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Land Transitions in the American Plains: Multilevel Modeling of Drivers of Grassland Conversion (1950 to 2000)

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Abstract

This paper examines drivers of land-cover change in the U.S. Great Plains in the last half of the twentieth century. Its central aim is to evaluate the dynamics of grassland preservation and conversion, across the region, and to identify areas of grassland that were never plowed during the period. The research compares land-cover data from 400 sample areas, selected from and nested within 50 counties, to aggregate data from the agricultural and population censuses. The spatially explicit land-cover data were interpreted from aerial photographs taken at three time points (1950s, 1970s and 2000s). Sample areas were chosen using a stratified random design based on the Public Land Survey grid within the target counties, in several clusters across the region. We modeled the sequences and magnitudes of changes in the interpreted air photo data in a multi-level panel model that included soil quality and slope of sample areas and agricultural activities and employment reported in the U.S. Censuses of Agriculture and Population. We conclude that land retirement programs and production subsidies have worked at cross purposes, destabilizing micro-level patterns of land use in recent decades, increasing levels of switching between cropland and grassland and reducing the size of remaining areas of native grassland in the U.S. Great Plains.

Keywords

Native grassland; conversion; preservation; aerial photography; long-term dynamics; stratified sampling; multilevel modeling

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1. Introduction

While agriculture activity in the Great Plains of the U.S. has disturbed natural ecosystems enormously over the last 200 years, resulting in significant declines in biodiversity (Fargione et al. 2008, Jangid et al. 2010), soil mass (Baveye et al. 2011, Pimentel & Pimentel 2006), and terrestrial carbon (Baer et al. 2002, Foley et al. 2005), the loss of natural habitat to agriculture has slowed considerably since the mid-20th century in the United States (Brown et al. 2005). Through a combination of price supports and land retirement, farm policy has reduced some of the environmental impacts of agriculture. In the aggregate, the conservation successes have been extensive. Roughly 34 million acres were enrolled in the Conservation Reserve Program (CRP) between 1986 and 1989, augmenting land retirement efforts first set in motion in 1956, with the Soil Bank program (Sullivan 2004). Land used for crops has fallen back to levels first recorded nearly a century earlier in 1910, down from a peak of 383 million acres in the 1982 census to 340 million in the 2002 census (Lubowski et al. 2006).

These aggregate trends mask regional variation and movement in the location and intensity of crop production. While the land area devoted to crops has declined six percent nationally since 1945, cropland use in the Corn Belt, Northern Plains, Pacific Northwest, Mountain and Pacific regions has expanded slightly. Cunfer (2005) has argued that the stabilization of crop expansion in the Great Plains region as a whole is mainly a function of natural limitations, illustrating that cropland reported in the agricultural census reached stable levels well before public policy set out to explicitly limit production. However, recent research offers less assurance about the limits of disturbance (Fargione et al. 2008, Hartman 2011, Stephens et al. 2008, Tilman 1999). At various times in the last 60 years, changing technology and economic conditions permitted farmers to expand production to less productive land, and the amounts of land shifting in and out of crop production has grown. Indeed, there is an increasing awareness that more native grassland is at risk of conversion and that biophysical limits and policy do not constrain short-term expansion to the degree they once did.

In this paper we take a closer look at cumulative levels of disturbance in native grasslands, using a new high resolution time series of land-cover data, developed specifically to examine the dynamics of land use. Based on a random stratified sample of 400 study sites across the Great Plains, the data offer repeat observations of fixed geographic areas, nested within larger contexts. This is very different from the monitoring of land use that is available from the returns of the agricultural census, which report on the activity of farms and farm operators. Census figures, available publicly at the scale of U.S. counties, tell us that the proportion of grassland has remained as high as two thirds of land in farms in the region since the mid-1930s (Cunfer 2005, Gutmann et al. 2005). Much of this native grassland is understandably located in the western plains, which receives less rainfall and is less suited to crop agriculture. In the western part of the region, some counties report as little as 10 percent of land in farms as cropland, while in the east, the proportion of cropland can reach as high as 75 percent (Gutmann et al. 2005: 94). By several measures, the proportions in the west and east of the region have remained remarkably stable.

However, the outward stability is misleading. To some extent it is an artifact of public policy. A series of crop allocation schemes introduced during the New Deal, and renewed after the war, sought to freeze acreage allotments within counties for several major crops. Movement of allotted acres between farms had to be negotiated in county committees overseen by farm leaders and USDA officials (Conkin 2008, Gardner 2002, Libecap 1998). The frequency with which cultivated lands were retired or reassigned to other locations was poorly understood before the introduction of Conservation Reserve Program, which mandated detailed farm-level monitoring (such as the USDA's Natural Resources

Inventory). The stability has also been challenged by policy incentives that have worked at cross purposes with conservation. Because farmers who agree to retire marginal land under the terms of CRP are not required to restrict cropping elsewhere, on other land they own or rent, many have substituted income by converting non-cropland to cropland to replace land enrolled in CRP. Agricultural economists have referred to the phenomenon as a slippage effect (Wu 2000, Wu & Lin 2010). Similarly the introduction of federal crop insurance in 1994 has encouraged cropland expansion by reducing the risks of converting environmentally sensitive land to cropping (Lubowski et al. 2006). Thus a simultaneous expansion and retirement of cropland is having a cumulative effect of actually increasing the total area of native grassland disturbed by cropland conversion at some time in the recent past. We present a different approach to estimating the proportions of native grassland by extending the record of spatially detailed land use and cover information back into the 1950s – before the era of remotely sensed satellite imagery.

2. Materials and Methods

2.1. Study Area and Sampling

We developed and analyzed a time series of aerial photographs (1950s-2000s) that were interpreted to identify cropland based on signs of plowing or tillage. The fixed geographic location of the time series developed is designed to uncover the maximum footprint of cropland use and to allow for multilevel panel data analysis.¹ The design relies on visual interpretation of sub-meter aerial imagery gathered by the Farm Service Agency of the USDA, at randomly selected sites, nested within 50 counties, and distributed across the major grassland biomes in the region. Though the sample is not as geographically complete as surveys undertaken by the USDA, USGS or even the agricultural census, the unit of analysis increases the resolution of observation, monitors the same land units over a 50-year period, and offers the strengths of repeated measure surveys. The fixed location captures the amounts of conversion over time, provides a more intensive assessment of the cumulative level of disturbance over the postwar period, and allows integration with geo spatial soil data. The nested nature of the design also allows us to estimate the relative contribution of various micro- (primarily biophysical) and macro-level (primarily demographic and economic) factors that are hypothesized as drivers of change in cropland area.

We defined the U.S. Great Plains, the study area, as the area bounded by a southern latitude of the 32nd parallel in Texas and New Mexico, an elevation of 1524 m (5,000 feet) along the front range of the Rocky Mountains, an isohyet of 700mm average annual precipitation in the east, and the Canadian border to the north (Figure 1). This combination of criteria led to inclusion of 475 counties in the Great Plains in the year 2000. The distribution of the 50 target counties, clustered to nest within Lands at satellite scenes for project objectives not reported here, captures a variety of ecosystems across the region. There are strong east-west and north-south gradients in the region shaped mainly by increasing precipitation and increasing temperature, respectively. Dry winters and wet summers are produced by a combination of three dominant air masses. Pacific and Arctic air flows dominate in the winter, and in the summer subtropical air flows from the Gulf of Mexico bring moisture into the region. The species composition of grasses in each region is framed by these dynamics (Burke et al. 1989, Sala et al. 1988).

¹ For another example of multilevel modeling in the literature see Colin Polsky and William E Easterling, Adaptation to climate variability and change in the US Great Plains, *Agriculture, Ecosystems and Environment*, 85, 1 (2001): 133-144.

2.2. Sample design

To characterize variability in ecosystems, we used Küchler's (1964) classic delineation of native vegetation zones in the United States. Refined in many ways since 1964, Küchler's vegetation regions neatly divide the larger region into shortgrass, mixed grass, and tallgrass eco regions, and can be stratified from north-to-south to embrace climatic variation. We chose three clusters of counties within each of the shortgrass, mixed grass and tallgrass plains, to capture the variation in growing conditions, and added a tenth cluster in southwestern Kansas, which embraces all three.

Within each county, we randomly selected 400 sample sites based on a block of three-by-three sections, as delineated by the Public Land Survey System (PLSS), and based exclusion rules on land cover visible in National Agricultural Imagery Program (NAIP) coverages for the 50 selected counties in 2006–2007. Our interest in measuring changes to agricultural land led to a decision to exclude areas that were interpreted as urban land cover in the recent imagery. We also excluded candidate sites that would not have fit entirely within a given target county. For a selected county, we used a random number generator to attach values to each PLSS section within the county, sorted the random number field and then selected the sample parcels in order from the top of the column. If the randomly selected PLSS section was not urban land and did not fall on the edge of the county boundary, then it and the surrounding sections on all sides were chosen as a sample site. Each resulting sample site included nine PLSS sections and had an area three miles by three miles (5760 acres or 2331 ha) in size. The process was repeated until eight sample sites were randomly selected from each target county.

The counties we selected in each eco region (see Figure 2) were among the more intensively managed in the mixed grass and shortgrass regions, and the distributions captured differed from each region as a whole - with less grassland overall captured in our sample. In part, this was an artifact of our decision to nest each of the ten county clusters within Küchler zones. But the departure from recent surveys is more obvious in the northwestern plains than elsewhere. Especially compared to a recent USGS survey of satellite imagery, the targeted counties in our time series in Montana were intensively managed.

The cluster of Montana counties in our sample reported 59 percent of land in farms as cropland in the 2002 agricultural census, in comparison to the 77% observed in the Northwestern Great Plains in a separate study (Drummond 2007). In contrast, grazing land accounted for about half of the land in our five-county cluster in northeastern Colorado, as reported in the 2002 agricultural census, which compares favorably with the 50% of grassland observed in the western High Plains (eastern Colorado, western Kansas, Oklahoma, Texas and New Mexico; Drummond 2007). Arguably, the over-representation of cropland in some county clusters in our historical survey makes it better suited to understanding the dynamics of disturbance. Our design allows for a greater focus on the land at risk of conversion, because conversion and restoration tend to happen close to existing cropland (Santelmann et al. 2004, Stephens et al. 2008, Wu 2000).

2.3. Data collection and interpretation

We chose imagery from the USDA's Aerial Photography Field Office (APFO; (Mathews 2008) with dates from the late 1950s, 1970s and 2000s (see Appendix A for list of counties and dates) based on comprehensive coverage for our study areas. Digital image files from the late 1950s and 1970s were ordered from APFO, and reproduced from original negatives as positive 8-bit scans. This resolution (20 microns) was adequate to render all the images at sub-meter (0.79 m) ground sample distance. The ground referencing information for these historical images was provided by the most recent natural color NAIP imagery available

from the USDA's Natural Resources Conservation Service Geo spatial Data Gateway, <http://datagateway.nrcs.usda.gov/>, and available online from NRCS's Arc GIS server. We also used the 1 arc-second (approximately 30m) National Elevation Dataset (NED) produced by the U.S. Geological Survey to ortho rectify the images.

Our land-cover classification protocols were based on the key distinction between grassland and cropland, and relied on central findings from grassland ecology about vegetation recovery. Several transect-based and repeat photography studies in the 20th century indicate that the signatures of tillage systems remain in the vegetation profile of grassland landscapes for some time (e.g., up to 50 years) after plowing activity has ceased (Costello 1944, Costello & Turner 1944, McGinnies et al. 1991, Shantz & Turner 1958). A sharp contrast between abandoned fields and unplowed vegetation could be observed in 1930s aerial photographs, allowing to identification abandoned cropland sites 53 years later with considerable precision (as confirmed by soil analysis) (Burke et al. 1995, Coffin et al. 1996, Lauenroth & Adler 2008). Vegetation during early succession – following the abandonment of a plowed field – appears more homogeneous because the species that colonize disturbed sites are more likely to be mixed and tallgrass species, like Big bluestem (*andropogongerardii*) and Side oats grama (*boutelouacurtipendula*), which are known for more rapid seed dispersal. The characteristic patchiness or uneven appearance of dominant perennial grasses is generally not evident until the end of the recovery period. The dominant perennial shortgrasses, like Buffalo grass (*buchodactyloides*) and Blue grama (*boutelouagracillis*), are more tolerant to grazing and drought, and will eventually dominate the composition of recovering grassland in dryland settings.

Once the airphotomosaics were completed, a team of student interpreters began the classification work. Manual interpretation relied on a modified Anderson scheme (Anderson 1976). Interpreters were asked to use a series of identification rules to proceed from five basic types of land cover (impervious or developed land, grassland, trees, water and barren land) to eleven more detailed classes. The classes included developed, transportation, cropland, orchard, pasture, grassland/rangeland, forest, forested grassland/rangeland, shelterbelt, water body, and non-forested wet land. To distinguish between cropland and grassland, for example, the interpreters were instructed to note the absence of trees, developed land, water or barren soil. If there were signs of tillage in the vegetation (plowing, mowing, parcel lines, and rectangular or geometric shapes with sharp tonal edges), they were asked to classify the land as cropland. If the grassland cover showed no signs of tillage, and the land cover was homogenous and green enough to suggest that it had been fertilized or seeded, they were asked to classify it as pasture. If it did not look richer than the surrounding vegetation, but instead looked uneven, or contained areas of bare soil (up to 40 percent of the land area) they were instructed to classify it as grassland (Holechek et al. 2004).²

Manual interpretation can be subjective, and interpretation accuracy improves with training and experience and the use of decision rules that constrain the choices facing interpreters. Nevertheless the advantages of using aerial photography are evident in detailed analysis of landscape features and the historical time-depth the sources offer in comparison to satellite imagery (Caylor 2000, Morgan et al. 2010). Typically black and white panchromatic air photos taken at a scale of 1:24, 000 on negative film can resolve ground objects smaller than a meter.

² The interpretive distinction was based on current practice in rangeland science to separate native vegetation communities (rangelands) from lands that are primarily used for the production of domesticated forage plants for livestock (pastures).

2.4 Statistical analysis

We developed two versions of multilevel Poisson regression models, a member of the family of generalized linear mixed models, to assess the scale and dynamics of movement between land use classifications. The Poisson error distribution, with the use of an offset variable, is an appropriate match to the data generating process because our outcomes are rates (proportions of land area allocated to grassland and cropland) and the multilevel framework allows for the introduction of explanatory (independent) variables at different scales. To create a uniform unit of analysis that we could use to account for spatial variability in soils, we subdivided each of the 400 sample sites into 36 smaller units (“sample boxes”) to yield a study sample of 14,400 units. Each sample box is just under the size of a quarter-section of land (160 acres).³

We developed two independent variables to account for soil quality (land capability class) and terrain (slope) at the sample box-scale. These covariates were derived in ArcGIS by intersecting our land-cover data with USDA soil data (SSURGO). These covariates are time-invariant. Our multilevel approach also readily supports the specification of a variety of county-level covariates that were derived from the agricultural and the population censuses. The data were extracted from the county-level data series (from 1954, 1959, 1974, 1978, 2002 and 2007) collected in the Great Plain Population and Environment dataset (Gutmann 2005). These contextual variables include total acres in wheat; in corn; and in pasture (reported in increments of 1,000 acres); the number of farms larger than 1,000 acres in size; and two measures for labor force participation: persons employed in service occupations and persons employed in agriculture.⁴

The data supported two approaches to modeling land use in the late 1950s, 1970s, and 2000s. One perspective focuses on the sequential pattern of land cover and another on change over time. For the sequential analysis, we created a rank-ordered dependent variable. We have three periods and two land covers, giving us $2^3 = 8$ different sequence classes. Giving priority in the temporal order to cropland we ranked these classes as follows: (1) CCC, (2) CCG, (3) CGC, (4) CGG, (5) GCC, (6) GCG, (7) GGC, and (8) GGG. So, for example, the CCC variable represents the total area (in sq km) in a sample box that was observed in cropland in the 1950s, 1970s and in the 2000s; CCG represents the total area that was in cropland in the 1950s and 1970s that became grassland in 2000s; and by GGC we give the total area that was grassland in the 1950s and 1970s that became cropland in the 2000s. We then aggregated the sequences into four categories: always cropped (= CCC); twice cropped (= CCG, CGC, GCC); once cropped (= CGG, GCG, GGC); and never cropped (= GGG).

Each of our four dependent variables (referred to as Models A, B, C, and D) is the total area (in sq km) in a sample box that is of the designated classification. The transformation of a model of “count data” to a model in which the outcome is a rate (proportion) is accomplished by regressing counts, e.g., area (in sq km) in a sample box of the designated classification, on an “offset” that gives the denominator of the rate, e.g., total area (in sq km) of the sample box (Osgood 2000). We refer to our version of this analytic model as a “multivariate rate model” because we treat each of the aggregated classifications as a dependent variable whose distribution is correlated with the distributions of each of the other

³ Sample box units are smaller than 160 acres in order to fit inside the slightly variably sized and shaped three mile by three mile sample sites. Several imperfections in the PLSS meant that the sample sites were not uniform in size. As a consequence, our sample box units are 142.75 acres in size.

⁴ We also include a county-level covariate of government payments (in \$10,000s) in our analysis of the land-use sequences, but this covariate is dropped from our temporal change analysis because the data were only reported beginning in the 1969 census of agriculture.

dependent variables. We account for the correlated errors by simultaneously estimating the four rate regression models, and in this manner the effect of an independent variable on each outcome is conditional on its effect on the other regressions. In other words, we estimate the effect of, say, slope (or soil quality) on the proportion of land that is never cropped, conditional on what is happening in the equations for the other three outcome types (always, twice and once cropped).

Our second approach is to develop “panel rate models” that estimate the proportion of land (in sample boxes) that was designated as cropland, conditional on year, slope, soil quality and other higher level or contextual variables. We estimated three rate regressions (simultaneously) using a count dependent variable (e.g., area in sq km in crop land in sample box) with an offset (total area in sample box). Our first regression is a 1950s baseline model (Model E), wherein the estimated coefficients may be interpreted as in a conventional regression: the effect of a unit increase in the independent variable on the level (proportion of area cropped) of the dependent variable. The dependent variable in our second regression model (Model F) may be interpreted as the change in the proportion of area cropped between the 1950s and 1970s and the third regression (Model G) gives the change between the 1950s and the 2000s.

Our data and analyses are susceptible to (positive) spatial autocorrelation between sample boxes because the rates of each aggregated classification (as well as values of our explanatory variables) in neighboring (or nearer) sample boxes are likely to be more alike than those from more distant sample boxes. We employed error covariance structures that account for within sample site correlation among sample boxes. We used the SAS GLIMMIX procedure (SAS Institute Inc. 2008, Schabenberger 2005, Verbeke 1997).

Poisson regression is a member of the family of probability models wherein the regression coefficients are linked to the outcome in a nonlinear fashion. Although this complicates their interpretation a bit, there are a number of popular transformations that ease interpretation (Liao 1994). We report the multiplicative effect of the independent variables on the expected value of the outcome by exponentiation of the regression coefficient, $\exp(\beta)$, similar to the interpretation of the effect of an odds ratio. Thus, $\exp(\beta)$ in Model A in Table 2 gives the multiplicative effect of a one unit increase in an independent variable on the expected proportion of area “never cropped.” Effects in Models B (always cropped), C (cropped twice), and D (cropped once) in Table 2 report the regression coefficients as multipliers relative to the proportion of land “never cropped.” By contrast the estimates of the area cropped over time in Table 3 present the effects in contrast to the levels of cropping in the 1950s. The $\exp(\beta)$ in Model E in Table 3 gives the multiplicative effect of a one unit increase in an independent variable on the expected proportion of area cropped in the 1950s. Models F and G in Table 3, report regression coefficients relative to the proportion of area cropped in the 1950s (Model E). For example, if $\exp(\beta)$ for variable X in Model F is 1.5, we interpret this as “for every one unit increase in X, the proportion of area that was cropland in the 1970s would be 1.5 times (or 50% larger than) the area that was cropped in the 1950s” (net of the other sample box- and county-level covariates).

3. Results and Discussion

3.1 Land Cover Trends

Cropland expanded into the late 1970s, with a small restoration of grass land occurring after the introduction of the Conservation Reserve Program. The Shortgrass sample areas reveal lower levels of cropland in the most recent decade, compared to the late 1950s; the Tallgrass areas returned to levels observed 50 years earlier; and the Mixed Grass areas stayed at the peak levels, first reached during the export boom of the 1970s (Table 1). Over the entire

sample, the proportion of cropland in any one period of observation is relatively stable. The percentage of area in cropland was 66.8 percent in the 1950s, rising slightly to 69.9 percent in the 1970s, and returning to a level of 66.6 percent in the 2000s.

In terms of total grassland area, the most striking example of movement masked by these aggregate statistics may be the dramatic loss of grassland in the shortgrass region prior to the 1970s, and the re-expansion or restoration of grassland in between the 1970s and the 2000s. The cumulative pattern of change indicates that native grassland remains a small fraction of the non-cropland area; the proportion of our 14, 400 sample boxes that were never cropped is only 14.3 percent. In between this relatively low proportion of never cropped grassland and the 56 percent of land that was “always cropped” (in the 1950s, 1970s and 2000s), 3.7 percent of the area was cropped once and 11.8 percent cropped twice during our three observation periods.

3.2. Statistical modeling

The result of our multivariate rate model suggests that the baseline estimate of never cropped land is even lower, when we control for other local factors. Comparing the never cropped status with the others over the entire study period, produces an estimate of only 11 percent remaining untilled (when the outcome is conditioned on the means of all the independent variables) over the whole time period (Table 2, Column 1). This suggests an even higher proportion of native grassland (“never-cropped grassland”) was at risk of conversion, below the cumulative proportion of never cropped land.

The effect of soil quality in Model A ($\beta = -0.57$) shows that a unit increase in the proportion of good soil in a sample unit reduces the proportion of never cropped land by a factor of 0.57, or about 43 percent ($[\exp^{\beta} - 1] \times 100 = -43.3$).⁵ But high quality soil has the opposite effect on the other outcomes. A unit increase in high quality soil increases the ratio of always cropped land to never cropped land by a factor of 2.1; that is, each unit increase in high quality soil doubles the area always cropped relative to area never cropped.⁶ Similarly, Models B and C show that a unit increase in high quality soil increases the area twice cropped and once cropped, relative to area never cropped, by factors of about 1.9 and 2.8, respectively. Slope works in the opposite direction. A one degree increase in slope increases the area never cropped by about 1.8 percent (or by a factor of 1.02). Reading across the table to the other outcomes, the contrasts suggest that as slope increases the area once cropped increases slightly, and the areas twice cropped and always cropped are reduced, relative to area never cropped. Indeed, the contrast is statistically stronger, in descending rank order, from once cropped, to cropped twice and always cropped, suggesting that slope has a predictable gradient effect on land use. As the terrain becomes more level, as slope decreases, it is more likely to be cropped.

Several of the contextual variables in Table 2 are suggestive of the drivers of change, as well. First, the differential effects of the amounts of wheat and corn agriculture in the counties are noteworthy, and capture some of the differences in crop systems in the eastern and western plains. Averaged over the period, the county wheat acreage reported in the census did not have any impact on never cropped land. Corn acres, however, did contribute to a reduction of never cropped land, and the contrast with always cropped land indicates

⁵ We could also say that a one percent increase in proportion of high soil is associated with an $\exp(\beta)$ percentage change in the outcome because both the independent variable and the dependent variables are measured as proportions and both could be multiplied by 100 to be on a percentage scale.

⁶ We can also easily recapture the “main” effect in Models B–D via the product of the relative effect in the model and the corresponding $\exp(\beta)$ in Model A. For example, for soil quality, 2.1031 (in Model D) $\times$ 0.567 (in Model A) gives the “main” effect, 1.1924 , in Model D: a unit increase in high quality soil increases the area always cropped by a factor of about 1.2, or by almost 20 percent ($[\exp^{\beta} - 1] \times 100 = [1.1924 - 1] \times 100 = 19.24\%$).

that corn is positively associated with this sequence in both absolute and in relative (to never cropped) terms. As might be expected, pasture acreages reported in the census boosted the proportion of never cropped, once cropped, and twice cropped land, but pasture acreage reduced always cropped land in both absolute and in relative (to never cropped) terms. By contrast, government payments had a negative impact (in absolute terms) on the proportion of land never cropped, once cropped, and twice cropped, while always cropped land was less likely to contribute to reductions in undisturbed native grassland. The implication is that government payments as a whole provide a significant incentive to till marginal land (land not consistently cropped over the period observed).

3.3. Change Over Time

The outcome from the models of change over time is the proportion of land area in crops, with Models F and G representing the contrasts of the 1970s and 2000s with the baseline period in the 1950s (Table 3). The intercept in Model E(1950) indicates that the starting estimate for the baseline period was 63 percent, for sample units with average values of all model covariates. This is slightly higher than the proportion of cropland reported in the agricultural census in 1959, in the 50 target counties, which was 60.5 percent. The exponentiated coefficients [$\exp(\beta)$] in the second column of Model E indicate the multiplicative effect of a unit increase in the variable on mean outcome. Multipliers below one indicate a negative effect, while odds ratios above one give a positive effect. Slope exerted a negative effect on the proportion of cropland and soil quality a positive effect. The concentration of wheat agriculture in a given area also increased the proportion of land cropped in the 1950s, as did acres of corn, the number of large farms greater than 1,000 acres in size, and persons employed in agriculture. Land use was less intense where pasture acres were larger and the level of persons employed in service occupations was higher.

The estimates for Models F and G serve as contrasts, which either weaken or strengthen the effects in the baseline estimates. The constants in Models F and G, for instance, suggest that cropland expanded into the 1970s, to meet the demands of an export boom in agriculture in that decade, and contracted to levels seen in the late 1950s in the last decade observed, a decade and a half after the introduction of the Conservation Reserve Program. The effects of the environmental variables were not both constant over time. In the 1950s, slope had the expected effect of reducing the estimated proportion of cropland and this effect remained largely unchanged in the 1970s and 2000s. By contrast the relationship between good soil and area cropped has weakened substantially over time. Good soil remained in many ways a powerful predictor of the proportion of area cropped in the air photo time series, but the contrasts with the values in the 1950s, illustrate that the relationship had become weaker by a factor of 0.98 in the 1970s and 0.82 in the 2000s. In essence, although slope continued to exert a strong constraint on decisions to expand cropland, good soil did not have early the effect it once did.

The contrasts in the contextual variables confirm much of what was observed in Model E. Wheat and corn agriculture were both positively related to the physical extent of crop land interpreted in the 1950s air photos, and these relationships have weakened over time. Pasture, on the other hand, continues to serve as a brake on cropland expansion. The contrasts with the main effect in the 1950s suggest an even stronger effect in the 2000s. The other variables from the population census had generally weak relationships to cropland expansion. The proportion of persons employed in agriculture continued to exert a positive and significant effect, and the proportion of persons employed in service occupations exerted a consistently negative effect, although not a statistically significant one in the 2000s. The growing impact of the remaining agricultural work force is surprising given the degree of change in the rural economy in the last 50 years, with the shrinking proportion of

persons living on farms and the growth of food processing and animal confinement operations in many areas (Hart 2003, Johnson 2006, Mayda 2008).

4. CONCLUSIONS

From an ecological perspective, our data indicate that the scope for natural disturbance has grown rather than stabilized in the Great Plains. Since the 1950s, the proportion of grassland that escaped tillage during the last half of the twentieth century is smaller than any single observation survey, like the agricultural census or remote sensing analyses, permits us to see. When we take the extra step of examining a time series of high-resolution imagery for signs of disturbance (the unique combination of tillage and tonal homogeneity in air photos), it is clear that the cumulative impacts are broader than recent accounts have suggested (Cunfer 2005). Part of the reason that the restoration of grassland in the shortgrass appear so large in the last thirty years, may very well be that we are finally seeing the impact of 50 years of conservation measures, of set-aside and land-retirement incentives, necessary for the restoration of formerly unplowed native grassland in the dryland areas of the western plains. The pattern of change that lies beneath the relative stability visible in the agricultural census is a cause for concern in all the eco regions within the Great Plains. The results raise significant questions about the limits to cropland expansion in the region.

For better than half a century policy has tried to limit the expansion of cropland agriculture. This has worked better in some of the sub-regions than the others. In the tallgrass and in the shortgrass it has led to substantial restoration of grassland. But in the mixed grass region the expansion has not fallen back and the movement of cultivation through the landscape, as wetland, woodland and brush ebb and flow, is likely adding to the cumulative impacts on the environment. Wheat and corn crop systems have both put pressure on native grassland in the region. Recent demand for bio fuel feed stocks and the demand for livestock feed do not appear to have added to the incentives to expand crop agriculture as of our final observation. While conservation policy has moderated the cumulative expansion, the most concerning finding may be that natural constraints have become less important over time. Overall, government payments in agriculture tend to work at cross purposes with conservation policy, raising rather than lowering the instability in the locations and physical extent of cropland. Increasingly, it is evident that soil quality and slope do not constrain the expansion or movement of cropland, as they once did - before the demand for grain exploded on world markets and policy makers introduced measures to simultaneously restrict the use of marginal land and support farm incomes. The mix of population change, technological innovation, agricultural demand, and policy supports has contributed to more experimentation in local environments, not less. With increased levels of switching between grassland and cropland, it may be time to rephrase the question. Perhaps the core ecological imperative is to focus on the right mix of natural habitat and agriculture in every setting - because it turns out that in highly productive landscapes there is far less native habitat than we generally imagine.

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Appendix A. Aerial Photography Flight Dates

State	County	Imagery		
		1950s	1970s	2000s
Colorado	Adams	1963	1977	2005
	Arapahoe	1963	1977	2006
	Logan	1963	1978	2006
	Morgan	1963	1979	2006
	Weld	1963	1977	2006
Iowa	Lyon	1962	1978	2006
	O'Brien	1962	1978	2006
	Osceola	1962	1978	2006
	Sioux	1962	1978	2006
Kansas	Ford	1960	1981	2006
	Gray	1960	1981	2006
	Haskell	1960	1981	2006
	Marshall	1962	1978	2006
	Seward	1960	1981	2006
	Stevens	1960	1981	2006
Minnesota	Clay	1958	1981	2003
	Nobles	1962	1979	2003
	Norman	1958	1974	2006
Montana	Cascade	1957	1977	2005
	Choteau	1956	1979	2006
	Hill	1960	1979	2006
	Liberty	1957	1979	2006
	Toole	1957	1979	2006
Nebraska	Gage	1959	1979	2003
	Jefferson	1962	1977	2007
	Saline	1962	1977	2007
	Seward	1959	1977	2006
North Dakota	Cass	1962	1980	2006
	Dunn	1958	1977	2006
	Grand Forks	1962	1980	2006
	McLean	1958	1976	2005
	Mercer	1958	1976	2006
	Morton	1957	1980	2006
	Oliver	1957	1980	2006
	Traill	1962	1980	2005
Oklahoma	Blaine	1957	1979	2006

State	County	Imagery		
		1950s	1970s	2000s
	Canadian	1957	1979	2006
	Garfield	1961	1981	2006
	Kingfisher	1957	1979	2003
	Noble	1961	1980	2006
South Dakota	Faulk	1957	1978	2006
	Hand	1957	1978	2006
	Hyde	1957	1978	2006
	Potter	1962	1976	2006
	Sully	1962	1976	2006
Texas	Crosby	1963	1980	2006
	Dawson	1962	1980	2006
	Lubbock	1962	1979	2006
	Lynn	1962	1980	2006
	Terry	1962	1980	2006

Highlights

- We compare land-cover trends in a stratified sample across the Great Plains.
- Analysis of high resolution aerial photography allows for longer timeframe.
- Magnitudes of change are estimated in a multilevel model.
- We conclude that the disturbance of native grassland has been underestimated.

Figure 1.
Great Plains Counties

Figure 2.

Sample Frame

Source: US Forest Service, Kuchler Potential Natural Vegetation Groups. Missoula, MT: Fires Sciences Laboratory, Rocky Mountain Research Station, 2000 (raster data).

Table 1

Land Cover in square kilometers					
	Küchler Zone		Late 1950s	Late 1970s	2000s
Grassland	Tallgrass	sq km	297	255	281
	Mixed Grass	sq km	950	896	847
	Shortgrass	sq km	908	879	1,110
	Tallgrass	%	12	10	11
	Mixed Grass	%	34	32	30
	Shortgrass	%	30	29	37
	Tallgrass	% Δ	-	-14.14	10.20
	Mixed Grass	% Δ	-	-5.68	-5.47
	Shortgrass	% Δ	-	-3.19	26.28
Cropland	Tallgrass	sq km	2,040	2,080	2,030
	Mixed Grass	sq km	1,610	1,740	1,740
	Shortgrass	sq km	1,910	1,990	1,770
	Tallgrass	%	82	83	81
	Mixed Grass	%	57	61	61
	Shortgrass	%	64	67	59
	Tallgrass	% Δ	-	1.96	-2.40
	Mixed Grass	% Δ	-	8.07	0.00
	Shortgrass	% Δ	-	4.19	-11.06

Table 2

Multivariate

Independent Variables	Model A: Never Cropped			Model B: Once Cropped			Model C: Cropped Twice			Model D: Always Cropped		
	coefficient (st. error)	exp(β)	t-value	odds relative to never cropped	t-value		odds relative to never cropped	t-value		odds relative to never cropped	t-value	
Constant	-2.1938 (0.01569)	0.11149	-139.86 **	0.3043	-132.24 **		1.0037	-147.79		4.6534	-123.71 **	
Slope	0.0178 (0.00071)	1.01797	25.13 **	1.0035	2.40 **		0.9748	-7.29 **		0.9683	-32.29 **	
Soil Quality: proportion in three most arable LCC	-0.5674 (0.04698)	0.56700	-12.08 **	1.8800	0.87		2.7790	10.47 **		2.1031	12.10 **	
Wheat Acres classes in county, 1, 000s	-0.0001 (0.00023)	0.99986	-0.61	0.9996	-0.98		0.9998	-1.30		1.0007	6.10 **	
Corn Acres in county, 1, 000s	-0.00279 (0.00042)	0.99721	-6.62 **	1.0015	-1.86 *		1.0016	-2.90 **		1.0047	16.73 **	
Government Payments in county, 10, 000s dollars	-0.00074 (0.00010)	0.99926	-7.75 **	0.9992	-8.60 **		1.0002	-5.44 **		1.0009	4.90 **	
Pasture Acres in county, 1, 000s	0.00155 (0.00009)	1.00155	17.34 **	0.9992	4.24 **		0.9991	5.98 **		0.9975	-24.59 **	
Number Farms 1, 000 acres or more , county	-0.00064 (0.00029)	0.99936	-2.26 **	1.0015	2.86 **		1.0015	2.77 *		1.0013	5.38 **	
Persons employed in service , proportion county population	0.142800 (0.04498)	1.15350	3.17 **	0.8565	-0.15		0.9013	0.78		0.8000	-4.57 **	
Persons employed in agriculture , proportion county population	-0.001180 (0.00407)	0.99882	-0.29	0.9986	-0.29		1.0193	4.01 **		0.9988	-0.76	

exp(β) in eq. 1 gives the multiplicative effect of a 1 unit increase in independent variable on the expected proportion of area "never cropped". Alternatively, $[\exp(\beta) - 1] \times 100$ gives the percentage change in the area in crops for a 1 unit increase in the independent variable. Effects in Models B, C and D are interpreted as conventional odds ratios (e.g., effect on the proportion of area "always cropped", "cropped twice", or "cropped once" for unit increase in the independent variable.)

* indicates level of significance for $p < 0.05$;

** indicates $p < .01$

Table 3

Panel Model

independent variable	Model E: Proportion of Area Cropped in 1950			Model F: Area Cropped in 1970		Model G: Area Cropped in 2000	
	coefficient (st. error)	exp(β)	t-value	odds relative to area cropped in 1950	t-value	odds relative to area cropped in 1950	t-value
Constant	-0.4586 (-0.004203)	0.6322	-109.13**	1.0483	249.28**	0.9988	0.37
Slope	-0.0183 (-0.000384)	0.9819	-47.67**	1.0006	4.73*	1.0008	5.26*
Soil Quality: proportion in three most arable LCC classes	0.3008 (-0.011360)	1.3509	27.24**	0.9823	4.27**	0.8283	238.73**
Wheat Acres in county, 10, 000s	0.0108 (-0.000542)	1.0108	19.84**	0.9956	80.69**	0.9963	31.07**
Corn Acres in county, 10, 000s	0.0157 (-0.000752)	1.0158	20.95**	0.9948	55.50**	0.9918	101.59**
Pasture Acres in county, 10, 000s	-0.0054 (-0.000301)	0.9946	-17.95**	1.0010	17.31**	0.9998	0.36
Number Farms 1, 000 acres or more, county	0.0002 (-0.000053)	1.0002	3.63	0.9998	61.90**	0.9994	19.95**
Persons employed in service, proportion total population in county	-0.0177 (-0.005969)	0.9825	-2.96**	0.9840	4.79*	1.0140	1.63
Persons employed in agriculture, proportion total population in county	0.0022 (-0.000853)	1.0022	2.54*	1.0044	19.24**	1.0042	12.88*

exp(β) in eq. 1 gives the multiplicative effect of a 1 unit increase in independent variable on the expected proportion of area in crops in 1950. Alternatively, $[\exp(\beta) - 1] \times 100$ gives the percentage change in the area in crops for a 1 unit increase in the independent variable. Effects in Model F and G are interpreted as conventional odds ratios (e.g., effect on the proportion of area in crops in 1970 relative to proportion of area in crops in 1950 for unit increase in an independent variable).

* indicates level of significance for $p < 0.05$;

** indicates $p < .01$