Climate, Livestock, and Vegetation: What Drives Fire Increase in the Arid Ecosystems of Southern Russia?

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ABSTRACT

Fire is an important natural disturbance process in arid grasslands but current fire regimes are largely the result of both human and natural processes and their interactions. The collapse of the Soviet Union in 1991 spurred substantial socioeconomic changes and was ultimately followed by a rapid increase in burned area in southern Russia. What is unclear is whether this increase in burned area was caused by decreasing livestock numbers, vegetation changes, climate change, or interactions of these factors. Our research goal was to identify the driving forces behind the increase in burned area in the arid grasslands of southern Russia. Our study area encompassed 19,000 km^2 in the Republic of Kalmykia in southern Russia. We analyzed annual burned area from 1986 to 2006 as a function of livestock population, NDVI, precipitation, temperature, and broad-scale

oscillation indices using best subset regressions and structural equation modeling. Our results supported the hypothesis that vegetation recovered within 5–6 years after the livestock declined in the beginning of the 1990s, to a point at which large fires could be sustained. Climate was an important explanatory factor for burning, but mainly after 1996 when lower livestock numbers allowed fuels to accumulate. Ultimately, our results highlight the complexity of coupled human-natural systems, and provide an example of how abrupt socioeconomic change may affect fire regimes.

Key words: burning; arid ecosystems; livestock; climate; broad-scale climate; Southern Russia; socio-economic change.

INTRODUCTION

Fire is one of the main disturbance agents in grasslands and savannahs, and can be an indicator of ecosystem change. Fire shapes vegetation structure and composition and represents an important land-management tool (Pyne [1984]). Grasslands, woody savannahs, and savannahs contain more

than 60% of the annual global burned area (Tansey and others [2004]), and in regions with high aridity, such as Central Asia, grassland fires account for 80% of all active fire counts (Csiszar and others [2005]). Fuel loads and emissions from grassland burning are relatively small (van der Werf and others [2006]), but grassland fires can foster the spread of invasive species (Brooks and others [2004]), affect wildlife habitat (Archibald and Bond [2004]), and generate air pollution that can spread as far as the Arctic (Stohl and others [2007]). Furthermore, interactions between grassland fires and human land use may lead to ecosystem degradation, hydrologic changes, soil disturbance, and

shrub encroachment (Archer and others 1995). At the same time, fire is an indispensable component of grassland ecosystems because fires stimulate germination and regrowth (Letnic 2004), and hence fires are often set deliberately to enhance pastures and raise the availability of nutritious forage for livestock (Guevara and others 1999). However, management, conservation, and restoration of arid grasslands require an understanding of the driving forces of burning, and such an understanding can only be gained from long-term fire records. Our goal was to understand the drivers of fire regimes in southern Russia, and particularly to identify the reasons for the marked increase in annual burned area since the mid-1990s (Dubinin and others 2010).

Wildfire patterns are determined by many factors, but ultimately the key factors are fuel availability (moisture and amount) and ignition sources (Bond and van Wilgen 1996; Meyn and others 2007). In southern Russia and elsewhere, almost all ignitions are human-caused and relatively constant in number since human populations have remained fairly stable. Fuel availability, on the other hand, has changed considerably over time, both in terms of fuel amounts and flammability, which in turn is determined by moisture. Although fuel moisture is largely controlled by climate, the amount of fuel in grasslands is highly dependent on land use and especially grazing. Grazing influences the rate of vegetation recovery and directly reduces both amount and contiguity of fuels by consumption, wallowing, and trampling of vegetation, eventually leading to catastrophic shifts in vegetation structure and composition if grazing levels are not moderated (van de Koppel and others 1997).

Most grasslands are experiencing intensifying land use, and long-term decrease in land use intensity is generally a rare phenomenon. However, periods of massive socioeconomic change may provide unique natural experiments (Diamond 2001) to study the effects of decreasing land use intensity (for example, lower grazing pressure) on fire patterns. Institutional changes in the former USSR have repeatedly led to changes in the vegetation, first after October Revolution and the Civil War of 1917–1920 and then after the end of World War II (1941–1945, Zonn 1995b). Vegetation recovered after these events due to substantial decreases in human populations and livestock numbers, as well as the cessation of other agricultural activities.

The collapse of the former USSR in 1991 resulted in a sharp decline in livestock numbers, and detailed livestock data provided a clear picture of the changes in livestock and hence grazing pressure for the 1990s (Figure 1). Soviet era livestock numbers were so high that they caused disastrous environmental effects (Vinogradov 1995; Zonn 1995a). Vegetation changes were particularly evident in the arid grasslands of the Caspian plains because of the fragility of the upper soil layer (largely alluvial sands). Rangeland scientists had calculated that even on the best pastures, sheep density should not exceed 28–30 units/ha, but sheep density reached 130 heads/ha by 1975, and continued to increase until the late 1980s (Zonn 1995b). Overgrazing proved to be ecologically
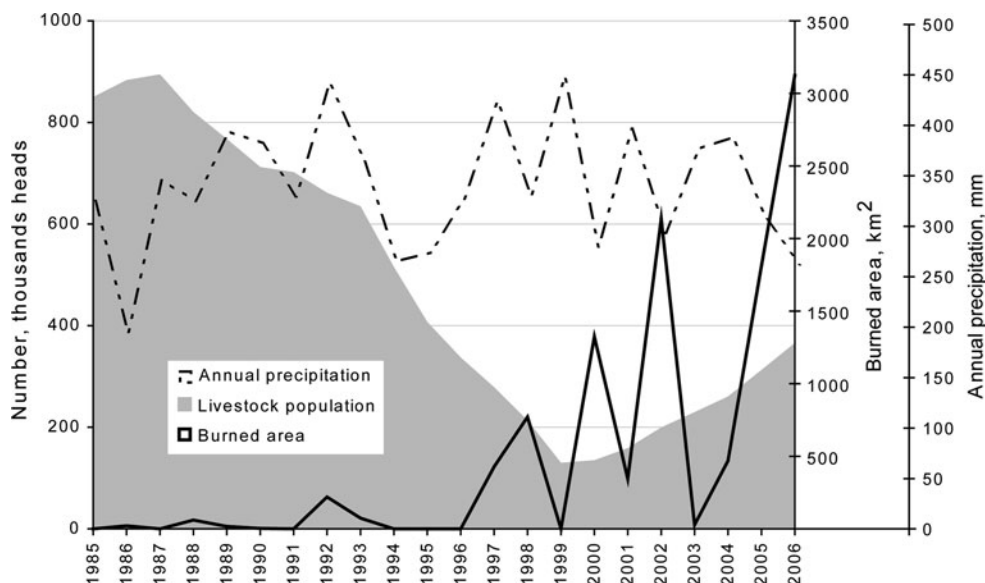

Figure 1. Sheep population, annual precipitation and burned area trends in the study area.

disastrous for the fragile arid ecosystems and ultimately led to desertification starting in the 1960s and continuing until the early 1990s (Saiko and Zonn 1997). The subsequent sharp decline in livestock numbers was paralleled by other substantial changes in ecosystem processes, including fire. During the period of overgrazing, fires were virtually absent in our study area (Dubinin and others 2010). However, within half a decade after the declines in livestock numbers, annual burned area increased very rapidly (Figure 1), especially on sites that had previously been highly degraded (Dubinin and others 2010).

The relationship between climate and burned area can be both direct and indirect. In seasonally dry, biomass-poor grasslands fuel amounts are typically the most important driver of fire because fuels desiccate always during the dry period, regardless of climate during the year (Meyn and others 2007). However, the relative importance of climate may increase as land use intensity weakens (Meyn and others 2007). Higher precipitation, especially during the fire season can impede burning due to higher fuel moisture. On the other hand, high precipitation during the growing season prior to the fire season can lead to an increase in area burned because the rain increases fuel abundance (Flannigan and Wotton 2001; Pausas 2004). In other words, the amount of burning in a given year might depend on the weather during the previous year, which may determine fuel availability (Knapp 1998).

When examining the effects of climate on annual burned area it is important to consider global climate oscillation patterns as important explanatory factors (Flannigan and Wotton 2001). Climate oscillations can be synchronized with fire weather conditions across large areas via teleconnection mechanisms. For example, El Niño-South Oscillation (ENSO) and North Atlantic Oscillation events are associated with increased fire activity in different regions of the world (Le Page and others 2008; Greenville and others 2009). Similar linkages occur between fire activity and the Arctic Oscillation (Balzter and others 2005). In semi-arid and arid ecosystems, where precipitation is the limiting factor for fuel production and hence fires, increased rainfall might result in a pulse of productivity and thus higher fuel availability in subsequent years (Holmgren and others 2006). The relationship between broad-scale climate oscillations and local temperature and precipitation are regionally specific and additional analysis is required to establish how broad-scale climatic patters affect fire patterns (Schonher and Nicholson 1989; Keeley 2004).

The goal of this study is to understand what explains fire regimes during rapidly changing socio-economic settings. Our general hypothesis was that socio-economic changes that followed the collapse of the Soviet Union lowered grazing pressure, allowed vegetation to recover, and increased fuel availability, thereby providing the necessary prerequisite for fires, the amount of which was then controlled by climate. From this general hypothesis stemmed several specific hypotheses which we tested. We hypothesized that the burned area in a given year was:

(a) positively correlated with the amount of vegetation during the spring growing season immediately prior to the summer fire season, because of higher fuel availability;
(b) positively correlated with the amount of vegetation during the secondary growing season in the fall of the previous year, again due to higher fuel availability;
(c) positively correlated with climatic conditions that are favorable for vegetation growth during spring and fall of the previous year, also due to higher fuel availability;
(d) more strongly correlated with climate during the period after livestock numbers had declined and grazing pressure lessened, because vegetation was able to recover to a point above which fires could occur;
(e) negatively correlated with livestock numbers, because fewer livestock result in more abundant fuel; and
(f) negatively correlated with higher precipitation and lower temperature during fire season because higher fuel moisture impedes fires.

To test these hypotheses, we conducted statistical analyses to identify the best set of variables to explain annual burned area from 1986 to 2006. In addition, we conducted our analysis separately for the two time periods before and after the collapse of the Soviet Union to test if the relationships between burned area and livestock, vegetation, and climate were changing between different management regimes. To our knowledge, no previous studies of comparable temporal extent have attempted to explain burning dynamics in the grasslands of southern Russia and Central Asia.

METHODS

Study Area

Our study area was located in the grasslands of Southern European Russia and occupied about

Figure 2. Study area boundary (hatched polygon) and location.

19,000 km^2 of the Republic of Kalmykia and Astrakhan Region (Figure 2). We had estimated annual burned area for this study area in previous research (Figure 1; Dubinin and others 2010).

The climate of the study area is arid, with hot, dry summers (mean daily temperature of +24°C in July; max +44°C, 280 days of sunshine per year on average). Annual precipitation is 150–350 mm (with a mean of 286 mm from 1985 to 2006). Summer droughts are common, and most of the precipitation falls in spring and fall, coinciding with the two major growing seasons (Walter and Box 1983). The topography is predominantly flat with a mean elevation of −15 m below sea level. The study area has a complex geological history of transgressions and regressions of the Caspian Sea. Soils are characterized by a gradient from sandy eolian deposits and sandy loams in the southeast corner of the study area, to clay loam in the northwest (Kroonenberg and others 1997).

Vegetation associations are typical for the northern Precaspian Plain and include both steppe and desert types. The main vegetation associations are shortgrass steppe (*Stipa* spp., *Festuca* spp., *Argopyron* spp., *Anizantha tectorum*, and other graminoids) and sage scrub (*Artemisia* spp., *Kochia prostrata*) (Golub 1994). Shortgrass steppe is characterized by a short growing season in April and May and rapid senescence in the dry summer. The perennial grasses are well adapted to fire due to dense bunches, which protect basal meristems with tightly packed leaf-sheaths, and can resprout after fire. Both annual and perennial grasses generate abundant fuels. Sagebrush (*Artemisia* spp.) dominated shrublands have less biomass, but a longer growing season, and

sometimes exhibit a second vegetation peak in the fall and early winter (Kurinova and Belousova 1989). *Artemisia* spp. is more susceptible to fire because its buds are situated above ground and can be killed or damaged by fires. The lack of fire tolerance by *Artemisia* spp. can lead to its substitution by *Stipa* spp. and other graminoids (Neronov 1998). The primary human land use of the grasslands in the study area is for grazing by domestic livestock, mainly sheep, and to a lesser extent cows and goats. The study area is sparsely populated (population density 0.8–1.4 persons/km^2 (CIESIN and CIAT 2005).

Broad-scale burning in the region can be traced as far back as the eighteenth century (Pallas and Blagdon 1802). However, little is known about spatial and temporal dynamics of fires both historically and in the recent past because practically no research has been done on fire patterns in southern Russia prior to our research and governmental statistics are largely inaccessible, incomplete, and biased low (Dubinin and others 2010).

Study Period and Data Sets Used

We studied burned area and its drivers from 1986 to 2006. The choice of the study period was determined by satellite image availability, and by the significant changes in land use that occurred after 1991. Our 21-year burned area record is one of the longest derived from coarse resolution satellite data. Other burned area studies of similar long time spans have either focused on forests and mesic grasslands or used indirect or approximate estimates of burning (Beckage and others 2003; Mouillot and Field 2005; Chuvieco and others 2008).

Fire

Historical and official records of burning in our study area are scarce and unreliable (Dubinin and others 2010) and remote sensing data can be used to reconstruct long-term burning trends. Our data set of burned area in Southern Russia consisted of 21 raster maps representing burned and non-burned areas for each year from 1986 to 2006. Burned area maps were generated based on National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) Local Area Coverage data. The resolution of the burned area maps was 1.1 km pixel size. We mapped burned areas with supervised decision trees applied to an annual image pair representing one image taken during the peak growing season in the spring right before the fire season, and a second image taken

right after the fire season in late summer (Dubinin and others 2010).

Livestock

Livestock population data originated from Ministry of Agriculture of the Republic of Kalmykia and represented the total population of sheep and goats for the study area. Goats are combined with sheep in official statistics, because they are rare (less than 4%). Cattle numbers are an order of magnitude smaller than those of sheep (Kalmstat 2008).

Vegetation

In terms of vegetation data, we focused on vegetation indices that served as a proxy for fuel amounts. The Normalized Difference Vegetation Index (NDVI) is significantly correlated with aboveground net primary production in many ecosystems, including grasslands (Tucker and others 1985; Paruelo and others 1997). We thus summarized vegetation as the mean monthly NDVI averaged for the entire study area. NDVI data were extracted from the GIMMS NDVI dataset (Tucker and others 2005). GIMMS NDVI data were available twice a month from 1981 to 2006 and had 8-km resolution. GIMMS data are well suited for vegetation studies in semi-arid regions (Fensholt and others 2009).

Climate

Climate data were extracted from the Climate Research Unit Time Series product version 3 (Mitchell and Jones 2005) which included 0.5° gridded mean and maximum temperature, as well as precipitation data interpolated from meteorological stations (New and others 1999). In addition to local climate measures, we also looked at broad-scale climatic oscillation indices. Because it was not clear which broad-scale climatic pattern might affect local climate in our study area we chose three: the North Atlantic, the East Atlantic/Western Russia, and the Arctic oscillations index, abbreviated NAO, WR, AO, respectively (Barnston and Livezey 1987; Hurrell and others 2003). The positive phase of AO indicates higher pressure in mid-latitudes, which results in more precipitation and enhanced greening in Central Asia during spring (Buermann and others 2003). The positive phase of the NAO is associated with anomalous low pressure in the Subarctic, higher precipitation in the oceans between Scandinavia and Iceland and lower precipitation in Southern Europe (Hurrell and others 2003). During the positive phase of the WR, temperatures above the North

Caspian region and West Russia are drier then normal (Krichak and others 2002). Climatic indices were averaged by season and year, thus each oscillation was represented by five variables. Additionally, we calculated seasonal and yearly precipitation totals and temperature averages and maxima.

Statistical Approach

Bivariate Analyses

We evaluated the relationships between burned area and potential predictor variables with Pearson's correlation coefficients and tested our hypotheses with linear regression models with and without interaction terms. Log-transformed annual burned area was the response variable. Predictor variables included livestock, vegetation, and climate, both for the current and the previous year. Residuals were examined for possible temporal autocorrelation using Durbin–Watson tests and autocorrelative function plots (maximum time lag = 10 years). Heteroscedasticity was evaluated via visual examination of normality plots. To identify the best predictors in our candidate models, we used best subsets analysis. The number of times that a particular variable entered the model was calculated for the 20 best models. Models were ranked according to their adjusted r^2 values. All statistical analyses were performed in CRAN R (R Development Core Team 2009).

Initial analyses showed that spring NDVI was a strong predictor of burned area, and this raised the question of what determined spring NDVI. We used the same statistical approach as outlined above, but used spring NDVI as the response variable, which was then modeled with the same set of explanatory factors, except for measures made later than spring.

Finally, we studied the effect of climate oscillations on local climate. Initial analyses showed strong correlations between climate oscillations at broad scales and local measures of temperature and precipitation.

Regression Modeling for Before and After Periods

To test the hypothesis that the relationship between climate and fire was fundamentally different before and after the breakdown of the Soviet Union, we stratified the data into two periods of time representing ''before'' and ''after'' the breakdown of the Soviet Union. We chose 1996 as a splitting year, resulting in 11 observations for the ''before'' period (1986–1996) and 10 observations for ''after'' (1997–2006). We chose 1996 because previous research found that 5–6 years were

required for the recovery of vegetation after grazing declined (Bananova 1992; Zonn 1995b). To assess how sensitive our results were in regards to the splitting year, we calculated the mean and standard deviation for a set of correlations separately for ''before'' and ''after'' periods while the splitting year was changed in annual steps from 1992 to 1997. To determine if slopes of the regressions were significantly different between before and after periods we used regression models in the form of:

$$Y = 1 + x + \text{dummy} + \text{dummy}:x$$

where x was a given independent variable, dummy indicated the period (0: before, and 1: after), and dummy:x represented an interaction between the dummy variable and the independent variable. We checked for changing variance structure by using a mixed-effect model that included group-effects. We used ANOVA to check if the more complex model was significantly different from the more simple one (that is, the null hypothesis was that variance was not significantly different before and after). If we were unable to reject the null hypothesis, then we used the simpler model, and otherwise the grouped-variance mixed effect model. We were particularly interested to test if there were significantly different slopes in the regression lines for particular variables in the ''before'' and ''after'' periods. Only variables which showed statistically significant correlations in either of the periods were included in these analyses.

We also selected the best two-variable regression model to estimate coefficients for two separate regressions, one for ''before'' and one for ''after.'' We tested if coefficients were significantly different using Chow tests, commonly used in time series analysis to test for the presence of a structural break (Chow 1960).

Structural Equation Modeling

Structural equation modeling can examine possible causal pathways among intercorrelated variables, identify associations among variables while statistically controlling for other model variables (that is, to partition relationships), and examine the likelihood of alternative models given the data at hand (Bollen 1989). To facilitate our analyses and interpretations, we developed a meta-model, which represented the main linkages between system components without statistical details. Our bivariate correlation analyses functioned as an indicator selection analysis for the structural equation model, and helped identify representatives for each entity of the conceptual

model, which included global climate that influenced local climate. Local climate, livestock, and burning all influenced fuels, and fuels in turn influenced burning. Significant variables indicated causal relationships and were used to construct a structural equation model (Grace 2006). Nested models included a common set of variables and assumptions about dependencies (for example, NDVI depends on livestock), but differed in the pathways deemed to be significant. We used maximum likelihood procedures to estimate coefficients and to evaluate model goodness-of-fit. Sequential application of single-degree-of-freedom χ^2 tests was used to determine which pathways should be retained in the final model. Decisions to keep or remove a variable or path from the model were also informed by modification indices (Jöreskog and Sörbom 1984; Grace and Bollen 2006). We conducted structural equation modeling in Amos 5.0 (Amos Development Corp 2003).

RESULTS

Our prior analysis of remote sensing data had shown that burned area increased very rapidly in southern Russia after 1996 (Figure 1; Dubinin and others 2010). Statistical tests confirmed that burned area in the 1997–2006 period was significantly higher than in the 1986–1996 period even though there was a high variability among years (1044 km^2 ($\pm$1032) vs. 37 km^2 ($\pm$66), $t = 3.08$, $P = 0.013$, Figure 3). The comparison of correlation coefficients using 1996 as the splitting year versus the mean and standard deviation of a set of correlations estimated while the splitting year was shifted from 1992 to 1997 confirmed that the use of 1996 as the splitting year did not bias our results (Table 1).

Livestock and Fire

Livestock numbers were significantly lower in the 1997–2006 period, and showed the strongest percent change (Figure 4). Both current- and previous-year livestock numbers were negatively correlated with burned area, but correlations were only significant when analyzed for the entire study period and not significant when the dataset was split into ''before'' and ''after'' periods. Burned area was more strongly correlated with livestock numbers in the previous year than livestock numbers in the current year. Both current and previous year livestock numbers were among the five top bivariate models and statistically significant at the $P < 0.05$ level (Table 2).
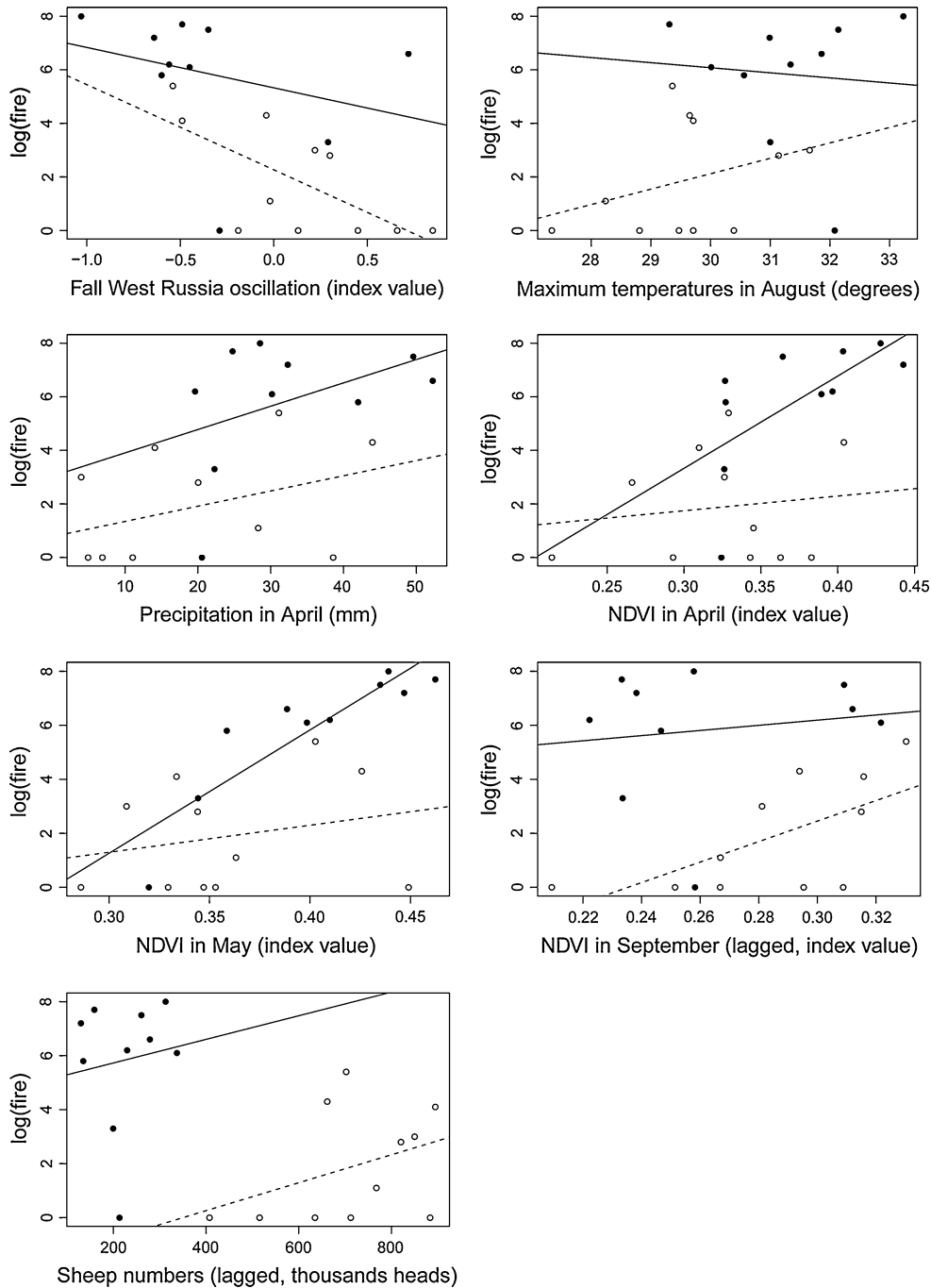
Figure 3. Relationships between selected explanatory variables and log-transformed burned area. *Solid dots* and *solid line* represent values and regression line for period "before" (1986–1996), *hollow circles* and *dashed line* represent values for period "after" (1997–2006).

Vegetation and Fire

Mean April NDVI was significantly higher in the "after" period compared to the "before" period, but although May NDVI showed the same trend, the difference was statistically not significant (Table 1). However, April NDVI and even more so May NDVI were the most powerful explanatory variables predicting burned area (May NDVI, $P = 0.0012$, $r = 0.66$) (Table 1). Correlation was particularly high for the "after" period. However, neither spring NDVI measure was significantly correlated with burning in the "before" period only. Among our other vegetation measures, during the "before" period, only September NDVI in the previous year was significantly correlated with burned area. Slopes of the relationships between May NDVI and fire were significantly different according to our models (Table 3). Best subsets analysis showed that May NDVI was present in 12 out of the 20 best candidate models (Table 4).

Table 1. Explanatory Variables that were Significantly Correlated with Burned Area in Univariate Correlations in the "Before" Period (1986–1996), "After" (1997–2006), and the Entire Time Series

Variable	r Before	r After	r Full	t Test	r Before stability	r After stability
WR spring	0.13	0.54*	0.00	0.27	0.09 ± 0.13	−0.40 ± 0.32
WR winter[1]	0.11	0.46*	−0.18	0.57	0.26 ± 0.09	−0.47 ± 0.18
WR fall[1]	0.45*	0.09	−0.62**	0.04	−0.79 ± 0.07	−0.39 ± 0.11
AO fall[1]	−0.43	0.83**	−0.05	0.11	−0.67 ± 0.17	0.56 ± 0.27
NAO fall[1]	−0.32	0.70*	−0.13	0.12	−0.48 ± 0.12	0.50 ± 0.21
August maximum temperature	0.34	−0.09	0.48*	<0.01	0.39 ± 0.06	0.18 ± 0.22
April precipitation	0.38	0.42	0.57**	0.04	0.23 ± 0.21	0.60 ± 0.14
June through August precipitation	0.40	−0.65*	−0.21	0.99	0.52 ± 0.08	−0.55 ± 0.18
April NDVI	0.14	0.64*	0.55*	0.04	0.22 ± 0.08	0.61 ± 0.04
May NDVI	0.24	0.89**	0.66**	0.06	0.18 ± 0.10	0.88 ± 0.01
September NDVI, previous year	0.63*	0.14	0.06	0.18	0.79 ± 0.12	−0.06 ± 0.16
Livestock[1]	0.38	0.13	−0.52*	<0.01	0.06 ± 0.22	−0.29 ± 0.34

t test shows P value for significance of differences between before and after datasets.
WR = West Russia; AO = Arctic Oscillation; NAO = North Atlantic Oscillation; NDVI = Normalized Difference Vegetation Index.
[1]Variable lagged 1 year back.
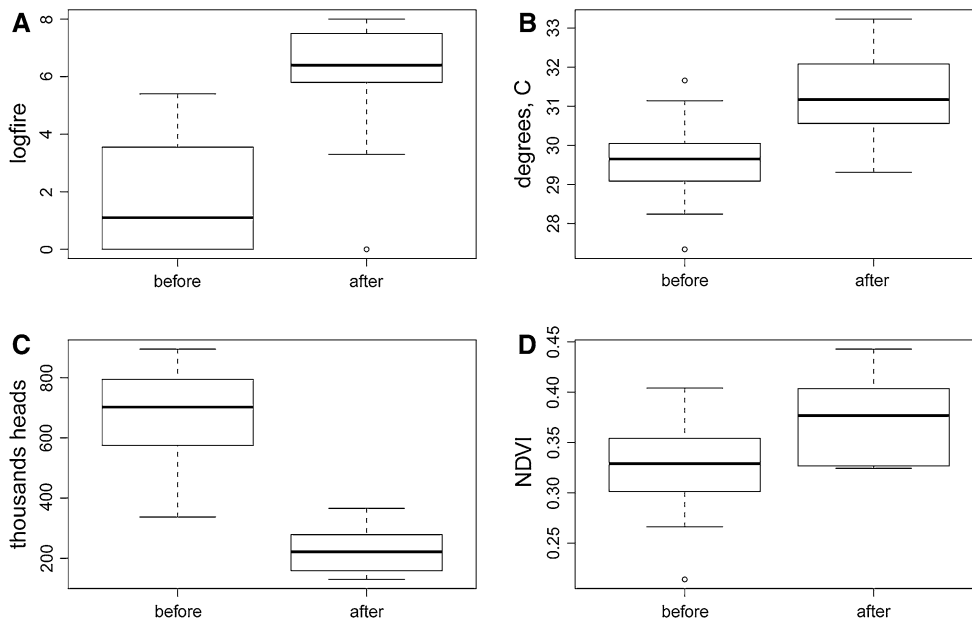*Significance levels: * < 0.05, ** < 0.01.*

Figure 4. Change in **A** burned area ($P < 0.01$, change in means: 210%), **B** maximum August temperatures ($P = 0.004$, change in means: 5.62%), **C** livestock numbers ($P < 0.01$, change in means: 192%), and **D** April NDVI between "before" and "after" periods ($P = 0.04$, change in means: 14.7%).

Climate and Fire

Correlations of burned area with precipitation and temperature were generally weaker than with vegetation. However, we found a significant positive correlation for precipitation in April (Table 1). The only significant correlation with temperature was for August, which was positive. Interestingly, the daily temperature range in August was more strongly correlated with burning than with maximum temperature itself. Furthermore, mean temperature, temperature range in August, and precipitation showed statistically significant differences between the "before" and "after" after periods, although the significance of the difference in precipitation was marginal (Figure 4). Correlations between burned area and climate variables were similar in the "before" and "after" periods, and correlations were not significant. Only total summer precipitation was found to be significantly negatively correlated with burning during the "after" period. Climate measures from the previous year were not significantly correlated with burned area either.

The relationships of burned area with climate oscillation indices were complex. Several climate oscillation indices were significantly correlated with burning either "before" or "after," but only

Table 2. Five Best Multivariate Models Explaining Variability in Log-transformed Burned Area (a) With and (b) Without Broad Climate Variables

Response	Variable 1	Variable 2	Interaction	Adj r^2	r
(a)					
Burned area	AO[1]	NDVI5**	AO:NDVI5	0.73	0.23
Burned area	AO spring[1]	NDVI5**	AO spring[1]:NDVI5*	0.64	0.01
Burned area	Livestock*	NDVI5**	Livestock:NDVI5*	0.58	−0.37
Burned area	Livestock[1]*	NDVI5*	Livestock[1]:NDVI5*	0.58	−0.43
Burned area	AO spring[1]	Pre4**	Laospr:Pre4*	0.57	0.14
(b)					
Burned area	Livestock*	May NDVI	Livestock: May NDVI*	0.58	−0.37
Burned area	Livestock*	May NDVI*	Livestock: May NDVI*	0.58	−0.43
Burned area	August maximum temperature*	May NDVI*	August maximum temperature previous year: May NDVI*	0.56	−0.00
Burned area	May NDVI*	June NDVI	May NDVI: June NDVI	0.50	0.52
Burned area	May NDVI	September NDVI	May NDVI:June NDVI	0.48	0.00

r denotes Pearson correlation between variables 1 and 2.
[1]*Variable lagged 1 year back.*
*Significance levels: * < 0.05, ** < 0.01.*

Table 3. Statistical Significance of Difference in Slopes

	Dummy	Slope	Adj r^2
May NDVI		*	0.65
AO fall[1]	**	**	0.65
July through September precipitation	**	**	0.61
June NDVI[1]	**	**	0.60
NAO fall[1]	**	*	0.56
June through August precipitation	**	*	0.56
WR winter[1]	**	*	0.56
WR spring	**	*	0.56
NAO	**	*	0.51

Dummy = statistical significance for keeping 0/1 variable representing periods ''before'' and ''after''; slopes = statistical significance for different slopes.
[1]*Variable lagged 1 year back.*
*Significance levels: * < 0.05, ** < 0.01.*

Table 4. Results of Two-Variable Best-Subset Analysis

Variable	Number of models
May NDVI	12
WR fall[1]	7
April precipitation	3
AO spring[1]	2
AO[1]	2

Only variables which participated in more than 1 model are shown.
[1]*Variable lagged 1 year back.*

the previous year fall Western Russia oscillation index showed any evidence of significant change between the two periods (Table 1). However, out of six indices that were significantly correlated with burned area, three were previous year fall indices. Previous year average fall WR index was a particularly strong predictor and was included in 7 of the 20 best models (Table 4).

Relationships Among Spring Vegetation, Climate, and Livestock

Vegetation productivity in spring was consistently positively correlated with spring precipitation and several fall and winter oscillation indices, and consistently negatively correlated with livestock numbers in the previous year (Table 5). NDVI in May was strongly correlated with NDVI in April. However, precipitation in the previous year was better correlated with spring NDVI during the ''before'' period and the entire time series, and the correlation was statistically not significant during the ''after'' period. We also found several strong correlations between spring NDVI and climate oscillation indices for the previous year, especially during the ''after'' period (Table 5).

Local and Broad-Scale Climate

High correlations between burned area and climate oscillations did not correspond to strong relationships between climate oscillation indices and local measures of temperature and precipitation. Though

Table 5. Relationships Between (a) April and (b) May NDVI and Other Variables

	r Before	r After	r Full
(a)			
WR fall	−0.40	−0.68*	−0.62**
AO fall[1]	−0.45	0.79*	−0.05
NAO fall[1]	−0.26	0.69*	−0.13
April precipitation	0.54	−0.26	0.57*
July through September precipitation previous year	0.65*	0.39	0.42
Livestock[1]	−0.53	0.04	−0.52*
October NDVI	0.64*	0.25	0.08
(b)			
WR winter[1]	0.41	−0.67*	−0.18
WR fall[1]	−0.17	−0.44	−0.62**
AO winter[1]	0.62*	−0.27	−0.21
AO fall[1]	−0.16	0.91**	−0.05
AO[1]	0.66*	−0.04	−0.38
NAO fall[1]	−0.02	0.75**	−0.13
April precipitation	0.87**	0.15	0.57**
March through June precipitation	0.61	−0.06	0.14
July through September precipitation	0.41	−0.82**	−0.04
March through June precipitation previous year	0.73**	0.23	0.17
July through September precipitation previous year	0.72**	0.58	0.42
Livestock[1]	−0.23	0.05	−0.52**
April NDVI	0.71**	0.83**	0.54**

[1]*Variable lagged 1 year back.*
*Significance levels: *<0.05, **<0.01.*

there were some statistically significant correlations between precipitation and temperature and oscillation indices for particular periods, correlations were weak (Table 6). For example, we found a significant negative correlation between both spring and summer maximum temperatures versus the NAO index in April, and cumulative summer precipitation was significantly correlated with the August WR index. However, none of the fall climate oscillation indices, which were well correlated with burned area, were significantly correlated with any precipitation of temperature measures. At the same time, there were a number of other correlations that were hard to interpret. For example, the April NO index was significantly correlated with August temperatures, and the winter WR index was correlated with April precipitation. Spatial correlation fields calculated for fall precipitation and temperature and respective oscillation indices confirmed that correlation between broad scale climate and local climatic patterns in the study area were not statistically significant (Figure 5).

Multiple Regressions

The model yielding the highest adjusted $r^2 = 0.73$ included previous year AO, NDVI5 and their interaction. However, previous year AO was not statistically significant by itself ($P = 0.1$) and the interaction term was only marginally significant ($P = 0.05$). The model where all the three parameters were statistically significant at the 0.05 level was ranked third and had adjusted $r^2 = 0.58$ and included May NDVI, livestock population and their interaction (Table 2). The five best models with broad-scale climate indices omitted yielded smaller adjusted r^2 values and were also dominated by NDVI.

Structural Equation Modeling

The final structural equation model included six exogenous variables and one endogenous variable ($\chi^2 = 7.7$, df = 13, $P = 0.862$, Figure 6). Results provided by structural equation modeling clarified a number of relationships that were not clear from the univariate and multivariate analyses. The structural equation modeling suggested that livestock mainly influenced vegetation productivity in April, but not in May. Vegetation productivity in April in turn was more influenced by the cumulative precipitation of the previous year than by precipitation in April itself. Structural equation modeling confirmed that vegetation productivity in

Table 6. Correlations Between Burned Area, Local Climate Measures, and Oscillation Indices AO, NAO, EAWR

	August maximum temperature	Sum of March through June temperatures	Sum of June through August temperatures	Sum of September through November temperatures	Sum of July through September temperatures	April precipitation	Sum of March through June precipitation	Sum of June through August precipitation	Sum of September through November precipitation	Sum of June through August precipitation
April AO	−0.20	0.05	−0.08	0.27	0.11	0.26	−0.17	0.26	−0.03	−0.01
August AO	−0.10	0.21	0.11	0.34	0.15	0.25	−0.30	−0.07	−0.22	−0.47
AO	0.15	0.17	−0.12	0.22	0.13	0.26	−0.37	0.43	0.10	0.17
AO winter	−0.17	0.12	−0.21	−0.04	0.09	0.17	0.11	0.21	0.21	0.09
AO spring	−0.26	0.08	−0.30	0.31	0.08	−0.06	−0.33	0.34	0.04	0.15
AO summer	0.07	0.24	0.10	0.48*	0.25	−0.27	−0.28	0.08	−0.23	−0.16
AO fall	0.13	−0.02	−0.18	−0.02	−0.01	−0.29	−0.01	0.16	−0.14	0.34
April NO	−0.48*	−0.57*	−0.63**	0.06	−0.41	−0.01	−0.01	0.19	0.15	0.39
August NO	−0.44*	0.12	−0.16	0.27	0.18	0.14	−0.30	0.05	0.13	−0.42
NO	−0.21	−0.02	−0.36	0.02	0.01	−0.35	−0.17	0.08	0.04	0.21
NO winter	0.07	0.41	0.05	0.15	0.33	0.23	−0.11	0.26	−0.07	−0.11
NO spring	−0.42	−0.34	−0.51*	−0.17	−0.31	−0.30	−0.03	−0.13	0.15	0.19
NO summer	−0.18	0.20	−0.15	0.61**	0.28	−0.58**	−0.33	0.25	0.06	−0.03
No fall	0.04	0.11	−0.09	−0.24	0.13	−0.07	0.06	−0.11	−0.04	0.18
April WR	−0.24	−0.51*	−0.25	−0.34	−0.43	0.06	0.19	−0.10	0.36	0.03
August WR	−0.19	0.37	0.16	−0.05	0.21	−0.26	−0.14	−0.46*	−0.21	−0.52*
WR	−0.31	−0.24	−0.47*	−0.23	−0.40	−0.03	−0.14	−0.08	0.09	0.10
WR winter	−0.08	−0.36	−0.25	−0.24	−0.37	0.54*	−0.04	−0.02	0.10	0.18
WR spring	−0.14	−0.20	−0.26	−0.18	−0.07	−0.05	0.04	−0.05	0.52*	0.15
WR summer	−0.18	0.05	−0.30	0.00	−0.05	−0.15	−0.29	4	0.08	−0.07
WR fall	−0.27	0.00	−0.32	−0.29	−0.35	−0.18	0.05	−11	−0.28	0.07

Monthly values summarized by season and yearly average.
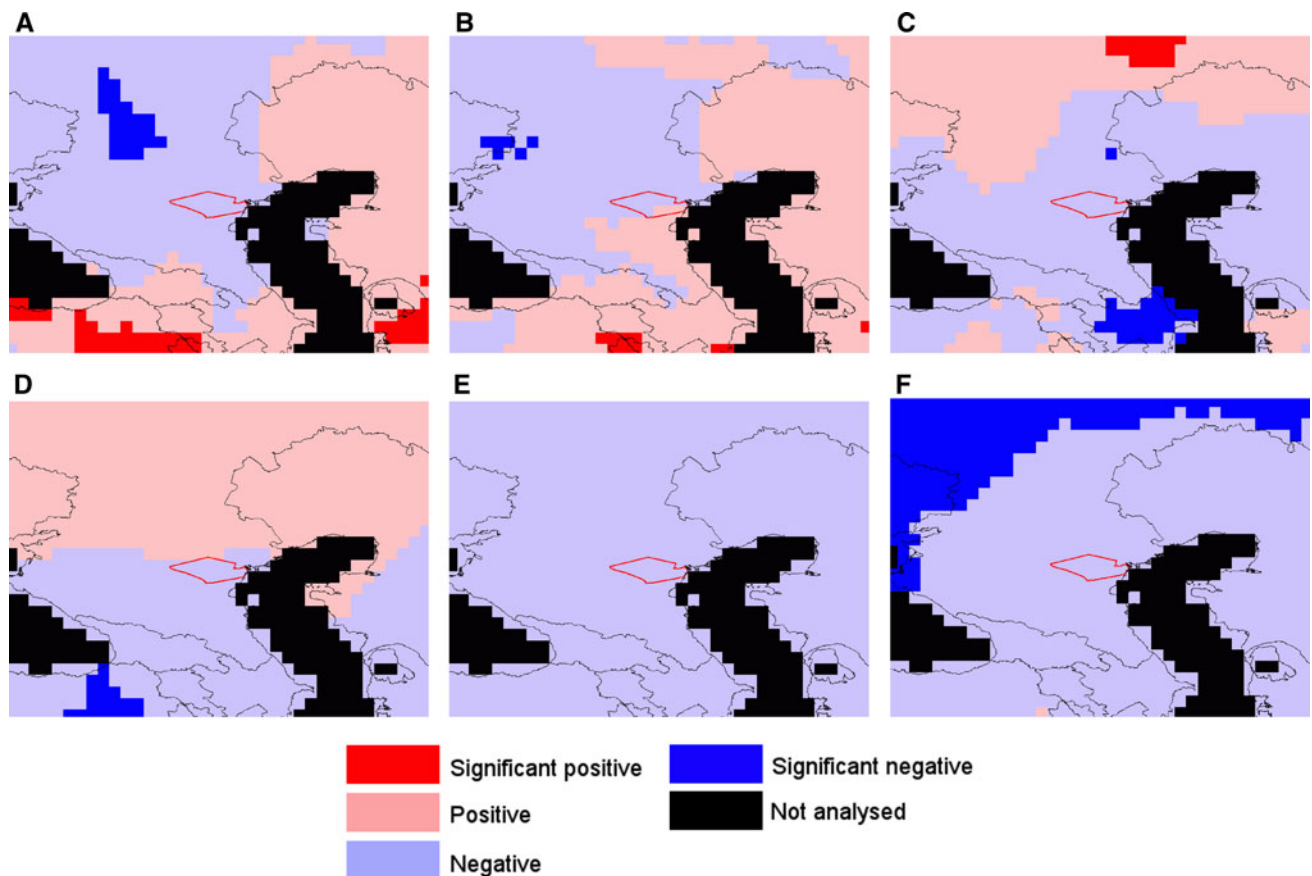*Significance levels: * <0.05, ** <0.01.*

Figure 5. Correlation fields of broad-scale climatic oscillation patterns and local climate during fall months. See legend over the top left figure for the color key. Statistical significance is at 0.05 level. **A** AO—precipitation, **B** NAO—precipitation, **C** WR—precipitation, **D** AO—temperature, **E** NAO—temperature, **F** WR—temperature (Color figure online).

May depended on April precipitation and April NDVI. There was no indication that NDVI in April by itself influenced burning. In models that included pathways between livestock and burned area, and between April NDVI and burned area, these pathways were all non-significant. The pathway between precipitation during the fire season and burned area was not significant either and we removed this variable. Because the bi-variate analysis did not reveal any mechanisms by which climate oscillations influence burned area, we did not include oscillation indices in the structural equation modeling.

DISCUSSION

Our study area experienced a rapid increase in burned area following the collapse of the USSR, and our results highlight that these fire patterns resulted from interactions between decreasing livestock densities and recovering vegetation, modulated by climate.

Our analysis supported the hypothesis that livestock numbers were significantly related to the increase in burned area through the amount of fuels. Though this relationship appears logical, the decrease of livestock and following increase in burning had rarely been documented explicitly and evidence is mostly historical (Savage and Swetnam 1990). Livestock numbers masked out the relationships between burned area and other variables during the period ''before'' (Figure 3). In contrast during the ''after'' period, the release of livestock pressure has led to accumulation of fuels and consequent increases in burning. This is different from what was observed in other areas of the world, for example, in the Sahel, where lands remained barren for 20 years after overgrazing (Sinclair and Fryxell 1985). However, the correlation between burned area and livestock numbers was not as strong as we expected, possibly due to a threshold effect (Turner and Gardner 1991; van de Koppel and others 1997). Critical livestock numbers may have been reached in the early 1990s and
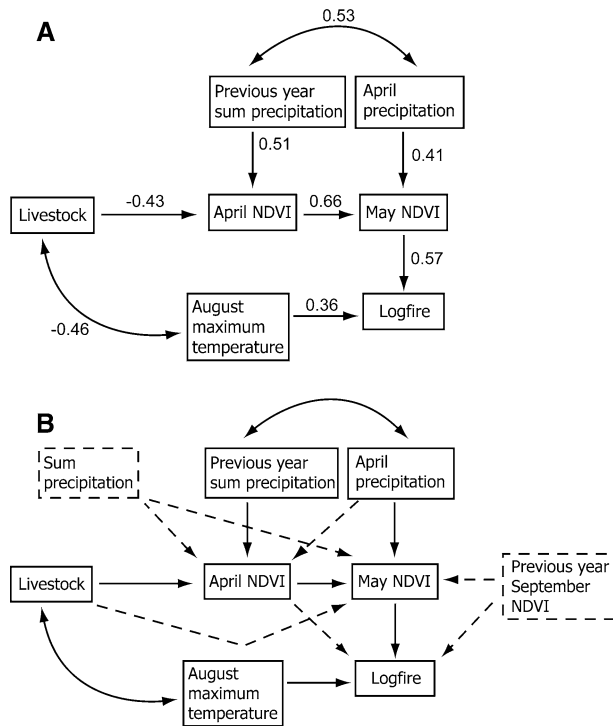
Figure 6. On *top*, **A** the final structural equation model with path coefficients, and *below* **B** full model with pathways and variables that were not retained (shown as *dashed lines*). *Straight single-headed arrows* represent significant effects of one variable on another ($\alpha = 0.05$), whereas *curved double-headed arrows* represent correlations between variables. The relative strength of the effect is indicated by a path coefficient. Only pathways that are significant at $\alpha = 0.05$ are included.

livestock density was no longer high enough to impact vegetation on a broad scale.

The decrease in livestock numbers was accompanied by an increase in vegetation productivity, especially in spring due to both natural and management reasons. Natural recovery of the vegetation was coupled with successes in restoration activities and creation of a nature reserve occupying a portion of the study area (Zonn 1995b). A strong relationship between spring NDVI and burning suggested that fuel amounts before the fire season were significantly lower when livestock numbers were high and fire was not able to spread as far. However, although NDVI is strongly related to primary productivity it is not a perfect measure of biomass (Box and others 1989; Paruelo and others 1997). The fact that we did not observe a strong change in NDVI between "before" and "after" suggests that changes in vegetation composition and structure might have also occurred. This is consistent with long-term plot-level studies of grass-dominated communities after release of livestock pressure that reported an increasingly higher

presence of perennial fire adapted grasses, such as *Stipa capillata* (Neronov 1998). Such a change has resulted in a considerable increase in biomass, from 0.5 to around 1 ton/ha aboveground biomass of *Stipa* spp. in *Stipa* spp. dominated communities (Dzhapova 2007). An increase in grassy fuels concomitant with an increase in burning is consistent with other parts of the world and represents a positive feedback loop (D'Antonio and Vitousek 1992; Brooks and others 2004).

Besides the main relationship between burning and spring vegetation, burning was also positively correlated with fall vegetation in the previous year. Burning during the "before" period was linked to previous year vegetation productivity of the secondary growing period (that is, fall NDVI). Fall NDVI represented secondary growth that was not consumed by fire and which became fuel in the form of dry litter in the subsequent year. The lack of a relationship in the "after" period can be explained by the increase in burning itself, leaving less vegetation for the secondary growing season. Alternatively, we could have missed some of the previous year effects due to litter accumulation, because non-photosynthetically active vegetation is not captured by NDVI but can contribute greatly to fire spread.

Climate influenced burning both during the summer fire season and during spring green-up. During the fire season high precipitation and low temperatures led to increased fuel moisture and inhibited burning in some years (for example, in 2003). A strong relationship existed between late summer maximum temperature and burning overall. However, summer precipitation was significantly correlated only during the "after" period.

High precipitation during green-up may have caused more fire due to more abundant fuel (Buermann and others 2003) and we found support for our hypothesis that spring precipitation was significantly related to burning. However, prior-year precipitation was only marginally related to vegetation productivity in April. The lack of a relationship with prior-year precipitation suggested a substantial non-limiting increase in available fuel biomass possibly due to continuing vegetation change resulting in an increase in spring-green species less dependent on stored water. In addition, the representation of climate by station-based local climate measures could be unsatisfactory due to lack of stations and might be improved by using broad-scale climatic indices instead.

The relationship between broad-scale climate variables, such as previous year fall Western Russia

oscillation, and burned area yielded significant correlations. Low values of the WR index indicate milder and wetter weather in the region, which in turn might have lead both to more fuel production and increased fuel moisture during that year. However, though such mechanisms were plausible, we were not able to confirm them with our precipitation data. Different oscillation indices often showed high correlations without clear linkages to local climate. High correlation was often found for seasonal indices that were timed well before or after corresponding measures of local climate. We thus caution that broad-scale climate variables should be used with care. A significant relationship, but lack of a mechanism raises a question of how such indices were related to local climate in other studies, where the relationship with local climate variables was not explored, but oscillation indices were used to explain burning (Greenville and others 2009).

Overall the effect of current climate was stronger than that of climate in the previous year. This was not consistent with the findings from analogous ecosystems in the Great Plains of the U.S., California chaparral, and arid spinifex grasslands of Australia where 1- and 2-years previous year climate variables were more strongly correlated with burning than current-year variables (Knapp 1998; Keeley 2004; Greenville and others 2009). Our analysis of the relationship between climate and vegetation productivity showed that previous year climate had little effect on vegetation during the period of intensive burning. However, the strong relationship between burned area and a range of broad-scale climatic indices, especially during fall, might suggest that local climate data are not adequate for our study area, or other parameters that we did not measure affected fires (for example, evapotranspiration).

In summary, we conclude that though climate was an important factor affecting burned area, especially in the Post-Soviet period, it could not explain the drastic increase in burned area between the two periods by itself. Substantial change in burning regime was driven by change in vegetation, which recovered after livestock plummeted and grazing pressure decreased. If the trend of rebounding livestock numbers since 2000 continues in the future, then this may lead to a corresponding decline in burning in the near future. The declines in grazing are to be expected in particular after strong institutional changes. In arid ecosystems, where fire suppression is weak lowered grazing pressure for 5–10 years is likely to result in an increase in burning with or without changes in climate.

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