories, we also calculated a measure of land-use diversity in each year in the historical record and in the model (DIV). Finally, to assess the concentration of land ownership, we calculated a Gini coefficient for farm size in each year in the historical record and in the model.

The base model (Model 0) incorporates the following parameters:

- Soil quality and arability correspond to the actual distributions of those characteristics in the two townships.
- Crop yields are based on historical yields for the counties in which the two townships are located, with the historical value being used for medium soil quality

and a multiplier increasing the yield for Parcels with high quality soil and decreasing the yield for Parcels with low quality soil.

- Beef, crop, and land costs and prices are based on national historical price series.
- Farmers' memories, used for land-use decisions, go back five years.
- Risk aversion for Farmers is uniformly distributed between 0 and 1.
- Once a Farmer designates a land use for a Parcel, the Parcel must remain in that land use for at least five years.

We ran several model experiments introducing various constraints to farmer decision making to contrast to the base model (changing one parameter at a time):

- Experiment 1: Crop, beef, and land prices, and all farming costs, are held constant at their 1875 values in all years.

This experiment explores the importance of variations in yield (primarily resulting from weather fluctuations) on model results.

- Experiment 2: Crop yields are held constant at the 25th percentile in all years; constant crop yields are set to the 75th percentile in all years.

This experiment simulates environmental conditions that are poor versus very good, and in each scenario explores the importance of price fluctuations on model results.

- Experiment 3: All Farmers have risk aversion of 0.5, then 0.9.

This experiment allows us to explore whether homogeneously higher or lower levels of Farmer conservatism produce land-use patterns that better match the historical record.

- Experiment 4: Farmers remember 10 years of land-use profitability, compared to five years in the base model.

By increasing the length of memory, we explore the effects of Farmers having access to more information about variability in prices and yield on model outcomes.

Results from each experimental manipulation are compared with the historical record, the base model, and each other in terms of overall land-use fractions over time and MDED, DIV, and Gini.

Results

Base model

In both townships, the most striking outcomes of the base model are the wide swings in land use in response to price signals (Figure 1), and the complete conversion from native grassland and pasture to cropland. Wheat, corn and hay for cattle feed (Beef Hay) completely dominate land use by about 1905 in both the eastern and the western settings. The net farm revenues on which these transitions are based are fairly stable prior to WWI

and then begin to fluctuate in the 1920s. Despite falling yields for corn, higher prices lead to corn's dominance in Washington, while generally lower yields in Wheatland lead to more switching between wheat and corn, in spite of the costs for switching between them included in the model. High beef revenues in the early 1880s produce small movements into this land use in the mid-1880s. But this effect is quite muted compared to the effect of high beef prices in Washington in the 1920s. After the high grain prices of the war years (1914–1918), when wheat first appears in the simulated fields of Washington Township, high beef prices drive a nearly complete shift into growing hay for beef raising. By contrast, consistently lower hay yields and negative net returns in Wheatland keep the farmer agents in the western township, with its much higher proportion of arable land, firmly in grains. Although Beef Hay returns during the 1930s, the main events of the war years and the 1920s in Wheatland are the dramatic swings between wheat and corn acreage, with the explosion of corn before the First World War, and the breathtaking switch back to wheat during the global conflict.

Land use in the historical record

Historically, these dramatic land-use changes in response to market signals were never part of the story. Change came more incrementally and land use remained more diverse. First, let us make a few technical points. In order to make the historical data commensurable with our model results, we had to compress some of the detail in the census data. Rather than displaying each land-use category as a proportion of the land in farms, we report the land use declared by census farmers as a percentage of the total area of the township. For purposes of the comparison, we treat land not included in the census as land that remains in pasture or native grassland (“Grass and Beef Grass”). To capture the dimension of more intensive use we wanted to operationalize in the model, the “Beef Hay” category in the historical data includes all acres reported in hay crops, plus acres in feed grains (oats, rye, barley, and sorghum).

In both townships, the most striking difference in the historical case is the greater preservation of pasture and native grassland compared with the simulated results. In neither the east nor the west did the plow-out exceed the proportion of arable land. In fact, in Wheatland, the conversion of grassland to cropping stopped far short of the 94 percent of the township's land area rated as suitable for arable production by the modern soil survey. Moreover, the conversion to cropland was a more gradual process that did not peak until 1930. In the historical record, wheat acres remained curiously flat during the war years, and didn't begin to grow dramatically until the 1920s, when producers stubbornly pursued wheat, even as prices fell. At the same time, despite commanding a higher price, corn remained a small fraction of the land use reported in Wheatland Township (Figure 2). In many ways, wheat cultivation is better suited to western climatic conditions, because it is more tolerant of the less-plentiful and less-reliable rainfall and can be sown in winter varieties, but corn and livestock would have increased profitability in the near term. All of this kept the number of farms in the township relatively constant at between 110–130 for most of the period, with the median farm size doubling between 1905 and 1930 to about 320 acres.

The story in Washington Township is even more cautious. Because of more-plentiful and more-reliable precipitation, corn cultivation represented a much larger share of land use. Wheat hardly entered the picture, except during the First World War, when Washington's farmers responded to higher wartime prices. But Beef-Hay and grassland remain a much larger part of the story in Washington because far more of its landscape was suited to grazing than plowing. Only half of the land base, mainly the bottomlands between its gently rolling hills, is regarded as arable by the modern soil survey. Devoting less than half of the land to grains, and growing an increasing proportion of hay on the steeper slopes of many fields, was probably a very sensible strategy on the part of Washington farmers for preventing soil erosion. This more balanced land-use strategy, dividing attention between field crops, haying, and livestock-raising, also was more intensive and demanded more labor. In spite of only being half the size of its western counterpart, Washington Township had roughly as many farmers (about 120), on much smaller farms, averaging 160 acres, for most of the period.

We use the three summary measures described above to explore areas of agreement between the base model and the historical record. These are similar to the approach taken in Magliocca et al (2013). The first, the Multidimensional Euclidean Distance (MDED), assesses the degree to which the historical and the modeled results depart from sameness. The less distance between the proportions of land use in the historical and modeled results (sum of squared differences), the closer the MDED is to zero. Figure 3 illustrates the level of agreement between the base model and the historical record for Wheatland and Washington. In both townships, the models perform well during the early settlement period, where the departure of MDED from zero is relatively modest. But after 1895 the model departure is substantial and never returns to 'sameness'. The base model tends to produce a series of rapidly changing, very different, yet fairly homogeneous landscapes, rather than the more incremental and balanced changes seen in the historical record. In Wheatland, the MDED performs better in the period from 1915 to 1940, but never really returns to sameness.

The reason for the divergence is illustrated by a comparison of the diversity index (DIV), between the base model results and the historical record (calculated separately for each). This index measures only the degree of balance between multiple land uses in the simulated and historical cases, and says nothing about the underlying composition. Historically, the diversity index reveals a consistently high balance of land uses in both Washington and Wheatland. This measure of diversity actually peaks during the First World War (when the incentives to specialize should have been at their highest). Then diversity remains high in Washington and falls in the 1920s in Wheatland, no doubt because of the shift to wheat growing described earlier. By contrast, the collapse of the simulated measures of diversity in Washington and Wheatland are most responsible for the departures from sameness indicated by the MDED. This process is less pronounced in Wheatland because of shifting back and forth between wheat and corn as the dominant crop choice. In these periods of change in the model, the diversity index performs better, because as land use shifts from one dominant crop to another in the model, the overall pattern remains more balanced in the near term. This is the case during the years of rapid switching between 1905 and 1925.

The Gini index is also calculated separately for the simulated results and the historical record and compared in order to evaluate the level of agreement. This measure of dispersion indicates the inequality among values of a frequency distribution, with zero representing complete equality and one representing complete inequality. Because there are no landless agents in our model, we would not see values of 1. In terms of the overall number of farms, the base model performs better in Wheatland than in Washington. In Wheatland, the number of agents matches the number of farmers more closely, but the land is more evenly distributed among farmers in the historical record. This is why the Gini index generated from the simulated results tracks higher than that for the historical record after 1905. In Washington, by contrast, the number of agents in the model is nearly twice the number of farmers enumerated in the agricultural census. The model does remarkably well in simulating the distribution (i.e., Gini) until 1905, but then encounters difficulty because agents in the model who own only a few parcels are unable to exit due to lack of buyers. Other mechanisms of redistribution in the community or in family lineages might have been part of the historical process.

Model Experiments

The literature suggests factors that might account for the mismatch between model results and the historical record. In order to test for them, we alter – one at a time – some of the input parameters and behavioral assumptions guiding agent decision-making. In our profit-maximizing framework, the land-use decisions Farmers make are based on expectations of net revenue, which is a function of yield and price. Experiments 1 and 2 model the effect of variation in yields and prices respectively, to assess the degree to which these factors influenced land-use decisions. Figures 4, 5, and 6 present analytic measures for these experiments, which assume that farmers are able to count on stable prices or on stable yields at both low and high levels.

Generally, none of these exercises produce results that match the historical record substantially better than does the base model (see also Table 1). Through 1930, the price-constant experiment brings the diversity of land use closer to the historical record in Washington, but the fit is much poorer in Wheatland. The price-constant model performs as well as or better than the base model in terms of the departure from sameness (MDSD), except that the simulation exaggerates the wartime wheat boom and makes wheat totally dominant in Wheatland by 1940. Perhaps the more revealing comparison, however, is the contrast in how the diversity index performs in both of the yield experiments. When yields are held constant at the lowest levels, land-use diversity simply collapses in both Washington and Wheatland. The trend is particularly evident in Wheatland, where diversity does not recover at all after 1900. Setting all yields to the lowest quartile moves each township quickly and permanently to the higher-performing and historically dominant crop — corn in Washington and wheat in Wheatland. By contrast, when yields are held at the 75th percentile, the simulations drive the diversity indices higher in both Washington and Wheatland. In Wheatland, in particular, holding yields constant at high levels moves the simulated diversity index much closer to the historical record, indicating that price variability can be a significant driver of land-use allocations when environmental constraints are removed from the decision making process.

The most suggestive results, however, came from our experiments in constraining how the agents reacted to the signals around them, especially the effort to simulate greater conservatism on the part of Farmers. Only by raising risk aversion uniformly to 0.9 for all agents were we able to come closer to replicating the actual pace of plow-out in both townships, though it produced a much closer fit between the historical and the simulated measures in Washington than in Wheatland. Nearly 50% of Washington and nearly 80% of Wheatland remained uncultivated under this constraint of almost complete risk aversion. With Farmers wary of any significant risk taking, the land-use pattern that existed at the end of the first stage of settlement (i.e., when all public land has been distributed) largely prevailed over the whole period, with far fewer changes during the remainder of the simulation. The results of this conservative simulation (Figure 7) generate lower values of MDED in Washington than do those of the base model. A separate run with risk aversion fixed at 0.5 (not shown) also produces lower MDED values than does the base model. The improvement in MDED reflects a closer correspondence between the simulated results and the historical record in terms of both diversity and composition of land use. In Washington, this is particularly evident after 1920, when the diversity index and land-use composition come closer to the historical record. High risk aversion does not perform as well in Wheatland because it hinders land transactions, and we assume in the model that Farmers cannot change land use while Parcels are for sale. High risk aversion also greatly reduces the probability of plow-out, which limits the amount of cropland. More cropland would be needed to improve the similarity of the diversity measure. None of our experiments manipulating risk aversion (uniform levels at 0.1, 0.5, and 0.9) brings the Wheatland model into alignment with the historical record in terms of diversity. The result is nevertheless intriguing because of the contrast between the two townships. The historical evidence suggests that there were forces at work, perhaps of a cultural or social nature, which are approximated by our adjustment of risk aversion, but which would require substantial refinement or additions to the complexity of the model in order to move the simulated results closer to the historical record.

In a final experiment we increase the length of a Farmer's memory of past revenues from 5 years to 10 years, which increases the decision-making memory window to include more extreme variability in yield and price. This change leads to somewhat smoother land-use transitions and more tentative responses to the high wheat prices of WWI. Land-use diversity increases overall, but the decline in Washington after the turn of the century remains. Diversity does not fully recover until the beginning of the 1920s. But in Wheatland, a longer memory has the effect of dampening the swing to corn seen in the base model in the 1910s and 1930s, following much higher levels of diversity from the 1890s to the 1910s. The longer-memory experiment, where farmers weigh decisions against greater experience, reduces the fluctuations produced in the base model. Extending a Farmer's memory to 15 years (not shown) further increases land-use diversity, and brings it closer to the historical record. The increased diversity could be the result of divergent decisions along the risk aversion gradient driven by more information collected over a longer time frame.

CONCLUSIONS

Our base model, assuming profit-maximization as the motive for land-use decision making, reproduced the historical record rather poorly in terms of both land use shares and farm size distributions in each township. We attribute the differences to deviations in decision making from profit-maximizing behavior. Each of the subsequent experiments illustrates how relatively simple changes in micro-level processes lead to different aggregate outcomes. With only minor adjustments to simple mechanisms, the pace, timing, and trajectories of land use can be dramatically altered. Although the basic simulation model presented is far from a perfect representation of profit-maximizing behavior (our own results hint at several potential areas of refinement), we argue that this effort represents an important contribution to a long-standing debate about why farmers are not more responsive to market signals. On the U.S. Great Plains there were few impediments to the pursuit of profit. Yet the farm communities in these historical settings simply did not shift their land use to respond to the opportunities presented by the outside world. The magnitude of the difference between the rapidly-shifting profit-centered worlds created in our simulations and the more diverse but stable ones inhabited by the historical actors only serve to illustrate how inadequate the rational actor model remains.

There is good reason to believe that these farmers moved toward higher returns for themselves and their families over time, but the evidence in our results indicates that the search for profit is an inadequate explanation for land-use decisions in the era before the New Deal. Farm families obviously weighed their decisions about how to use their land against many feedbacks. But if earnings had been the main focus, the transformation and use of these landscapes would have been far more dramatic and intensive. Farm families would have switched more seamlessly between different grains, fodders, and livestock-raising regimes to respond to opportunities in the marketplace. And they would not have produced the diversity that is the consistent and unexplained thread in this comparison of simulated and historical worlds. The comparison of simulated and recorded history makes our central finding all the more dramatic. Profit is an important part of the explanation, but short-term responses were too exaggerated in the simulation models to match the historical record. Like other efforts in this kind of 'generative' social science, the attempt to recreate observed patterns with a model produces a number of deviations that are suggestive of further refinements both in the model and in our theoretical understanding of the processes at play. In our case, we think that trajectories of land-use depended not just on economic returns, but other slow processes of change, demographic, cultural, and ecological, which shaped the decisions of farmers before and long after the middle of the twentieth century.

Appendix: Overview Design concepts and Details (ODD)

- Overview
 - Purpose
 - To simulate the land-use practices of profit-maximizing farmers in two Kansas townships with differing environmental characteristics.

- To determine whether economic motivation adequately explains historical land use patterns.
 - To determine the extent to which environmental characteristics affect the land use decisions of economically-motivated farmers.
 - State variables and scales
 - The model consists of Parcels and Farmers.
 - Parcels – attributes:
 - Arability – all parcels are designated either arable or non-arable
 - Soil quality – an indicator of the productivity of the soil, taking values of low, medium, and high
 - Land Use – parcels are either plowed or unplowed; an unplowed parcel may be in grass or beef-grass (cattle being raised on grass), and a plowed parcel may be in corn, wheat, or beef-hay (cattle being raised on cultivated hay)
 - Farmers – attributes:
 - Cash – the amount of money or debt held by the Farmer, updated each year
 - Risk aversion – a measure of a Farmer’s conservatism, ranging from 0 to 1 and constant throughout the model run
 - Process overview and scheduling. The model runs from 1875 to 1940, with each time step representing one year. At each time step:
 - New Farmers are introduced and assigned or sold Parcels.
 - Existing Farmers decide whether to sell a Parcel.
 - Farmers decide whether to buy additional Parcels.
 - Farmers decide whether to plow one grass Parcel.
 - Farmers decide which land use to implement on each Parcel.
 - Farmers’ cash supply and memory are updated on the basis of historical yield and price data for that year.
 - Some Farmers exit randomly, with the probability of exiting increasing exponentially, reaching .05 after 30 years in the model and 1 after 60 years in the model.
- Design Concepts

- Emergence
 - Patterns of land use/land cover and land ownership emerge from the collective decisions of individual profit-maximizing Farmers under different environmental conditions.
- Adaptation
 - If a Farmer has produced a certain crop on one Parcel, the cost of converting other Parcels to that land use is reduced, encouraging the Farmer to specialize in that crop.
 - Farmers change their number of Parcels and their management of those Parcels based on yields and prices they observe in the recent past.
- Objective
 - The objective of each Farmer is to maximize his cash through earning profits on his Parcels.
 - If cash is not increasing, a Farmer is required to sell Parcels until cash does increase or until he has fewer than four Parcels left, at which point he must leave the model.
 - Farmers make decisions about land ownership and land use calculated to maximize profits based on what they would have earned within their period of their memory.
- Learning
 - Farmers' behavior is based on their memory of past outcomes; as they are in the model longer, they have more memory, up to a maximum specified as a parameter in the model.
- Prediction
 - Farmers predict the amount of income that will be generated by each possible land use on the basis of the earnings of each land use category in the recent past.
 - Farmers predict the future profitability of a Parcel on the basis of its past profitability.
 - Farmers assume that the future will be identical to the recent past.
 - Farmers discount value of future earnings by 5% per year when comparing with the potential sale price of a Parcel.
- Sensing
 - Farmers have complete knowledge about the soil quality and arability of each Parcel and the income generated by each land use category for each soil type in the recent past.

- Farmers do not know the land-use choices other Farmers have made.
 - Farmers do not know the future yield or price of a given crop in advance of choosing land use.
 - Interaction
 - Farmers can own more than one Parcel.
 - Parcels can be owned by only one Farmer.
 - Farmers buy Parcels from and sell Parcels to one another – a Farmer can only buy a Parcel another Farmer has put up for sale, and a Farmer who puts a Parcel up for sale continues to own it until another Farmer buys it.
 - Land-use decisions made by previous owners of a Parcel affect the choices available to the current owner (if a previous owner has plowed a Parcel, the current owner cannot choose to put it in grass or beef-grass).
 - Stochasticity
 - Attributes of Farmers and Parcels are assigned randomly from specified distributions.
 - Decisions to buy, plow, and choose land uses for Parcels have stochastic elements.
 - Collectives
 - Farmers do not act collectively.
 - Observation
 - The model tracks
 - the land use for each Parcel in each time step,
 - the number of Farmers and Parcels owned by each Farmer at each time step,
 - cash of each Farmer at each time step.
- Details
 - Initialization
 - At the start of the run, Parcels are created and assigned values for arability and soil quality based on specified distributional parameters. Distributions are based on the actual distributions in the two townships measured in the current digital soil surveys (Soil Survey Geographic Database, 2004), summarized to the township boundaries, and are time-invariant.

- All Parcels are initially in native grassland and owned by the government.
- Additional parameters are specified at the beginning of the model run:
 - mean and standard deviation of the distribution of Farmers' initial cash (for details, see "Submodels, Introduction of New Farmers" below);
 - number of years a farmer must wait between land use changes;
 - mean and standard deviation of logged rate of cattle mortality from disease, calculated from the Grasslands Settlement data;
 - number of years a farmer can remember.
- Input
 - A schedule file for each township with values for each year from 1875 to 1940 indicates, on the basis of historical data:
 - number of entering farmers, based on newly observed farmers in the longitudinally-linked Grasslands Settlement data.
 - market price of parcels (price for medium soil quality with multipliers for high and low). Land price data are county-level values from Haines 2010 (ICPSR Study No. 2896) and vary over time. We assume that the average of these prices reflect medium soil quality. Before 1910, the price of a Parcel with high-quality soil would have been higher, and the price of a Parcel with low-quality soil would have been lower, but that these differences became less meaningful over time, as more useful inputs became available. In both townships, until 1890 the price of a high-quality Parcel is twice that of a medium-quality parcel and the price of a low-quality Parcel is half that of a medium-quality parcel. Between 1890 and 1910, these multipliers (2 for high quality and 0.5 for low quality) move linearly toward 1.
 - income earned by farmers with only grass parcels based on the prevailing wages for farm laborers in Kansas, without board (for 1875–1892, USDA 1892; for 1891–1909, Holmes 1912; for 1910–1929, USDA 1945; for 1930–1940 USDA 1930–1940). Adjustments were made to wages for 1910 to 1929 that were only reported with board, based on ratios where the two series were

available. Missing data was linearly interpolated. Values are the same for both townships. Our assumption is that farmers without crops or livestock would be employed by other farmers.

- prices received for corn (USDA ERS 2011), wheat (USDA ERS 2011), and beef (USDA Nebraska Agricultural Statistics Service 2005). These are national annual data, and are the same for both townships in each year.
- value of the machinery necessary to cultivate crops, assuming that corn and wheat require different implements, but that one set of wheat implements can be used on all of a farmer's wheat parcels and one set of corn implements can be used on all of a farmer's corn parcels. Equipment values are from a national series (United States. Bureau of the Census 1975)
- cost of plowing one grassland Parcel. This cost is set to \$100 in each year, which represents a diminishing cost to Farmers over time in real dollars as plowing technology improves. Based on Danhof's (1941) estimates of plowing costs, \$2.50 per acre.
- cost of beginning to raise beef on grass (Holechek 1988; USDA – Nebraska Agricultural Statistics, 2005)
- cost of beginning to raise beef on hay (Holechek 1988; USDA – Nebraska Agricultural Statistics, 2005)
- cost of continuing to raise beef on hay and on grass. Based on dressed weight hundredweight price (USDA – Nebraska Agricultural Statistics, 2005).
- cost of maintaining a corn or wheat crop (Goodsell and Jenkins 1961).
- corn and wheat yield (yield for medium soil quality with multipliers for high and low). Medium yield is county-level yield reported in Decanio, Parker, and Trojanowski 2000 (ICPSR Study No. 7594). Multipliers for soil quality were derived from the SURGO data (Soil Survey Staff 2004). Both corn and wheat are grown in rotation; wheat yield is multiplied by 1/2 (wheat-fallow rotation) and corn is multiplied by 2/3 (corn-corn-fallow rotation).
- yields for beef on hay and on grass. Based on Holechek (1988), estimates of forage yield from hay and grass on 40 acre parcels.

- percent of cattle killed by winter conditions, only for years with significant winter kill. Beef-grass yield was reduced by 80% in 1886 and 1887, and by 40% in 1885 and 1890 (McNeal 1922; Olmstead and Rhode 2008; Wheeler 1991; Flora 1948). This modification to yield is only applied to Beef-Grass (meant to capture pastured cattle, which are most at risk of severe winter conditions). In the years with winter kill greater than zero, cattle mortality from disease (in the schedule file) is not used to modify the yield of Beef-Grass.
- Submodels – Each time step
 - *Introduction of new farmers.* For each Farmer to enter at each time step (from one to the defined number of farmers entering in that year, as derived from the historical record and specified in the schedule file):
 - create a new Farmer
 - assign starting cash to Farmer from a log-normal distribution, adjusted to simulate change over time. The distribution is calculated using farm-level data from the Grasslands Settlement database of the acres in each farm, numbers of livestock, equipment value, and rods of fencing. Farm acres are multiplied by county land price (Pressley and Thomas 2001). Numbers of livestock from the GS database are multiplied by values taken from various sources. The value of milk and neat cattle, sheep and swine are state-wide figures from Parker, DeCanio and Trojanowski 2000. Values for horses and mules are from Towne and Rasmussen 1960. Rods of fence were multiplied by the value of fencing published in Primack 1969. All data were linearly interpreted to produce annual series.
 - ◦ Distribution:
 - Washington: mean = 8.1, sd = 0.77
 - Wheatland: mean = 7.42, sd = 0.35
 - Adjustment factor:
 - To calculate the adjustment factor, we created a similar distribution to that described in the section above. Sources and data available varied somewhat over time. After 1915 the value of equipment was taken from the value of machinery described above. From 1910 to

1940, the value of horses and mules were derived from relative changes shown in Olmstead and Rhode 2008, page 337. We then created an adjustment factor that mimicked the change in the distribution over time.

- Washington through 1920 = $1 + 6(\text{year} - 1875)/45$
- Washington after 1920 = $7 - 2.8(\text{year} - 1920)/20$
- Wheatland through 1920 = $1 + 4(\text{year} - 1875)/45$
- Wheatland after 1920 = $5 - (\text{year} - 1920)/10$
- assign risk aversion (between 0 and 1) to Farmer from uniform distribution
- assign Parcels to Farmer:
 - if free Parcels (half of the total) remain, randomly assign four Parcels (one homestead) to Farmer
 - else if Farmer can afford at least two Parcels (if buying two Parcels will not put him over his Operating Debt Limit (ODL), defined as half the value of the machinery he owns), he buys as many as he can afford, up to a maximum of four
 - else Farmer exits the model
- *Existing Farmers decide whether to sell parcels.* For each Farmer who did not enter the model in the current time step:
 - if Farmer is not making money (defined as currently having less cash than in the most distant year remembered) and owns fewer than four Parcels, Farmer puts all Parcels up for sale and may not purchase any additional Parcels
 - else if Farmer is below his Operating Debt Limit he puts his worst Parcel up for sale
 - else Farmer puts up for sale all Parcels he has owned at least five years and for which the sale price is more than he would expect to earn from them over the next five

years (calculated on the basis of the past five years' profit, discounted 5% for each year in the future)

- *Farmers decide whether to buy additional parcels.* For each Farmer who did not receive a free homestead in the current time step:
 - if Farmer can afford the best parcel on the market (if buying it will not put him over his ODL)
 - if Farmer is making money then the probability he will buy = $1 - \text{RiskAversion}/2$
 - else probability he will buy = $1 - \text{RiskAversion}$
 - if he successfully purchases the Parcel, he repeats this step for the next best Parcel on the market
 - Else no purchase is made
- *Farmers decide whether to plow a grass Parcel.* For each Farmer:
 - if Farmer has an arable Parcel that has not yet been plowed then probability of plowing = $1 - \text{RiskAversion}$ in Washington and $(1 - \text{RiskAversion})^{2/3}$ in Wheatland
 - else if risk aversion is less than 0.5 then probability of plowing = $1 - \text{RiskAversion}^{*2}$ in Washington and $2/3 - \text{RiskAversion}^{*4/3}$ in Wheatland
 - else parcel is not plowed
- *Farmers choose a land use for each Parcel.* For each Farmer, for each Parcel that has been under the same ownership and in the same land use at least 5 years:
 - Farmer chooses an ideal land use based on past performance and level of risk aversion
 - high risk aversion (0.8–1): Farmer chooses the land use that has been most lucrative under poor conditions (yields at their lowest for all crops)
 - medium risk aversion (0.2–0.8): Farmer chooses the land use that has been most lucrative under average conditions
 - low risk aversion (0–0.2): Farmer chooses the land use that has been most lucrative under

ideal conditions (yields at their highest for all crops)

- if the parcel is not already in that land use and if the farmer can afford the new land use, the probability of switching = $1 - \text{RiskAversion}$
- else Farmer continues the current land use
- *Farmers' attributes are updated and their future in the model determined.* For each Farmer
 - Farmer's cash is incremented by the net revenue for each Parcel for the year (based on historical yield and price data)
 - Farmer's memory is updated by the performance of all land use options in that year
- *Farmers may exit the model (simulating death or retirement).* The probability of exiting is $e^{t/10-6}$, where t represents the number of years a farmer has been in the model.

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Figure 1.
Land use fractions produced by the reference version of the ABM.

Figure 2.

Land use fractions observed in the historical record.

Source: Kansas State Board of Agriculture Statistical Rolls 1875–1941. U.S. Department of Agriculture Census 1880.

Figure 3.

Measures of land use pattern and difference in reference model and historical record.

NOTE: Multi-Dimensional Euclidean Distance (MDED) is the difference between the land-use fractions in the model versus the historical record. Diversity (DIV) is the degree of evenness in land-use fractions across the township for the model and the historical record, respectively. Gini is the Gini coefficient of evenness in farm sizes for the model and the historical record, respectively.

Figure 4.

Measures of land use pattern and difference in model with constant prices and the historical record.

NOTE: Abbreviations are as defined in Figure 3 caption.

Figure 5. Measures of land use pattern and difference in model with constant high yields and the historical record.

NOTE: Abbreviations are as defined in Figure 3 caption.

Figure 6.

Measures of land use pattern and difference in model with constant low yields and the historical record.

NOTE: Abbreviations are as defined in Figure 3 caption.

Figure 7.

Measures of land use pattern and difference in model with high risk aversion and the historical record.

NOTE: Abbreviations are as defined in Figure 3 caption.

Washington - Farmers Remember 10 Years

Wheatland - Farmers Remember 10 Years

Figure 8.

Measures of land use pattern and difference in model with long memory and the historical record.

NOTE: Abbreviations are as defined in Figure 3 caption.

Table 1

Numerical results from multiple output measures and different experimental settings

Washington															
Gini Coefficient								Wheatland							
Year	Historical	Base	1875 Prices	Low Yield	High Yield	Risk Aversion 0.9	10-Year Memory	Year	Historical	Base	1875 Prices	Low Yield	High Yield	Risk Aversion 0.9	10-Year Memory
1875	0.550	0.005	0.005	0.005	0.005	0.006	0.005	1875	0.029	0.036	0.036	0.036	0.036	0.036	0.036
1880	0.316	0.336	0.349	0.238	0.317	0.123	0.258	1880	0.208	0.243	0.304	0.207	0.253	0.081	0.242
1885	0.380	0.377	0.360	0.310	0.354	0.235	0.342	1885	0.075	0.291	0.305	0.199	0.271	0.136	0.250
1895	0.445	0.335	0.328	0.358	0.368	0.237	0.377	1895	0.303	0.319	0.337	0.362	0.333	0.242	0.300
1905	0.352	0.432	0.359	0.444	0.373	0.273	0.430	1905	0.384	0.458	0.319	0.495	0.350	0.351	0.395
1915	0.379	0.503	0.429	0.480	0.476	0.321	0.478	1915	0.256	0.501	0.378	0.547	0.514	0.381	0.419
1920	0.299	0.495	0.529	0.476	0.519	0.353	0.516	1920	0.319	0.548	0.458	0.574	0.545	0.382	0.501
1925	0.246	0.475	0.571	0.481	0.489	0.380	0.483	1925	0.257	0.584	0.554	0.582	0.599	0.381	0.585
1930	0.258	0.391	0.555	0.432	0.452	0.425	0.440	1930	0.252	0.570	0.594	0.583	0.577	0.393	0.586
1935	0.309	0.441	0.538	0.435	0.490	0.419	0.406	1935	0.308	0.571	0.648	0.572	0.586	0.380	0.588
1940	0.252	0.422	0.484	0.396	0.479	0.347	0.447	1939	0.584	0.555	0.643	0.569	0.569	0.371	0.570

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Multidimensional Euclidean Distance															
Year	Historical	Base	1875 Prices	Low Yield	High Yield	Risk Aversion 0.9	10-Year Memory	Year	Historical	Base	1875 Prices	Low Yield	High Yield	Risk Aversion 0.9	10-Year Memory
1875	0.000	0.089	0.089	0.089	0.089	0.089	0.089	1875	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1880	0.000	0.035	0.035	0.019	0.017	0.093	0.032	1880	0.000	0.004	0.004	0.004	0.004	0.013	0.003
1885	0.000	0.099	0.051	0.061	0.090	0.168	0.079	1885	0.000	0.056	0.045	0.039	0.062	0.015	0.054
1895	0.000	0.313	0.276	0.317	0.181	0.268	0.182	1895	0.000	0.336	0.248	0.114	0.344	0.053	0.188
1905	0.000	0.525	0.500	0.435	0.270	0.110	0.443	1905	0.000	0.645	0.548	0.464	0.685	0.141	0.429
1915	0.000	0.481	0.927	0.752	0.761	0.066	0.697	1915	0.000	0.257	0.285	0.315	0.567	0.429	0.314
1920	0.000	0.297	0.342	0.718	0.510	0.043	0.320	1920	0.000	0.299	0.259	0.322	0.993	0.418	0.256
1925	0.000	0.363	0.478	0.544	0.633	0.033	0.326	1925	0.000	0.245	0.281	0.263	0.330	0.448	0.220
1930	0.000	0.329	0.289	0.634	0.274	0.061	0.433	1930	0.000	0.228	0.121	0.130	0.202	0.638	0.111
1935	0.000	0.692	0.274	0.752	0.325	0.062	0.577	1935	0.000	0.241	0.254	0.221	0.466	0.449	0.204
1940	0.000	0.436	0.462	0.834	0.384	0.044	0.763	1939	0.000	0.336	0.554	0.492	0.787	0.184	0.351

Year	Diversity Index							Diversity Index							
	Historical	Base	1875 Prices	Low Yield	High Yield	Risk Aversion 0.9	10-Year Memory	Year	Historical	Base	1875 Prices	Low Yield	High Yield	Risk Aversion 0.9	10-Year Memory
1875	0.566	0.000	0.000	0.000	0.000	0.000	0.000	1875	0.004	0.000	0.000	0.000	0.000	0.000	0.000
1880	0.599	0.541	0.539	0.567	0.567	0.042	0.528	1880	0.249	0.143	0.135	0.133	0.143	0.008	0.144
1885	0.743	0.713	0.823	0.782	0.699	0.143	0.692	1885	0.287	0.474	0.448	0.428	0.485	0.043	0.468
1895	0.886	0.320	0.372	0.311	0.549	0.402	0.527	1895	0.569	0.773	0.799	0.642	0.727	0.180	0.918
1905	0.879	0.063	0.096	0.256	0.715	0.576	0.170	1905	0.746	0.353	0.414	0.426	0.649	0.304	0.680
1915	0.928	0.472	0.161	0.016	0.207	0.716	0.090	1915	0.847	0.564	0.338	0.175	0.739	0.372	0.696
1920	0.927	0.747	0.641	0.026	0.345	0.784	0.682	1920	0.829	0.648	0.575	0.128	0.354	0.398	0.571
1925	0.919	0.646	0.532	0.276	0.108	0.831	0.675	1925	0.762	0.255	0.118	0.104	0.679	0.423	0.400
1930	0.941	0.581	0.670	0.042	0.598	0.835	0.465	1930	0.630	0.778	0.266	0.097	0.647	0.444	0.559
1935	0.957	0.078	0.712	0.006	0.571	0.809	0.232	1935	0.695	0.799	0.049	0.089	0.663	0.471	0.697
1940	0.947	0.493	0.631	0.001	0.580	0.837	0.036	1939	0.756	0.743	0.008	0.084	0.535	0.492	0.676