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Changes in grazing patterns explain post-Soviet fire trends on the Eurasian steppe better than climate

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Abstract

In grassland ecosystems, fire plays an important role in maintaining biodiversity and ecological functioning but also causes substantial greenhouse gas emissions. Both climate and herbivory are key determinants of fire regimes, yet the relative importance of these factors remains debated. We focused on the steppes of Kazakhstan—one of the world’s largest grasslands and a global fire hotspot—to assess the relative importance of climate and grazing patterns on fire regimes. Specifically, we made use of the natural experiment that the post-Soviet collapse of the Kazakh livestock sector provided. We used the MODIS Burned Area Product and calculated annual livestock grazing demand (required forage intake) from 2001 to 2019. We estimated a binomial mixed-effects model to extricate the impact of grazing demand and climate factors on fire occurrence. Our results show that fire regimes changed markedly on the Kazakh steppes, with exceptionally high fire frequencies and extent in the 2000s. We found a clearly negative association between grazing demand and burned area; in other words, more heavily grazed areas burned less frequently. Moreover, annual grazing demand appeared in more of the best-performing models than precipitation, temperature, relative humidity, or growing degree days. Given that livestock herding is declining in many grassland regions, and native grazers have been lost or greatly reduced in the past, our study highlights the increasing risk of fire with less grazing, but also the potential for grazing restoration to mitigate such risks in the world’s grassland regions.

Keywords Fire regimes · Burned area · Livestock grazing · Grasslands · Kazakhstan

Introduction

Grasslands cover more than a quarter of Earth’s ice-free land surface (Dinerstein et al. 2017), harbor unique biodiversity, and are an integral part of the global carbon cycle (Bai and Cotrufo 2022). However, large areas of former grasslands have been converted for human uses, such as cropland, cities, and infrastructure (IPBES 2019; Ramankutty and Foley

1999; Stevens et al. 2022; White et al. 2000). Moreover, even where grasslands were not converted, they are often used for livestock husbandry, either as pastures or for growing fodder and forage (Herrero et al. 2013). As a result, few grasslands remain undisturbed by human land use (IPBES 2019; Scholtz and Twidwell 2022). Grasslands are among the most at-risk ecosystems in the world, imperiled by conversion due to expanding agriculture (Hoekstra et al. 2005; Lambin and

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Meyfroidt 2011), fragmentation (Haddad et al. 2015; Hobbs et al. 2008), degradation (Bardgett et al. 2021; Prishchepov et al. 2021), and climate change (Godde et al. 2020). Additionally, grassland conservation receives less attention than other habitats, such as forests (Andrade et al. 2019; Grau et al. 2015; Pärtel et al. 2005; Scholtz and Twidwell 2022). Much remains unknown or hotly debated about grasslands, from the seemingly simple estimation of their global extent to their capacity to store carbon, their resilience in the face of climate change, and what sustainable livestock production on these grasslands entails (Arneth et al. 2019; Carbutt et al. 2017; Godde et al. 2018; Piipponen et al. 2022). With regard to global grassland extent, we follow the definition of Dinerstein et al. (2017), which comprises the vast majority of grazed ecosystems.

Fire is an integral feature of grassland ecosystems, with widespread effects on their functioning (Bond et al. 2005). For example, fires determine plant community composition and plant diversity in grasslands (Fuhlendorf and Engle 2004), and recurring fires can suppress the growth of woody plants and herbs while favoring fire-adapted grasses (Freitag et al. 2021). Fires release nutrients stored in plants and can promote post-fire vegetation productivity increases. Many charismatic animals, such as large, mobile grazers, apex predators, and birds of prey, benefit from the conditions fires create in grassland ecosystems (Smelansky et al. 2015). Likewise, restoring natural fire regimes, and thus the links between fire and grazing, can lead to healthier, more sustainable grasslands, regardless of whether the grazing is done by wild animals or livestock (Fuhlendorf et al. 2009). However, fires can also promote the spread of invasive species and cause considerable air pollution (Dubinin et al. 2010; Scholes and Archer 1997). The carbon cycle on grasslands is greatly influenced by the predominate fire regime, with fires leading to considerable greenhouse gas (GHG) emissions (van der Werf et al. 2010). Many land-use practices, including livestock husbandry, have been linked to increases in fire occurrence and thus higher pollution and emissions (Moreno et al. 2014). Altering natural fire regimes can also have detrimental effects on biodiversity, with savannas and grasslands at the highest risk of species extinction from changes in fire activity (Kelly et al. 2020). Many smaller grassland animals, such as rodents and ground-nesting birds, have a precarious relationship with fire, a balance that, when upset, can be disastrous for species populations (Koshkina et al. 2022; Smelansky et al. 2015). Given that globally up to 40% of total burned area occurs on grasslands (Rabin et al. 2015), it is important to understand the trends in grassland fires and which factors determine these trends.

Three factors contribute to fire occurrence in grasslands: ignition sources, fuel moisture, and fuel load (Bowman et al. 2011; Dubinin et al. 2011). Ignition sources may be

natural—predominantly through lightning—or anthropogenic, either inadvertent (e.g., sparks from agricultural machinery, cigarettes) or intentional (e.g., to remove senescent vegetation from pastures) (Bradstock 2010). Fuel moisture is driven by temperature, precipitation, wind, and humidity (Bradstock 2010). These variables can be measured over short time periods (i.e., weather) or longer periods (i.e., climate), with fire occurrence being strongly linked to both weather and climate (Flannigan and Wotton 2001). Finally, fuel load is determined by two opposing factors. On one hand, fuel load is driven by net primary productivity (NPP), which in turn is driven by climate, soils, and anthropogenic factors such as land use (Marlon et al. 2008). On the other hand, fuel load is also determined by the amount of biomass that is removed, which happens predominantly through herbivory (i.e., wild herbivores or domestic livestock) and harvesting (i.e., straw- and haymaking). Where herbivory is suppressed or absent, fuel loads increase and fire becomes the main force through which biomass is consumed (Fuhlendorf et al. 2009). There are also important interactions and feedbacks between fire and grazing. For example, recently burned areas produce higher quality forage, which can attract grazers, increasing herbivory and promoting vegetative growth (Allred et al. 2011; Díaz et al. 2007). Conversely, heavy grazing suppresses fires through a reduction of fuel loads. Blanket policies based on a simplified understanding of fire ecology and management, though well-intentioned, can worsen conditions (Johansson et al. 2021). Given these complex interactions between climate, fire, and herbivory, it is perhaps unsurprising that the relative importance of these factors continues to be understudied and weakly understood, particularly for temperate grasslands (Smelansky et al. 2015).

Two additional factors contribute to burned area, and thus complete the picture of regional fire regimes: wind speed and fuel continuity, both driven by topography and land cover (Bowman et al. 2011). Globally, burned area has decreased considerably, by approximately 30% from 2000 to 2019 (Zheng et al. 2021). Precipitation patterns explain much of the inter-annual variability in burned area, but changes in climate parameters do not explain well the long-term decline in burned area, which appears to correlate more strongly with land use, including livestock grazing (Rouet-Leduc et al. 2021). Importantly, burned area has not declined universally, with some areas seeing an increase in fire activity. Areas that deviate from the global trend are particularly interesting and can help to unravel the relative importance of climate vs. land-use factors in determining burning. One such region is the Eurasian steppes, an arid grassland region where fires are frequent, intense, and large (Archibald et al. 2013), rendering the region a global fire hotspot (Cao et al. 2015; Hantson et al. 2013). Understanding what drives fire patterns and trends in these steppes is therefore valuable.

Fire occurrence in the Kazakh steppe is widespread, but spatially and temporally diverse. There is a strong north–south precipitation gradient, from 350 mm per year on the northern edge down to 150 mm per year on the southern edge of the steppes (Afonin et al. 2008). However, this precipitation gradient does not appear to be well-reflected in spatial patterns of burning (Xu et al. 2021). At the same time, Kazakhstan has seen drastic fluctuations in livestock populations over the last decades, resulting in spatial and temporal variations in grazing pressure. Specifically, with the collapse of the Soviet Union, grazing livestock numbers in Kazakhstan plummeted to 30% of 1990 numbers in less than 10 years (KazStat 2019), with an 80% decline in sheep numbers and a more than 50% decline in cattle numbers after 1991, and there was widespread cropland abandonment (Kraemer et al. 2015). Since the 2000s, grazing livestock numbers have recovered to over 60% of 1990 numbers (KazStat 2019); however, these increases were neither uniform in space nor among farm types (which have varying degrees of access to advanced technology and infrastructure). As a result, there is large heterogeneity in grazing pressure on Kazakh steppes (Kerven et al. 2021). This provides a unique “natural experiment” to study the links between fire, grazing, and climate variables.

Steppe fires have been identified as both a threat to biodiversity and a major research need in Kazakhstan (Kamp et al. 2016). Prior work has attempted to assess aspects of fire regimes and the factors that determine them but have often focused on limited time periods or study regions. Recently, burned area in northcentral Kazakhstan was mapped across three time periods (Dara et al. 2020a, b): the peak of agricultural production in the late Soviet period (1989–1991), the low point of agricultural production (1999–2001), and after a major recovery of cropping and livestock sectors (2014–2016). Fires increased in size and number on croplands and pastures between 1990 and 2000, especially on abandoned former cropland. Between 2000 and 2015, total burned area decreased slightly, and burning shifted from croplands to grasslands (Dara et al. 2020a, b). While this revealed important insights, the work is limited by the snapshot-like analysis, failing to capture the temporal variability, and not exploring the relevance of climate variables. The latter is particularly noteworthy, as in nearby Kalmykia, southern Russia, climate became strongly correlated with burned grassland area after livestock numbers had plummeted (Dubinin et al. 2011). In a nation-wide study for Kazakhstan, wetter climate conditions and increased grazing pressure were the principal drivers of the decline in burned area between 2002 and 2016 (Hao et al. 2021). However, Hao et al. (2021) utilized coarse, global climate and vegetation products, and province-level livestock numbers, which is a major limitation given that there are distinct and spatially heterogeneous patterns of grazing pressure as

shown by Dara et al. (2020a, b). In addition, no conversion to livestock units was made (i.e., a sheep was treated as equal to a cow), and horses, which are a major grazer in Kazakhstan, were ignored altogether (Hao et al. 2021). In sum, although prior work has highlighted the potential roles of both livestock grazing and climate variables in driving the strong changes in fire regimes in Kazakhstan’s steppes, an assessment at the spatial and temporal resolutions necessary to unravel the relative importance of these factors is missing.

Against this background, we aimed to answer two overarching research questions: (1) How has the burned area extent evolved across the Kazakh steppe from 2001 to 2019, and (2) what were the important factors determining observed changes in burned area? We hypothesized that grazing demand is an important predictor of burned area when compared to the climate predictors, of precipitation, temperature, relative humidity, and growing degree days. We further hypothesized that grazing demand in 1 year will have a larger impact on the subsequent year’s burned area than the current year, and that this impact will be negative.

Materials and methods

Study area

Northern Kazakhstan contains a massive tract of the Eurasian steppe, including large, intact areas (Scholtz and Twidwell 2022). Much of the far northern part of this region is used for rainfed agriculture. Aridity increases toward the south and southwest, where the landscape transitions to semi-desert and eventually desert around the Aral Sea and along the border with Uzbekistan. To the east and southeast, foothills and eventually the western edge of the Altai Mountains and the northern edge of the Tien Shan Mountains rise up, supporting alpine ecosystems. We limited our research area to the region that has the highest co-occurrence of grazing and fire (1.83 million km² across northern Kazakhstan, encompassing 124 districts (*rayon*); Fig. 1). We chose to use the land-cover map of Klein et al. (2012) at a spatial resolution 250 m for its representation of the midpoint of the study period and its creation specifically for Central Asia with local expertise and ground-truthing. We further masked areas where livestock grazing is unlikely to occur: urban areas, forests, and croplands. Of the 1.83 million km² total, we considered 1.48 million km² available for grazing.

Livestock grazing demand

Grazing demand is the required intake of forage by livestock. We expanded the calculations of Hankerson et al. (2019) (originally calculated for 2015) to determine the annual livestock grazing demand across the study region

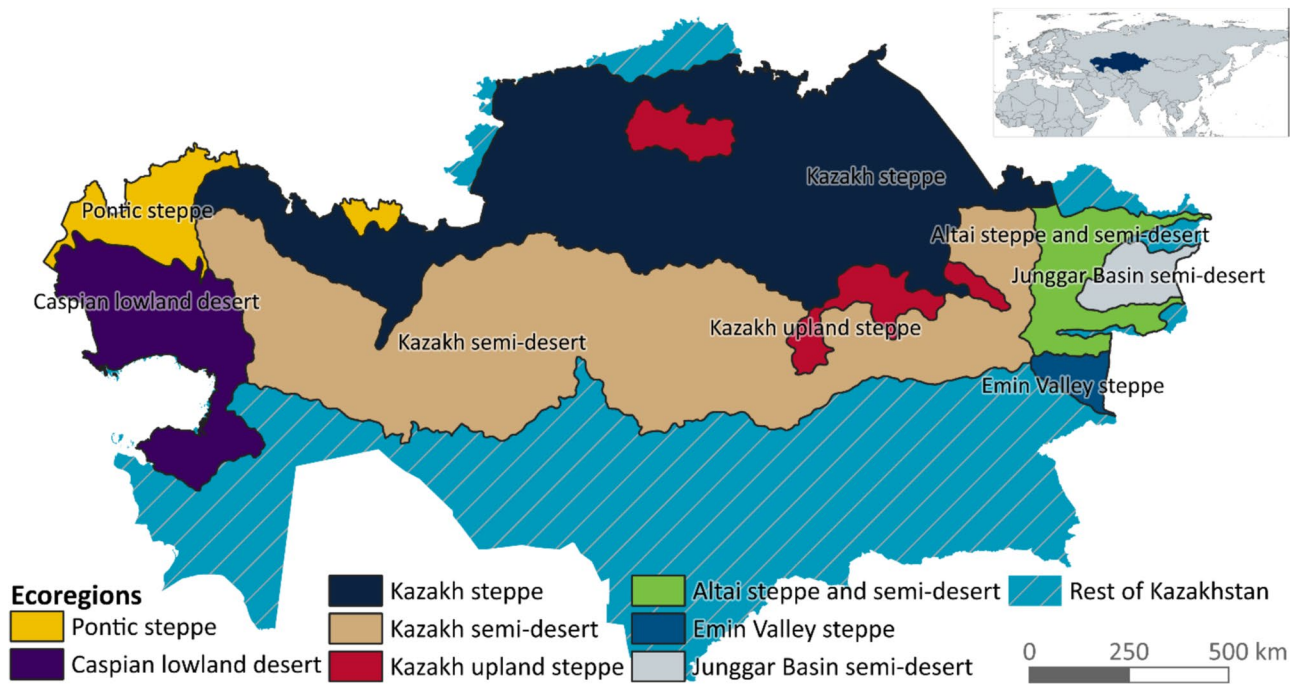


Fig. 1 Ecoregions used in this research (Dinerstein et al. 2017). The Kazakh steppe and its ecologically similar neighboring regions (colored polygons) encompass 124 of Kazakhstan's 200 administrative districts

for the years 2001 to 2019. We obtained annual livestock numbers at the district level from the Kazakh National Statistics Agency (KazStat 2019). To determine the energy demand of the livestock, we used the 2006 agricultural census to divide the herds into age and function groups (e.g., beef heifers) (KazStat 2008). We then applied recommended energy intake values for each functional group from the Ministry of Agriculture (Zhazylbekov et al. 2008). We summed these values to create a total livestock energy requirement for each district. We used district-level gross yields of each fodder crop (KazStat 2019) to determine annual fodder production (all crops grown for livestock consumption, predominately hay, silage, and grain), which we converted to energy equivalents and then subtracted from total livestock energy demand, resulting in the total energy demand of livestock from grazing. We then divided the annual grazing demand by the grassland area of each district. We introduced a lag of 1 year to account

for the “end of year” value of grazing demand (Table 1). Datasets not published online by KazStat (i.e., functional groups and energy intake values) can be found in the supporting information of Hankerson et al. (2019).

Climate indicators

Monthly precipitation and average temperature values were obtained from the Climate Research Unit (CRU, spatial resolution 0.5°) (Harris et al. 2014). Annual growing degree days (base 5 °C, spatial resolution 0.5°) (Wouters 2021) and monthly relative humidity (spatial resolution 0.25°) (Hersbach et al. 2018) were taken from ERA5 reanalyses. The gridded data were area-weighted to produce a single value for each district. Here, we were interested in annual and seasonal values—spring (March–May), summer (June–August), fall (September–November), and winter (December–February), as well as fire season (May–October), and

Table 1 Marginal and conditional R^2 values for model results of three different land-use masks with and without a 1-year lag of burned area with respect to grazing demand (Nakagawa and Schielzeth 2013)

Set of variables	Without lag		With 1-year lag	
	Marginal R^2	Conditional R^2	Marginal R^2	Conditional R^2
Grazing on all land types	0.157	0.369	0.327	0.526
Grazing on grasslands and croplands	0.215	0.424	0.404	0.612
Grazing on grasslands	0.295	0.522	0.505	0.749

fire off-season (November–April). For simplicity, we refer to these variables as climate, for both annual and long-term analyses. For precipitation, the sum of the given period was calculated. For temperature and relative humidity, the mean of the given period was calculated. There were 124 districts and 19 years, of which we used 18 after excluding the lag year, hence 2232 observations of each variable. Lagging the climatic variables by 1 year did not improve the model; therefore, the current-year climatic variables were combined with the previous year's grazing demand.

Fire indicators

We used the Terra and Aqua combined MCD64A1 v6 Burned Area product to estimate the annual area burned in the study area (Giglio et al. 2015). We stacked the monthly MODIS 500 m resolution images to create a binary time series of burned and unburned areas annually for 2001–2019. We used the land-cover map of Klein et al. (2012) to mask cultivated areas, artificial surfaces, forests, bare areas, ice and snow, and waterbodies. The resultant grassland map, along with an administrative district map (GADM 2018), allowed us to calculate the proportion of burned and unburned grassland in each district for each year.

Statistical analysis

We used a binomial generalized linear mixed-effects model (GLMM) to regress the predictors against the observed values of burned area (Bolker et al. 2009; Warton and Hui 2011). The calculations were performed using the “arm” and “lme4” packages within R (Gelman et al. 2022). Fixed-effects variables in our models were annual grazing demand (MJ/km^2), annual cumulative growing degree days, and seven aggregations of total precipitation (mm), average temperature ($^{\circ}\text{C}$), and relative humidity (%): annual, fire season, off-season, spring, summer, fall, and winter. We included administrative district identifiers as random effects to account for the non-independence of repeated sampling of burned areas within the same district in different years. We assume that topography does not change over the study period, and thus slope—an important driver of fire—is accounted for at the district level as a random effect. All variables were standardized to compare different units and different scales of magnitude. The binomial regression followed the form $p = \frac{e^{\beta_0 + \beta_1 x + \beta_2 x^2}}{1 + e^{\beta_0 + \beta_1 x + \beta_2 x^2}}$ where p = proportion burnt and $\beta_0 + \beta_1 x + \beta_2 x^2$ is the quadratic (or linear if reduced to $\beta_0 + \beta_1 x$) regression expression (Crawley 2013). We determined the goodness-of-fit for the aforementioned combinations of variables using conditional and marginal R^2 . Marginal R^2 measures variance explained by fixed factors, while conditional R^2 measures variance explained by both fixed

and random factors (Nakagawa and Schielzeth 2013). Akaike Information Criterion (AIC) was calculated to determine model strength (Mazerolle 2006). In addition to single-variable models, we explored multi-variable models to determine if combining variables produced better models.

Results

Temporal trends in burned area

Between 2001 and 2019, the annual burned area exceeded 5% (about $74,000 \text{ km}^2$) of the total grassland area in 7 years (Fig. 2a), of which 6 years occurred between 2001 and 2010. The Kazakh steppe has experienced a general downward trend in burned area of 3670 km^2 per year over these 19 years, though with high variation between years. Precipitation experienced a general decrease during the 2000s, followed by large inter-annual variation throughout the 2010s (Fig. 2b). Temperature was relatively stable and relatively high during the 2000s, before also entering a period of larger inter-annual variability in the 2010s. Grazing demand has risen steadily (mirroring the rebounding livestock numbers since circa 2000) (Fig. 2c). The observable break in 2011 is an artifact of a referendum in statistical counting (Nazarbayev 2010), and is accounted for by the GLMM.

Spatial trends in burned area

Across the Kazakh steppe, the most frequently burned areas occurred across the middle and northeast of the study area, bordering the predominately crop-producing region in the northcentral (Fig. 3). Of the grassland in the study area over the 19-year study period, 42% burned at least once, 21% at least twice, 10% at least three times, and 4% four or more times. Each proportion is a superset of the remaining proportions (e.g., $21\% - 10\% = 11\%$ burned exactly twice).

Analyses of determinants in fire patterns and trends

We first tested our assumption of restricting the area of interest to grasslands available for pasture. We tested three different scenarios, first where grazing demand can be spread across all land types, second where grazing demand can only be spread across grasslands and croplands (grazing is known to occur on croplands (Coughenour et al. 2008)), and third where grazing demand can only be spread across grasslands (Table 1). Using grasslands only for the distribution of grazing demand had the highest R^2 values (last row of Table 1). We then examined the lag effect of the variables, to determine whether burned area is more a result of

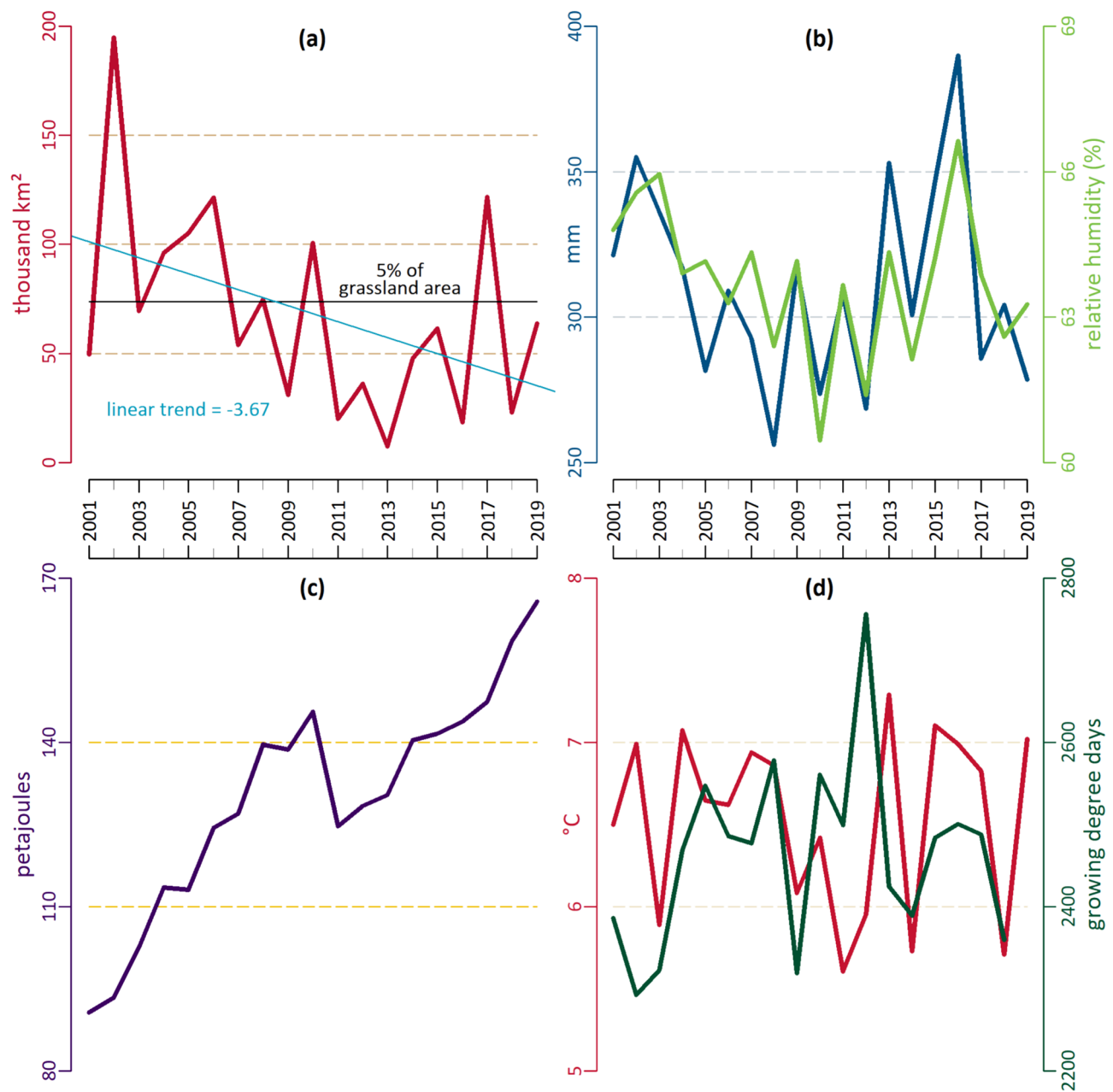


Fig. 2 **a** Annual burned area extent on grassland in our study region (Giglio et al. 2015). The linear trendline is for visualization purposes only. **b** Average annual precipitation (blue) and average annual relative humidity (green) across the study region (Harris et al. 2014; Hersbach et al. 2018). **c** Annual grazing demand of grazing livestock in the study region. The energy equivalent was calculated using

annual national statistics bulletins (KazStat 2019), the 2006 agricultural census (KazStat 2008), and recommended intake values (Zhazybekov et al. 2008). See Hankerson et al. (2019) for calculations. **d** Average annual temperature and average annual growing degree days (Harris et al. 2014; Wouters 2021)

the conditions in the current year or in the previous year. Applying a 1-year lag of burned area with respect to precipitation, temperature, relative humidity, growing degree days, or combinations of them did not increase the models' R^2 values. However, applying a 1-year lag of burned area with respect to grazing demand increased the R^2 values by approximately 0.2 (last two columns of Table 1). This makes

sense considering that the livestock statistics were reported "at end of year." Therefore, we chose to use the climatic variables of the current year in combination with the previous year's grazing demand, which has precedent in similar regions (Dubinin et al. 2011).

We then fitted the GLMMs with all possible combinations of grazing demand and climate variable combinations as

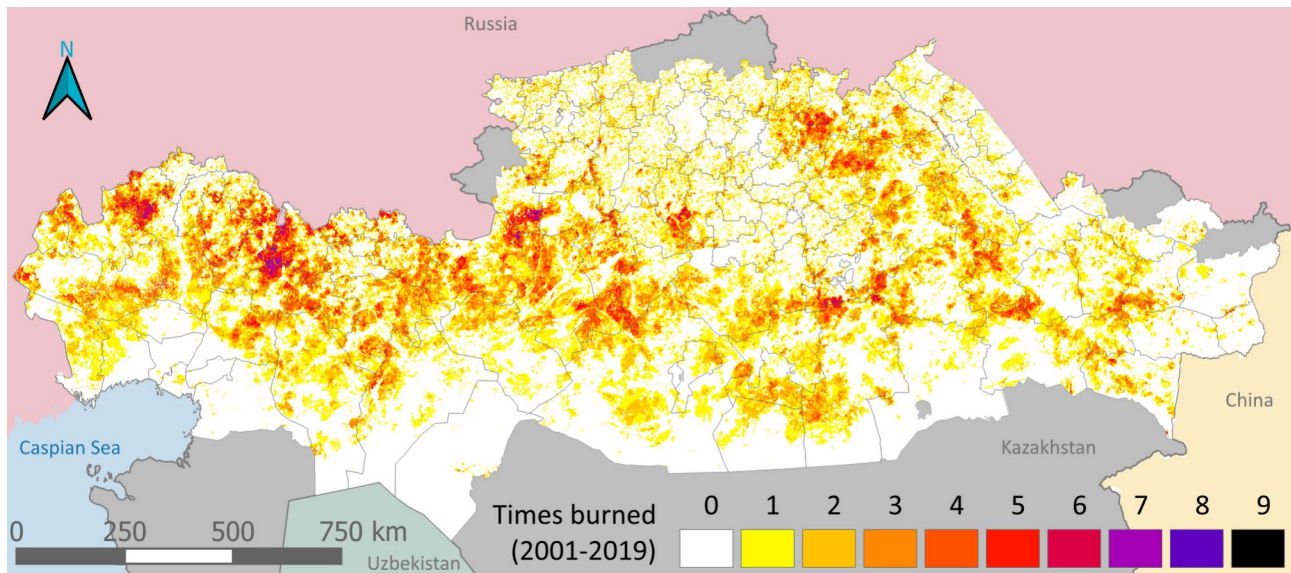


Fig. 3 Frequency of fires (measured as the number of years with burned area) across the study area from 2001 to 2019. Only burns on grasslands are shown. Gray area shows the rest of Kazakhstan, with neighboring countries (GADM 2018)

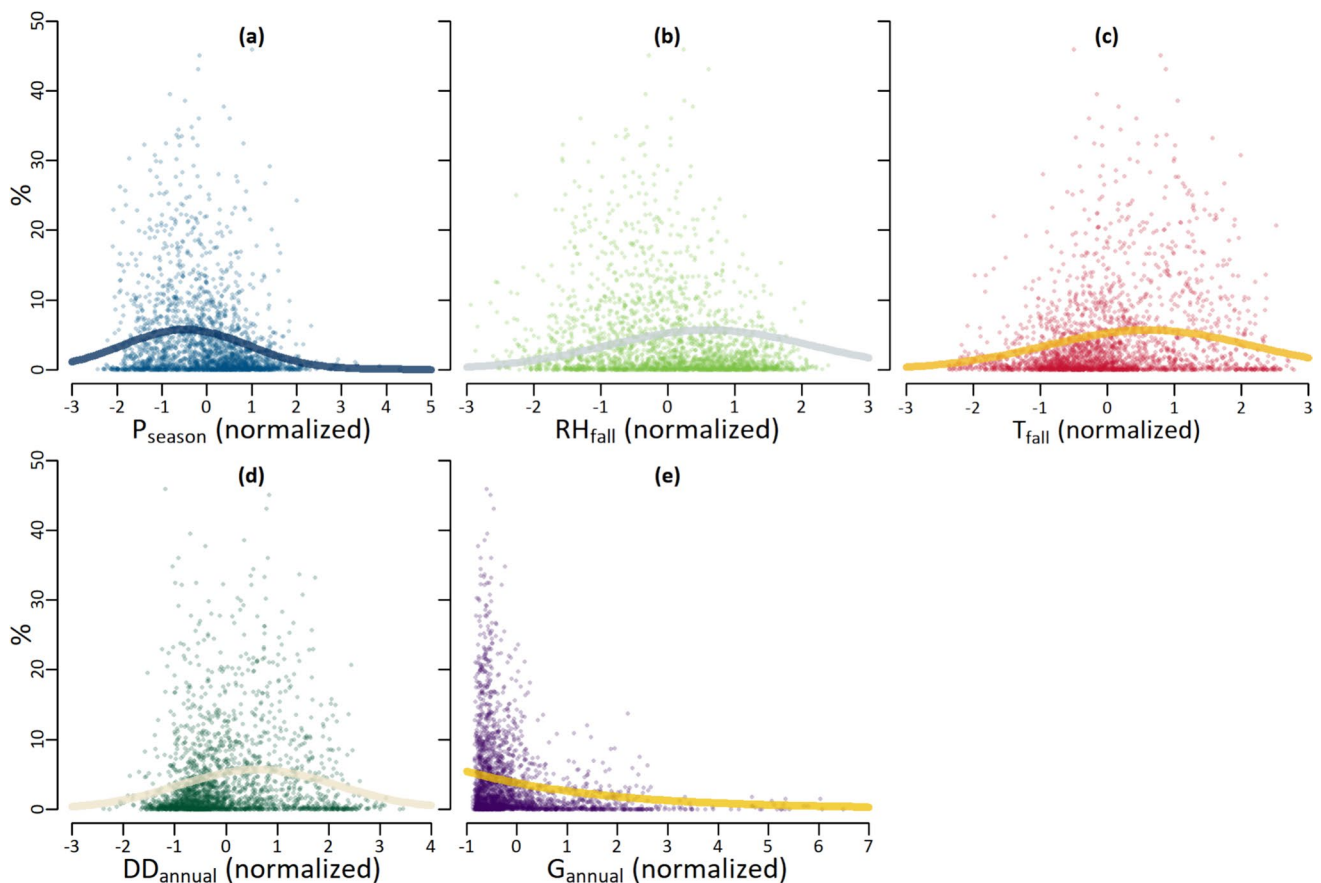


Fig. 4 Burned area of a district-year with fitted binomial regression for standardized values of **a** fire season precipitation (P), **b** average fall relative humidity (RH), **c** average fall temperature (T), **d** annual growing degree days (DD), and **e** annual grazing demand (G)

predictors, and the proportion burned area per grid cell as the response variable (over 16,000 models were analyzed, a complete list can be provided upon request). An analysis of R^2 values produced the highest values when burned area was a function of the previous year's grazing demand. Figure 4 plots the standardized values of precipitation, temperature, relative humidity, growing degree days, and grazing demand (previous year) against the proportion burned in a given district and year. For each set of climate variables, we chose

the best-performing single-variable model according to AIC. Not surprisingly, time periods for climate during peak fire occurrence explained burned area better, either the whole fire season for precipitation (Fig. 4a), or during the fall for relative humidity (Fig. 4b) and temperature (Fig. 4c). Degree days (Fig. 4d) and grazing demand (Fig. 4e) are only available as annual values.

We found that any model that included grazing demand greatly increased both marginal and conditional R^2 values

Fig. 5 Marginal and conditional R^2 for increasingly complex models. Asterisks are applied to the best model of its type for each climate and grazing variable. For example, **h** has only two graphs; the first is the best-performing four-variable additive model that has relative humidity in it, and the second graph is shared among every other variable as their best-performing four-variable additive model. The overall best-performing model (by AIC value) is the five-variable model including interacting summer precipitation and fall relative humidity, interacting annual temperature and growing degree days, and grazing demand, shown in **k**. ann, annual; ssn, fire season; off, fire off-season; spr, spring; smr, summer; fal, fall; win, winter

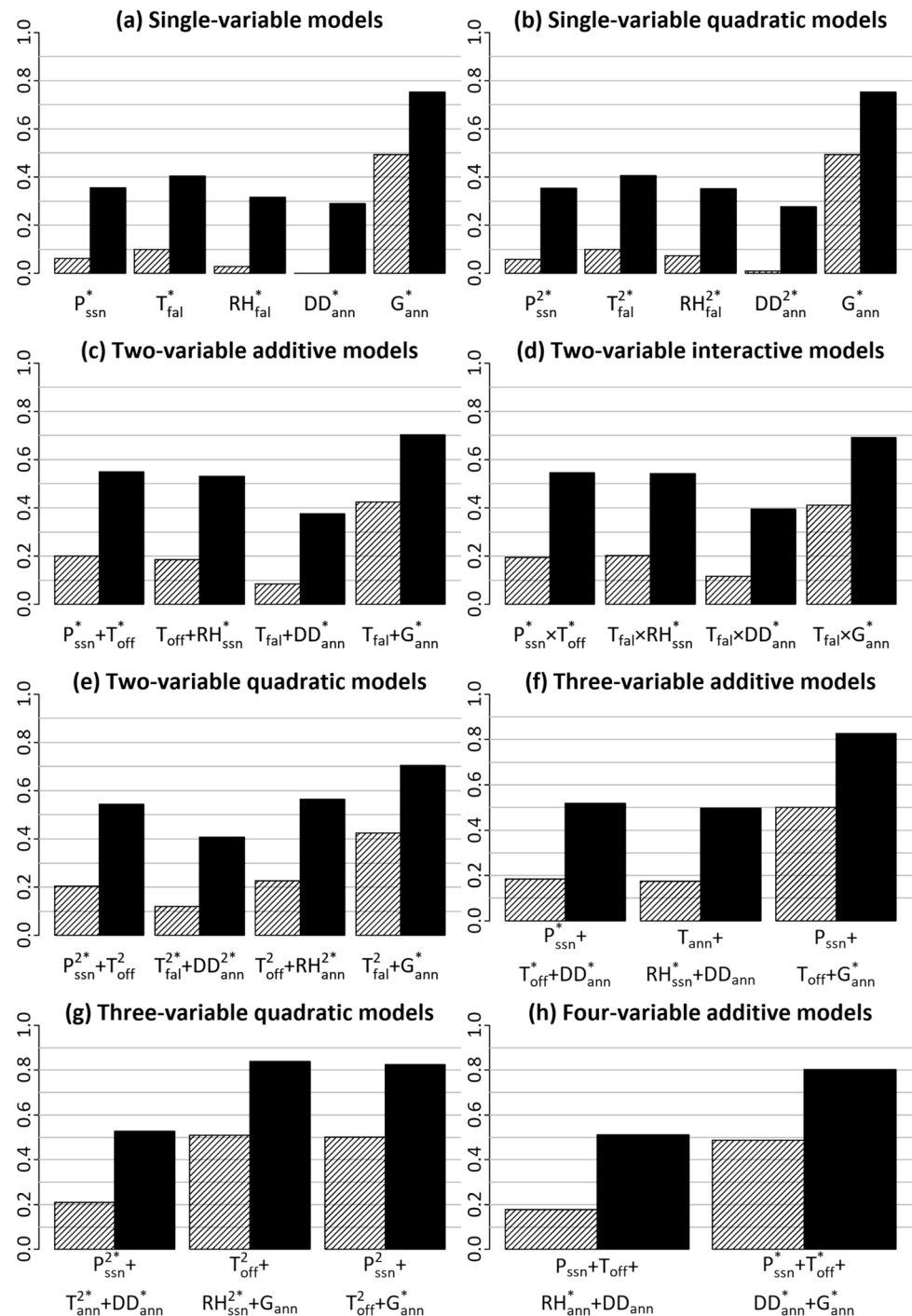
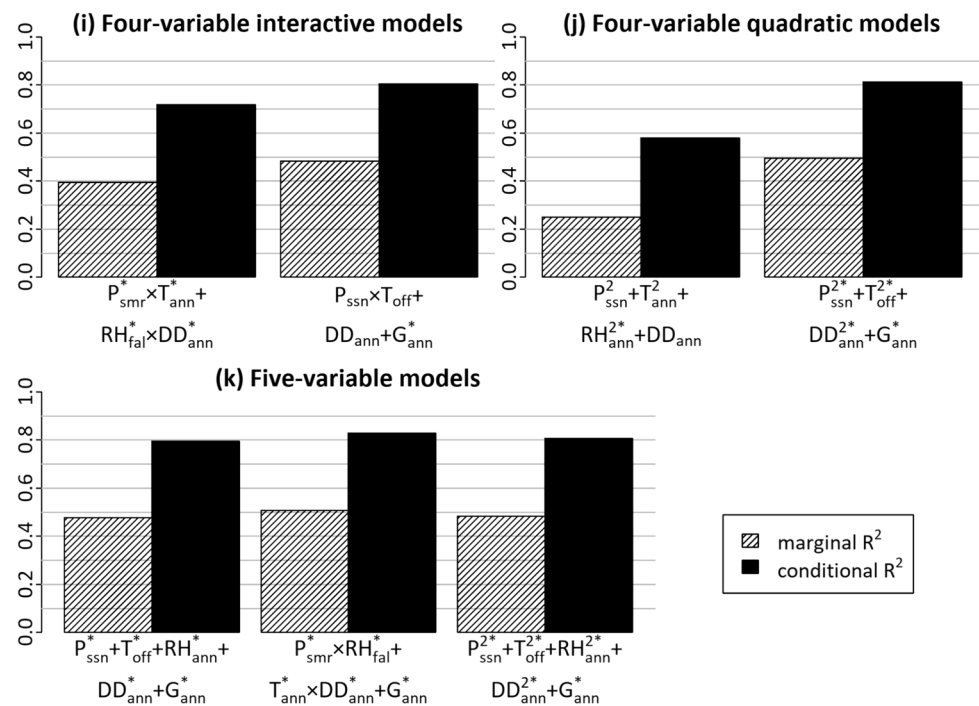


Fig. 5 (continued)



compared to models without that variable (Fig. 5). The best combination of solely climatic variables was the interaction between summer precipitation and fall relative humidity combined with annual temperature interacted with growing degree days (Fig. 5k). However, whenever grazing demand was combined with at least two other variables, the vast majority of such models had better R^2 values than models with solely climatic variables.

Regional analyses

We evaluated the ecoregions separately to determine possible variations in burned area determinants. Two ecoregions, the Junggar Basin semi-desert and the Emin Valley steppe, encompass only a single district, and were therefore

left out of the ensuing analysis, resulting in six regional analyses. Per ecoregion, both the best set of predictive variables (determined by AIC) and the model with the highest conditional R^2 was determined (Table 2). Notably, the best predictive power (AIC) was obtained by including all variables in all ecoregions, with the two most well-represented ecoregions (Kazakh steppe and Kazakh semi-desert) having the best associated R^2 values.

Looking at the models chosen for their conditional R^2 values, there was more variation between ecoregions (cf. Figure 1). The Kazakh steppe ecoregion has the largest number of districts, but only moderate R^2 values, with a quadratic model producing the highest R^2 values. The Kazakh upland steppe covers only three districts and encompasses predominately crop-producing regions, where the burned area is

Table 2 Models with the lowest AIC value and the highest conditional R^2 for each ecoregion

Ecoregion	No districts	Value	Best-performing model	R_m^2	R_c^2
Kazakh steppe	73	AIC	$P_{ssn}^* RH_{fal}^*, T_{off}^* DD_{ann}^*, G_{ann}^*$	0.39	0.60
		R_c^2	$P_{win}^2, T_{spr}^2, RH_{smr}^2, DD_{ann}^*, G_{ann}^*$	0.54	0.75
Kazakh upland steppe	3	AIC	$P_{win}^* RH_{ssn}^*, T_{ann}^* DD_{ann}^*, G_{ann}^*$	0.42	0.46
		R_c^2	$P_{win}^* DD_{ann}^*, T_{smr}^* RH_{fal}^*, G_{ann}^*$	0.47	0.64
Altai steppe and semi-desert	6	AIC	$P_{spr}^* DD_{ann}^*, T_{win}^* RH_{off}^*, G_{ann}^*$	0.28	0.37
		R_c^2	$P_{spr}^2, T_{win}^2, RH_{ann}^2$	0.47	0.81
Kazakh semi-desert	24	AIC	$P_{ssn}^2, T_{off}^2, RH_{ssn}^2, DD_{ann}^2, G_{ann}^*$	0.23	0.67
		R_c^2	$P_{ssn}^2, T_{ann}^2, RH_{ssn}^2, G_{ann}^*$	0.26	0.74
Pontic steppe	8	AIC	$P_{smr}^2, T_{smr}^2, RH_{fal}^2, DD_{ann}^2, G_{ann}^*$	0.22	0.52
		R_c^2	$P_{smr}^* RH_{spr}^*, G_{ann}^*$	0.60	0.80
Caspian lowland desert	8	AIC	$P_{smr}^2, T_{off}^2, RH_{fal}^2, DD_{ann}^2, G_{ann}^*$	0.26	0.53
		R_c^2	$T_{smr}^2, RH_{spr}^2, DD_{ann}^2, G_{ann}^*$	0.50	0.97

small. Here, an interactive model produced the highest R^2 values, though conditional R^2 is the lowest of any ecoregion. The Kazakh semi-desert is the second-largest ecoregion and exhibited a high degree of variation and uncertainty. However, accounting for spatial distribution through inclusion of random effects (districts) greatly increased the conditional R^2 with a quadratic model. The Pontic steppe was the only ecoregion without temperature in its best R^2 model. The Caspian lowland desert was the only ecoregion without precipitation in its best R^2 model and had the highest R^2 values of any ecoregion. The Altai steppe and semi-desert is the second smallest ecoregion and did not have a grazing demand in its best R^2 model. Relative humidity was the only variable found in every ecoregion's best R^2 model.

The ecoregions can be split roughly into two groups, the “wet” group—Kazakh steppe, Kazakh upland steppe, and Altai steppe and semi-desert—and the “dry” group—Kazakh semi-desert, Pontic steppe, and Caspian lowland desert. The “dry” group is situated in the south and west of the study area, and share several characteristics, including many of the lowest precipitation and highest temperature values. In these, burned area shows a stronger relationship with spring, summer, and fire season climate variables. The “wet” group is in the north and east of the study area and has the highest precipitation and lowest temperature values. In these, winter and spring climate variables are more common in the best-performing R^2 models. These groups also share the type of predictive model (based on AIC), with the “wet” group preferring interactive models and the “dry” group preferring quadratic. Perhaps most notably, when analyzing on the scale of ecoregions, the seasonality of climate variables is revealed as many more of the shorter time periods (spring, summer, fall, and winter) appear in the best-performing models.

Discussion

Climate factors and grazing both have been shown to be important determinants of fire patterns and trends, but their relative importance has often been elusive. Understanding their roles is key as climate change progresses. Making use of the natural experiment of rapid, widespread, and spatially heterogeneous declines in livestock numbers in the steppes of post-Soviet Kazakhstan, a global fire hotspot (Archibald et al. 2013; Hantson et al. 2013), we assessed the relative importance of changes in grazing demand and climate variables on burned area at unprecedented spatial and temporal detail. Our analyses yield three major insights. First, fire regimes changed markedly, with exceptionally high frequency and extent of fires in the 2000s followed by a decline in the 2010s, corroborating earlier findings for smaller subregions and from other parts

of the post-Soviet sphere (Dara et al. 2020a, b; Dubinin et al. 2010; Hao et al. 2021). Second, there was a strong negative association between grazing demand and burned area, suggesting that restoring grazing regimes—either with domestic livestock or wild grazers—can suppress burning in Eurasian steppes. Third, changing livestock grazing demand after the breakdown of the Soviet Union explained fire dynamics better than both broad-scale climate patterns and inter-annual climate variation, highlighting the importance of grazing and, more generally, the need for better data on grazing pressure in grasslands.

Answering our first research question, we found that burned area extent varied greatly from year to year (Fig. 2a). Linear regression showed an average decrease in burned area of 3670 km²/year from 2001 to 2019. As percent change (about −5.4%), this is well above the global trend of about −1.6% over the same time period (Zheng et al. 2021). We also found that the most frequently burned areas are located predominantly along the border between the Kazakh steppe and the Kazakh semi-desert, as well as in the Pontic steppe (cf. Figure 1 and Fig. 3). This agrees with the median fire return interval for this region found by Archibald et al. (2013), which extends westward across the Southern Federal District of Russia (Dubinin et al. 2010).

The negative association between grazing and fire in our study area is in line with Dara et al. (2020a, b), who found fire occurrence to be correlated with livestock presence in a subset of our study area. Similarly, Dubinin et al. (2011) found livestock population to be negatively associated with burned area in a region adjacent to our study area. We also find agreement with Hao et al. (2021), who looked at a similar time period across a large area in northern Eurasia and found grazing demand to be strongly correlated with declining burned area. Importantly, we go beyond prior work in that the relationship between fire and grazing has neither been studied across a broad range of environmental conditions and vegetation zones while using high-resolution data on grazing demand and fire activities, nor across such a length of time while using sub-annual data.

We have shown that grazing demand is strongly, and negatively, correlated with burned area (Fig. 4), and can be used alone or in cohort with climate variables to produce a robust model (Fig. 5). Indeed, as grazing demand has steadily increased over the period 2001–2019, burned area has become less variable and generally smaller. While we did not measure forage quantity or quality, our findings corroborate the linkages between large grazers and fire occurrence (Reid et al. 2022). We identified trade-offs between conservation, fire suppression, and livestock production, which can inform policy makers and local governments looking to optimize the allocation of resources assigned to fire prevention and control. The results corroborate that livestock grazing can be used to mitigate fire occurrence on temperate

grasslands, which more broadly can support mitigation of greenhouse gas emissions from fire and promote production from grazing livestock in regions with large grassland resources at lower environmental costs. This is timely for Kazakhstan and the former Soviet Union in general as they start to release carbon that had been sequestered in the years immediately following the dissolution of the Soviet Union (Schierhorn et al. 2019).

A few limitations need mentioning. First, there were several variables that may have added explanatory value. Topography, wind patterns, fuel continuity, and access to ignition sources are all unaccounted-for variables that also determine fire frequency and extent (IAFC and NFPA 2019). Our intent was not to create a definitive model for ranking fire drivers, but rather to investigate the rank of grazing demand in comparison to some of the most important climatic variables (Oliveira et al. 2012). Second, the MODIS burned area product may not capture all burned areas, especially small burns. However, small burns are not characteristic of our study area, and indeed, temperate grasslands and xeric shrublands (the biomes of our study area) are among the most highly accurate biomes in terms of burned area estimates (Boschetti et al. 2019). Third, despite our use of district-level statistics, our spatial representation of grazing demand remains a coarse aggregation, with no way to definitively allocate livestock within the district (Hankerson et al. 2019). Finally, small sample sizes reduced the goodness-of-fit for some ecoregions, even when including all variables and quadratic terms (Table 2). Some ecoregions, especially in eastern Kazakhstan (cf. Figure 1), are small, isolated, and unique, not lending themselves well to analyses at the district level. Larger ecoregions, however, produced robust results.

Our work also has major policy implications. As much of the steppe is too arid for profitable crop production, livestock grazing has little competition from other land uses for Kazakhstan's grassland resources (Fetzel et al. 2017), a bias which may strengthen under continuing climate change (Weindl et al. 2015). Additionally, Kazakhstan is not considered a priority area for climate change mitigation and adaptation (Bonilla-Cedrez et al. 2023), suggesting that it is a suitable candidate for livestock expansion. As a predominately pastoralist society, the mitigation of fire occurrence on the Kazakh steppe could at least in part be achieved through the management of grazing practices, providing that livestock numbers continue to grow in order for large-scale reduction of fuel loads, possibly with the help of targeted governmental programs. Any program implemented by the government would have to take into account the vast differences in grazing practices between large agricultural enterprises with tens or hundreds of thousands of animals, medium-sized private farms—which are the fastest growing farm type—and small households with a handful of animals, which is where the majority of grazing livestock

in Kazakhstan are still raised, but whom are rarely able to take advantage of any of the government's current support programs (Kerven et al. 2021).

Despite a potential revival of livestock husbandry in the steppes of Kazakhstan, inevitably there will also be large areas where livestock grazing remains infeasible (e.g., too remote, too marginal) or prohibited (e.g., inside protected areas) (Dara et al. 2020a, b; Kamp et al. 2016; Kerven et al. 2016). These areas provide opportunities for trophic rewilding, that is, restoring populations of wild grazers, such as saiga antelopes, goitered gazelles, kulan, wild horses, or wild camels (Bakker and Svenning 2018; IPBES 2018; Perino et al. 2019). This would make a major contribution to conservation, given the currently imperiled status of some of these species (Rosen Michel and Röttger 2014). It would also help in achieving Target 2 of the recently agreed upon Convention on Biological Diversity goals: restoration of at least 30% of the world's degraded areas by 2030 (UNEP 2022). At the same time, such trophic rewilding has the potential to reduce fire activity, improve carbon storage, and thus mitigate climate change in a range of ways (Johnson et al. 2018; Sandom et al. 2020).

Conclusion

Human-induced changes in fire regimes at the global scale pose challenges to ecosystem health and biodiversity, as natural fire regimes become rare. As we venture further into the Anthropocene, we must recognize, analyze, and respond to the critical role that fire plays in shaping ecosystems (Kelly et al. 2020). While more widespread and intense fires are dangerous to people and infrastructure, blindly intensifying grazing pressure in the world's grasslands without consideration for carrying capacity and ecosystem services ultimately endangers the people depending on grasslands for their livelihood and sustenance (Qi et al. 2017). With functional populations of native grazers having largely disappeared from many grasslands, the choice of animal species used to intensify grazing pressure, as well as the land-use change itself, will have ramifications for carbon emissions (Rolinski et al. 2021). Our research provides the framework needed to begin restoring the balance between grazing and fire, offering an opportunity to maintain the world's grasslands while mitigating the inherent dangers of fire.

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Data Availability All data is freely available and is correspondingly cited in the Methods.

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