Landscape Ecol
https://doi.org/10.1007/s10980-020-01174-7

RESEARCH ARTICLE

Restoring steppe landscapes: patterns, drivers and implications in Russia's steppes

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Received: 3 September 2019 / Accepted: 2 December 2020

Abstract

Context Agricultural land abandonment across the steppe belt of Eurasia has provided an opportunity for the restoration of steppe landscapes in recent decades. However, global food demands are about to revert this trajectory and put restored steppe landscapes at risk.

Objectives We analysed steppe development in southern Russia in the last 40 years, assessed its spatial patterns and drivers of change for several periods.

Methods Using Landsat imagery, we mapped the permanent steppe and steppe restoration from 1990 to 2018. Based on regression tree models, we evaluate and explain its dynamics. Results were compared with district-level trends in land-use intensities of cropland.

Results We found 70% of the steppe in 2018 represented permanent steppe and 30% of former cropland dominantly abandoned in the postsocialism (1990–2000). The permanent steppe and steppe restored in the postsocialism (1990–2000) were located far from settlements, on rough terrain and in districts of the Virgin Land Campaign (1954–1963). In recent decades, the patterns of steppe restoration (2000–2018) were mostly determined by unfavourable agroclimatic conditions and distance from grain storage facilities. The restoration pattern reflects regional differences in land-use intensities, e.g., isolated steppe patches mostly appeared in areas of intensive agricultural land-use.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10980-020-01174-7.

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Conclusions Steppe restoration has appeared in areas marginal for agricultural production, with poor natural conditions and little human footprint. Consequently, the permanent steppe became less fragmented and a more continuous steppe landscape resulted. The remaining isolated steppe patches require attention in restoration programs as they are mostly located in areas of intensive agricultural land-use.

Keywords Agricultural land abandonment · Land-use · Land cover · Land-use intensity · Steppe · Remote sensing · Driving forces · Spatial determinants · Eurasia

Introduction

Steppe and savannah biomes are recognized as globally important ecosystems, playing a fundamental role in global biogeochemical cycling, hosting biodiversity and supporting the livelihoods of the global population (Ellis et al. 2010; Fetzel et al. 2017). These biomes are characterized by uneven and low precipitation with frequent droughts, often leading to an agricultural frontier situation where agricultural expansion and contraction (i.e., abandonment) alternate, depending on climatic or socioeconomic conditions (Horion et al. 2016). Steppe and savannah biomes were massively ploughed up during the twentieth century because of their abundant fertile soils and the low costs of agricultural expansion (Levykin et al. 2012; Moon 2013; Kraemer et al. 2015). The ploughing up of the steppes resulted in severe ecological consequences, such as soil degradation, salinization, desertification, loss of soil water holding capacity, and the emission of greenhouse gases (Garcia-Franco et al. 2018). In recent years, however, several studies have shown that the reverse process, namely, agricultural land abandonment, has become an important land-use change process, including in steppe biomes (Alcantara et al. 2013; Kraemer et al. 2015; Estel et al. 2016). Agricultural land abandonment in steppe biomes often results in steppe restoration, and after several decades, a close-to-natural grassland ecosystem can be regained (Kurganova et al. 2015; Brinkert et al. 2016).

One of the global hotspots of agricultural land abandonment is northern Eurasia, where this process was primarily triggered by the collapse of the Soviet Union (Schierhorn et al. 2013). The corresponding reduction of subsidies and the restructuring of the economy led to a precipitous decline in livestock numbers paralleled by a decrease in beef consumption (Rozelle and Swinnen 2004; Schierhorn et al. 2019). In Russia alone, 50 to 80 Million ha of agricultural land (both cropland and grassland) became abandoned from 1990 to 2016 (ROSSTAT 2002, 2010; Uzun et al. 2019; Uzun and Lerman 2017). While some of the abandoned lands were recently brought back into cultivation, most of it remained idle and reverted over time into a forest or secondary steppe landscapes (Potapov et al. 2015; Kraemer et al. 2015).

Agricultural land abandonment has multiple positive and negative effects on the environment and society (van der Zanden et al. 2017). Among the positive outcomes reported are—depending on the specific conditions—impacts on wildlife (Kuemmerle et al. 2011), increase in biodiversity and recreational potential (Navarro and Pereira 2012; Kamp et al. 2018), and the increase in carbon stocks (Kurganova et al. 2015). Negative effects can include an increase in fire risk (Rey Benayas 2007; Dubinin et al. 2011), and a decrease in landscape cultural values and biodiversity (Plieninger et al. 2016).

While agricultural land abandonment primarily affects the boreal and temperate regions of Russia, such transitions are also widespread in the steppe belt (Schierhorn et al. 2013). Estimates suggest that in the Russian forest-steppe and steppe belt from 1990 to 2010, 23 (Smelyansky 2012) to 25 Million ha (Schierhorn et al. 2013) of formerly cultivated cropland became abandoned, resulting in a partial restoration of the steppe landscape.

Previous studies have often been based on official statistics and remote sensing, which made it possible to assess the rate and extent of cropland abandonment

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and steppe restoration (Ioffe et al. 2004; Meyfroidt et al. 2016; Baumann et al. 2020). However, it must be considered that restored steppes can also be used agriculturally for grazing and haymaking, which both have an impact on the structure and composition of the grassland vegetation. Steppe restoration may proceed successfully with a certain degree of grazing (Hankerson et al. 2019), as long as the overall succession pathway towards restored steppe is not hindered (i.e., the activities exceed a site-specific intensity leading towards steppe degradation) (Brinkert et al. 2016).

The changes in the extent and spatial configuration of the steppe in Russia during the nineteenth and twentieth centuries have been significantly influenced by a series of ploughing-up campaigns initiated by the government (Dronin and Bellinger 2005; Prishchepov et al. 2020). As not all of the ploughed-up soils were suitable for cultivation, the campaigns resulted in soil degradation, the precipitous release of the carbon sequestered in the soils, and the decline of steppe habitats, threatening, for example, the endangered Saiga antelope (*Saiga tatarica*) (Bekenov et al. 1998; Stolbovoi 2002; Frühauf and Toralf 2010). Thus, the reverse process, that is, the recovery of the steppes due to agricultural land abandonment since the 1990s, can be seen as a positive land transformation that potentially contributes to steppe compactness, improved soil quality, carbon sequestration and biodiversity recovery (Kamp et al. 2011; Kurganova et al. 2015; Baumann et al. 2020).

Today, a globally increasing demand for agricultural products calls for the intensification of agricultural production in suitable areas (Erb et al. 2013; Grass et al. 2019). Consequently, the steppe belt has, again, received attention as potential cropland (Lambin et al. 2013; Meyfroidt et al. 2016), possibly opening up a new chapter in the story of dynamic agricultural expansion and steppe contraction, thus threatening again the ecologically positive effects hitherto achieved.

Under the premise of newly increasing interest in farming in the Russian steppe, information about the pattern and processes of recent restoration and related driving factors is of great relevance (Baumann et al. 2020). Such information may help to avoid repeating mistakes made in the past and contribute to an optimal balance between the different pressures put on the steppes, such as food production, carbon sequestration and habitat protection.

In addition to increasing the extent of steppe areas, restoration processes may also help to defragment existing steppe patches. Such restoration may positively impact the ecological quality of the restored steppes by linking to species pools of permanent steppe (Knapp et al. 2016) and increasing the function of steppe areas as wildlife corridors (Sluis et al. 2009; Baumann et al. 2020). Thus, understanding the spatial configuration of steppe restoration could help to assess the ecological value of the steppe restoration and identify areas of isolated steppe patches that may be prone to the recultivation but have an important ecological function.

Although there have been several attempts at mapping agricultural land change over the Russian steppe (de Beurs and Ioffe 2014; Bartalev et al. 2016; Brinkert et al. 2016; Dara et al. 2018), none of these studies considers the temporal change in the spatial configuration of restored steppes. Potential reasons for the lack of spatio-temporal studies are low data availability and quality and lack of methodologies for linking the information on steppe land-use and its ecological functioning. Information on the dynamics and configuration of steppe is important to assess the steppe's ecological value and support the framing of future pathways of land-use on steppe landscapes.

In this paper, we aim to tackle these limitations by identifying the spatial patterns, determinants and land-use intensities related to steppe restoration in southern Russia, combining newly available spatial data with statistical information. Taking the Orenburg province, located at the centre of the Eurasian steppe belt, as an example, we evaluated steppe development over several time steps in the last thirty years. In order to better understand the past development of steppes, we considered the differential roles of natural and anthropogenic factors, as well as spatial configuration and land-use intensities on agricultural land.

Materials and methods

Study area

The Orenburg oblast (province), located at the centre of the Eurasian steppe belt (Fig. 1), was established in 1744 and covers 124,000 km^2. It may be considered as a typical steppe region based on environmental conditions and historical land-change trajectories.

The temperature and precipitation in the months of the growing season (April-September) range between 12–17 °C and 120–180 mm, respectively (Karger et al. 2017). There is a gradient of soil quality, with more productive soils in the north-west (Chernozem) and less favourable conditions for farming in the south-eastern (Solonetz) parts of the province.

The agricultural history of the province illustrates the frontier-characteristics of farming in the steppe belt. Already in the eighteenth century, the most productive soils of the forest-steppe region in the north-western parts of Orenburg were converted into cropland (Mishanina 2017), and by the mid-nineteenth century, 6% of the province was cropland, much of which had been ploughed up by the Orenburg Cossack troops (Starikov 1891). The abolition of serfdom in 1861 and the activation of a resettlement movement promoted the moving of peasants from central provinces of the Russian empire to the virgin lands in South Ural, West Siberia and Kazakhstan (Treadgold 1957; Okladnikov 1968; Prishchepov et al. 2020). In Orenburg province, cultivated areas increased by almost 20% from 1868 to 1885 and continued to grow until 1916 (Survey of the Orenburg province in 1885, 1886, 1904, 1905 and All-Russian Agricultural Census of 1916). The beginning of the twentieth century saw a considerable reduction in cultivated areas in the years following World War I and the Civil War. After a recovery, World War II again led to a decrease in cropland, before Stalin proposed his “Great Plan for the Transformation of Nature” aiming at overcoming steppe droughts. The main goals of the plan were to extend the area of crop production, introduce crop rotation on perennial grasses, implement large-scale forest reclamation and field protection reforestation, and construct ponds and water storage facilities (Levykin et al. 2012). In 1954, a new agrarian project started, promoting the reclamation of virgin and fallow lands in the south-east regions of Russia (i.e., Khrushchev’s Virgin

Fig. 1 Location of the study area: Orenburg province (bold black outline). The dashed line indicates the border of the steppe biome (Olson and Dinerstein 2002)

Lands Campaign—*Campaign*). This resulted in the ploughing-up of approximately 20 Million ha of steppe landscape in Russia from 1954 to 1963 (McCauley 1976), triggering massive migration to the steppe regions (Thomas 2015). In the Orenburg province, 1.8 million ha of so-called virgin and fallow land was ploughed up, of which 1.5 million ha were concentrated in districts in the east of the province and along its southern border with Kazakhstan. The peak of the Orenburg steppe cultivation was reached in the 1990s. This was followed by a steep decline in cropland caused by the collapse of the former Soviet Union, further reinforced by heavy droughts in 1996 and 1998. Since then, approximately 100,000 to 150,000 ha of restored steppes have been formed in Orenburg province (Levykin et al. 2012).

Mapping land-use change

To assess the extent of steppe restoration, we produced separate land-cover classifications maps for circa 1990, 2000, 2010 and 2018 and then performed post-classification change detection to produce land-cover-change maps for those periods.

Classification catalogue

The classification catalogue for each period consisted of the classes 'cropland', 'grassland', 'forest' and 'other'. The cropland class represented spring and winter crops, such as spring and winter wheat, sunflower, clean and green fallow as a part of crop rotation. The grassland class represented perennial grasslands used for hay cutting and pastures as well as steppe grasslands without evidence of agricultural land use. The forest class represented coniferous, deciduous and mixed forest stands, riparian vegetation and wind protection tree lines. The other class, included impervious surface, bare soil and water. Land-cover changes were classified by representing the transition from cropland to grassland. We classified those areas that transitioned from cropland to grassland and persisted as a grassland area in the subsequent period of analysis as steppe restoration. Grasslands, which were later recultivated, were not considered as areas of steppe restoration. An exception was the most recent period (2018), where all new grassland areas were classified as steppe restoration (Fig. S1).

Satellite image processing

To produce the land cover maps we construct a classification model based on systematically corrected surface reflectance products from Landsat-4 and 5 Thematic Mapper (TM) for circa 1990, Landsat-5 TM and 7 Enhanced Thematic Plus (ETM+) for circa 2000, Landsat-5 TM for circa 2010, Landsat-8 Operational Land Imager (OLI) and Sentinel-2 MultiSpectral Instrument (MSI) for 2018. We processed satellite imagery for each time step separately. For each period (1990, 2000, 2010, 2018) all available images were acquired during the phenological period from May 1st till November 1st. To enrich cloud-free observations for the 1990 period, we used all available images from 1988 to 1990, for 2000 the period from 1998 to 2001, for 2010 the period from 2009 to 2011 and all available images for 2018. In that way, we also controlled for crop rotation, including clean and green fallow fields (Baumann et al. 2011; Prishchepov et al. 2012a; Kraemer et al. 2015). To construct and validate the classification model we used Google Earth Engine ™ (GEE) online cloud mapping service (Gorelick et al. 2017). For the classification we used Red, Green, Blue, NIR, SWIR 1 and SWIR 2 bands. Prior to the classification we synchronize the waveleng of different satellite sensors and masked clouds and snow with a quality flag product (Zhu and Woodcock 2012). For each epoch, we constructed three bimonthly median composites (May + June "Spring", July + August "Summer", September + October "Fall"). Based on all available satellite imagery from May to October we then calculated for each band seven seasonality metrics, which were helpful in the accurate separation of land-cover classes (Alcantara et al. 2012; Bleyhl et al. 2017): (1) minimum value, (2) maximum value, (3) mean value, (4) median, (5) first quartile value, (6) third quartile value, (7) standard deviation. Three median composites and seven phenological metrics for each band were combined into image composite (band stack), which was used later for the classification. In total, for each period we constructed an image with 60 band in 30-m spatial resolution.

Classification procedure

The constructed band-stack image of land-cover for each epoch was classified with a random forest classifier. Random forest is an assemble machinelearning classifier, which makes the splits of the desired classes based on training data (Gislason et al. 2006; Belgiu and Drăguţ 2016). Random forest is a non-parametric classifier and handles well non-normal distribution of reflectance. For splitting into LC classes it uses multiple decision trees instead of one single tree, such as CART and overcome potential model overfit (Belgiu and Drăguţ 2016). The final decision about thematic classes' assignment is made based on the majority vote among the generated trees. Several parameters can be tuned to achieve higher classification accuracy with random forest, namely the number of generated trees, utilized variables per split, minimum leaf population and bag fraction (proportion of pixels utilized in building up the tree). In general, more trees, more variables per split, smaller leaf population and larger bag fraction results in higher classification accuracy (Millard and Richardson 2015; Belgiu and Drăguţ 2016). Based on the preliminary tests, we parametrised the model with 500 trees, 16 variables per split, minimum leaf population equalling to 10, out of a bag fraction of 100% (all training pixels were used to construct the trees).

Training data

To prepare training data for supervised random forest classification, we used several sources of information. For the period 2018, approximately 30% of the Orenburg province was covered with high-resolution imagery available via GEE mapping service. We used this dataset and complemented it with field observations collected during the 2018 field campaign. We also visually checked the high-resolution imagery, field data and multiseasonal Landsat-8 OLI and Sentinel-2 MSI imagery and enriched training data with additional points in areas where very high-resolution imagery and field data were not available. For the periods 2000 and 2010, similarly to 2018, we relied on very high-resolution imagery available via GEE and Landsat-5 TM, 7 ETM + multi-seasonal imagery. For the epoch 1990, we reconstructed land cover and assigned the classes based on multi-seasonal Landsat 4, 5TM imagery and gained prior expertise on the relationship of land cover and reflectance for the periods 2000, 2010, 2018 and previous studies in a similar environment (Baumann et al. 2011, 2020; Prishchepov et al. 2012a; Kraemer et al. 2015; Löw et al. 2018). In total, we generated and used approximately 6500 training points for each period—approximately 2,000 cropland points, 3,000 grassland points, 1,000 for forest and 500 for the other class (as classified in 2018). Such proportions of points reflected the thematic classes' approximate distribution based on available land-cover products for the study area (Rogova and Skvortsov 2016; Bartalev et al. 2016).

Validation data and accuracy assessment

To assess the accuracy of classifications for 1990, 2000, 2010, 2018, we prepared validation data based on two-stage stratified random sampling (Edwards et al. 1998; Prishchepov et al. 2012b; Kraemer et al. 2015). We accounted for the potential spatial autocorrelation by using the minimum distance between the points of 500 m. For the epoch 2018, some of the generated points were visited in the field and land-cover classes were assigned. For non-accesible points, the land-cover classes were assigned based on spectral similarity (Landsat, Sentinel-2 OLI, very high-resolution imagery available via Google Earth$^{\text{TM}}$ mapping service). We utilized the same points for each period and validated classifications for the periods 1990, 2000, 2010, 2018. Such an approach was used previously and was covered in the published studies (Baumann et al. 2011; Prishchepov et al. 2012b; Kraemer et al. 2015).

The accuracy of produced land-cover maps was assessed using contingency tables and user's, producer's and overall accuracy measures (Congalton and Green 2008). Before performing the accuracy assessment, all land cover maps were passed through a majority filter to reduce the salt-and-pepper effect that resulted from the classification of the single image. Based on testing different thresholds, we selected 0.18 km^2 (200 of 30-m pixels) as an input for a majority filter that reclassified areas smaller than this threshold based on the neighbourhood class that shared the major proportion of the border with these areas. This majority filter influenced the correctly classified agricultural fields only a little as the average cropland field size in our study area was found to be 1 km2. As a result of the postprocessing, the agricultural parcels became more continuous without containing, e.g., single grassland pixels within the cropland. Using 1663 validation points, we found, the overall accuracy rates in 2018 reached 0.93 with the highest accuracy of the cropland mapping (producer's and user's accuracy 0.95 and 0.94, respectively) and lowest rates on the forested areas when compared to ground-true data (producer's and user's accuracy 0.99 and 0.77, respectively) (Table S1,S2,S3).

The evaluation of land-change pattern

The fragmentation of steppes severely reduces its ecological quality. Therefore, defragmentation is one of the main aims of steppe restoration programs. We evaluated the spatial configuration of the steppes in 2018 with morphological spatial pattern analysis (MSPA) (Soille and Vogt 2009). In our case, the MSPA framework assessed the geometry and connectivity of steppe areas. The classification describes the shape, connectivity and spatial arrangement of steppe patches based on a set of operations (e.g., intersection complementation and translation) controlled by the connectivity rule of neighbourhood pixel and a window-size over which the operations are performed (Vogt and Riitters 2017; Riitters et al. 2007).

The MSPA analysis was done with GUIDOS software (Vogt and Riitters 2017), which can distinguish between compact patches of steppe (including areas of Core, Perforation and Edge in the standard GUIDOS classification), isolated patches (including areas identified as Islet, Loop, Bridge and Branch in the standard GUIDOS classification). For the MSPA analysis we used the most recent map of steppe areas in 2018. Subsequently, we clipped the map with extent of permanent steppe and areas that contributed to the steppe restoration within the analysed periods of land-cover change. This spatial analysis resulted in 4 maps that identified the contribution of permanents steppe or restored areas to the spatial configuration of the most recent steppe patches (Fig. S2).

The edge-width of a single steppe patch was set to 90 m (equals to three Landsat pixels) to distinguish the patches with core areas, narrow and isolated patches using the GUIDOS morphological classification (i.e., areas below a 90-m edge-width were considered as isolated elements). When using the 90-m edge-width distance, theoretically no internal elements are defined within the patches with a minimum area size, which is often taken into account when quantifying the landscape structure (3 ha) (Pe'er et al. 2014).

Spatial determinants of steppe restoration

To analyse the drivers of steppe restoration, we selected spatially-explicit variables reflecting the land's suitability for agriculture and distance to infrastructure and settlements, assuming that remote areas with poor biophysical conditions for agriculture were prone to abandonment (Prishchepov et al. 2013; van Vliet et al. 2015; Pazúr et al. 2020). All data were calculated for a raster cell size of 30 m. Assuming rugged terrain to be less suitable for farming and, therefore, prone to cropland abandonment, we calculated the roughness of terrain from the ALOS World 3D digital elevation model (Takaku et al. 2014). As farming is further challenged by drought stress, we used Selyaninov's hydrothermal coefficient (HTC) long-term average (1979–2013) (Karger et al. 2017) as an aridity index, which is the ratio of total precipitation to average daily air temperature during the growing season (days with an average temperature > 5 °C) (Selyaninov 1928; Kraemer et al. 2015). In areas with insufficient humidity, the aridity index is < 1 (Voropay et al. 2011). Furthermore, soil quality was assumed to be relevant for the decision to abandon the crop production. Therefore, a georeferenced and rasterized soil map (initial scale 1:600,000) was classified into three major categories of farming suitability. The ranking was made based on the content of organic components, which officially defines the suitability of soils for crop production and expected yields in Orenburg Province (Blokhin 1997). For instance, Chernozem soils with high organic matter content represented rank #1, Kastanosem soils with medium organic matter content—ranked #2, and Solonetz soils with the lowest organic matter content and the least suitable for crop production were rank #3. Such ranking was in line with a previous study in neighboring northern Kazakhstan (Kraemer et al. 2015).

In line with earlier studies on agricultural land abandonment in temperate Russia (Prishchepov et al. 2013) and Siberia (Nguyen et al. 2018), we assumed that the distance to attractors of economic activities plays a significant role in explaining the spatial patterns of spontaneous steppe restoration. For this reason, we included population density, distance to settlements, distance to paved roads and distance to silos (large grain storage facilities) as explanatory variables. A smoothed, continuous estimate of population density was calculated by kernel density function (using Gaussian kernel), considering population numbers for 1989, 2002 and 2010 reported at settlement-level and the settlement footprint. Kernel density is particularly useful in such a combination of the data as it maps the clusters and hotspots of the distribution and provides much lower densities for less frequent observations (Cai et al. 2013). The settlement footprint was mapped by digitizing the 1:100,000 Soviet declassified maps from circa 1980 (VTU 1989) covering approximately the same time period as the district-level statistics. The mapped settlement footprint was also used to determine the distance to settlements based on Euclidian distance. We digitized the locations of grain silos, which were constructed mainly during the Soviet era along major railway lines. As silos still serve as nodes to store grain before transportation, we assume them to positively influence the spatial allocation of cropland. To allocate the silos we used the yellow pages (telephone books) to identify the companies that provide the services on grain storage and high-resolution images from GoogleEarth to identify their spatial coordinates.

Districts (in Russia administrative level-3 “rayons”, similar to EU NUTS-3 administrative districts), which were officially included in Khrushchev’s Virgin Lands Campaign (1954–1963, further called “the Campaign”—see “Methods” section), were considered to be especially prone to abandonment since croplands primarily expanded at the expense of remaining environmentally and socially less favourable agricultural frontiers during the Campaign (Kraemer et al. 2015). The indexed campaign districts were included as a dummy variable in the modelling.

Modelling steppe restoration

We modelled the patterns of permanent and restored steppe and their relationship with spatial determinants. We developed one model for the entire Orenburg province and another two stratified models that split the mapped areas by distinguishing either compact or isolated patches. The stratification was determined by the MSPA classification (described in the previous section). For each model run, we derived 2000 random samples (points) of both presence and absence of the phenomena (allocation of permanent steppe or restoration). Boosted regression trees (BRTs), also known as stochastic gradient boosting (Friedman 2002), were used to develop the models. The BRT-approach has been applied in earlier studies on species distribution modelling (Elith and Leathwick 2014) and land-change modelling (Müller et al. 2013; Smaliychuk et al. 2016; Levers et al. 2018). The advantages of BRT modelling compared to conventional statistical methods, such as ordinary least squares and logistic regressions, is that it allows capturing the non-linear relationship between the dependent and independent variables, does not require a normal distribution assumption and is robust against the multicollinearity of variables (Elith et al. 2008). The fitting and combining a large number of decision trees that stand behind the BRT algorithm also allows identifying the dominant pattern and complex interactions between variables. With the capability to explore the variable dependences, such robustness is particularly important for studying land change outcomes as it allows to explain the strength and direction of variable influence (e.g., on which distances from settlement was the restoration most common). The BRTs model outputs sensitively depend on the initial set of the number of trees and interaction depth parameters. We, therefore, performed a cross-validation run of all possible combinations of these two parameters in the range between 100–2,000 (iterative increase by 200) and 1–9 (iterative increase by 1), respectively, and compared their resulting accuracies. We then selected those models (full and stratified) that resulted in the highest cross-validation accuracies (Zeileis and Grothendieck 2005). The accuracy of cross-validation was assessed with an independent sample of 400 points (20% of the original sample size) using AUC (Area Under the Curve), a goodness of fit measure that has been found to be appropriate for the evaluation of land-use model accuracies (Braimoh and Onishi 2007) (Table 1).

Assessment of agricultural land-use intensity change

We hypothesize that areas with lower land-use intensity will result in a higher likelihood of abandonment, i.e. restored steppes, and less fragmented steppes. To test this hypothesis we used time-series district-level socioeconomic data for 35 Orenburg districts available from 1995 to 2018 (Table S4). As spatial proxies of land-use intensity changes from 1995 to 2018, we used the district-level data on cumulative change in

Table 1 Spatial determinants of permanent steppe and steppe restoration

Determinant	Data type	Time period	Initial format	Source
Biophysical				
Roughness (focal 150 m)	Digital elevation model	2017	Raster; 30-m resolution	ALOS World 3D (Takaku et al. 2014)
Temperature	Average temperature; April–October	1988–2010	Raster; 1 km	CHELSA climate data (Karger et al. 2017)
Rainfall	Average rainfall April–October	1988–2010	Raster; 1 km	CHELSA climate data (Karger et al. 2017)
Socioeconomic and accessibility				
Population density	Gaussian kernel density raster	1989, 2002, 2010	Vector of settlements and district level statistics	Vectorized boundaries of settlements from Soviet declassified 1:100,000 topographic maps circa 1980s (VTU, 1989). Settlement-level statistics from 1989, 2002 and 2010 population censuses (ROSSTAT 2002, 2010)
Distance to settlement	Euclidian distance raster	1989, 2002, 2010	Vector of settlements footprint	Vectorized boundaries of settlements from Soviet declassified 1:100,000 topographic maps circa 1980s (VTU 1989)
Distance to roads and railroads	Euclidian distance raster	1980s	Line vector	Vectorized paved roads and railroads from Soviet declassified 1:500,000 topographic maps circa 1980s
Distance to silos	Euclidian distance raster	2018	Point vector	Vectorized silos from high-resolution satellite imagery circa 2000–2018 available from Google Earth with additional aid of Yellow pages telephone books for the Orenburg province circa 2018

[a] All data were converted to a 30-m resolution raster stack

sown areas, grain and sunflower yields, number of goat and sheep and proportion of isolated steppe among the areas of restored steppe over the same period. The district-level statistics was evaluated in pairs by using correlation coefficient which allowed us to statistically assess the relationship on district-level land-use intensity and compactness of the restored steppe. The partial composition of land-use change, in this case, was defined as the ratio of the total proportion of isolated patches (defined in MSPA analysis) to the total area of restored steppe within the period 1990–2018 (1990–2000–2018). The outputs were analysed by cross-correlation, which allowed to identify the potential correlations of each pair of selected variables and omitted the effect of spatial autocorrelation, which may be introduced through the use of time-series in the district-level panel regressions or multivariate regression models. For a better overview and description of the development of agriculture in Orenburg from 1995 to 2018, we additionally interpreted the dynamics in cattle statistics and the number of agricultural organizations as proxies of land-use intensity.

Results

The rates and spatial patterns of steppe restoration

By 2018, approximately 57% (more than 7.1 million ha) of the Orenburg province was covered by steppe (managed and unmanaged grasslands), of which about

70% were permanent steppes (i.e., have persisted since 1990), and 30% represented restored steppes as a result of cropland abandonment sind 1990 (Figs. 2, 3, S1). The rate of steppe restoration due to abandonment was not constant over time. With reference to the 30% restored by 2018, the first period from 1990 to 2000 (i.e., post-socialism) contributed with almost 12% mostly to the restoration occured predominantly in the former Campaign districts. Another 9% of the steppe areas were restored similarly in both time periods of 2000–2010 and 2010–2018 (Fig. 3). The restored steppe patches contributed to the defragmentation of the compact patches in Orenburg's South along the border with Kazakhstan and the development of isolated steppe patches mostly in Orenburg's north (Fig. S2).

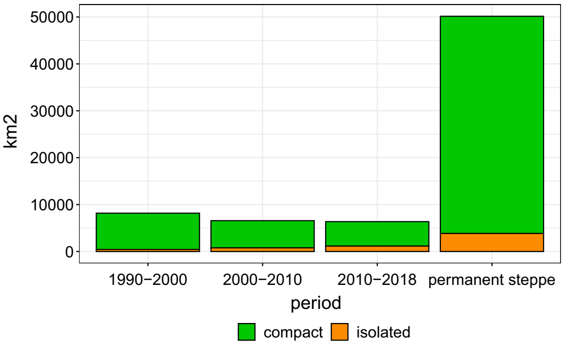

Fig. 3 Area extent of restored (from 1990 to 2018) and permanent steppe

Modelling steppe restoration

The BRT models which aimed at explaining the spatial pattern of steppe restoration, indicated that the selected variables explain a significant part of the spatial variation, but large differences can be seen for the different periods. The models' goodness of fit was found to be relatively high. The AUC values ranged between 0.72–0.77 and 0.61–0.80 for the overall model and the model stratified according to the steppe configuration, respectively.

Permanent steppe persisted mostly in the Campaign districts, with rugged terrain conditions, in areas with poor soils and low aridity index values (Fig. 4). From the socioeconomic perspective, distance to settlements played an important role as permanent steppe was found to be more likely located far from settlements. The spatial compactness of the permanent steppe was significantly influenced by spatial determinants that showed different magnitude and strength of influence

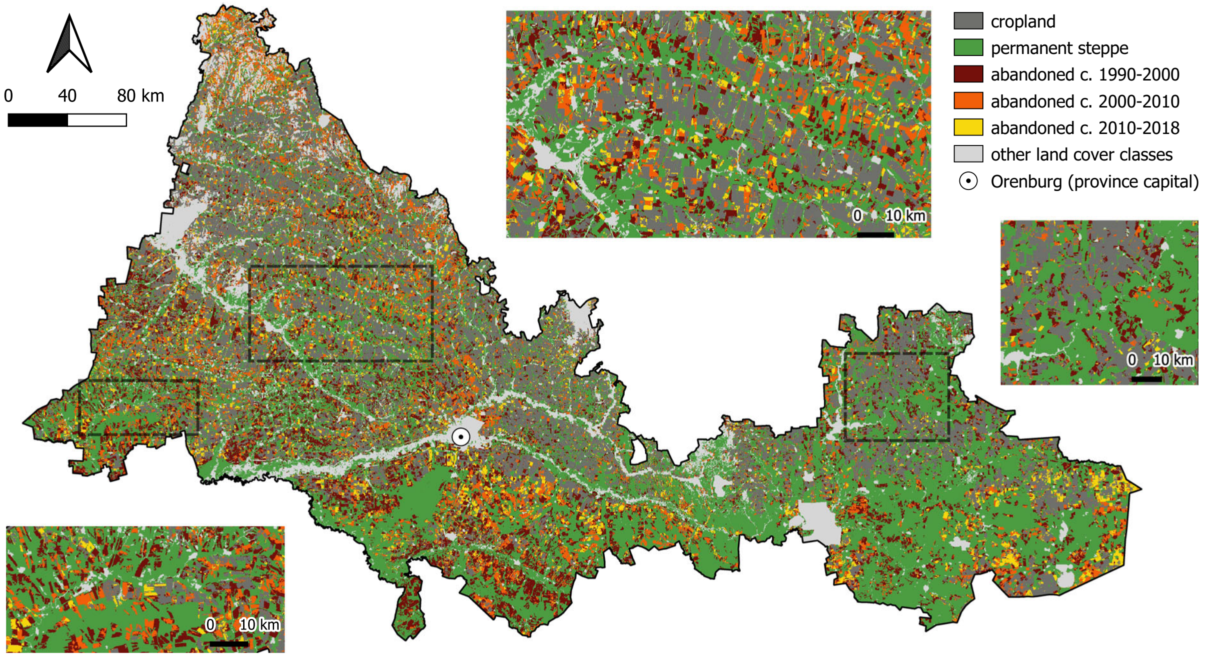

Fig. 2 Patterns of land-cover change (permanent) steppe and restored steppe in 1990, 2000, 2010, 2018s mapped with Landsat and Sentinel-2 imagery. Note that the restored steppe does not contain abandoned cropland, which was recultivated

among the compact patches as compared to the isolated patches of steppe. The influence of the biophysical factors (HTC, soil quality) explaining the location of permanent steppe was similar to those factors that explained the distribution of steppes restored during postsocialism (1990–2000). The influence of socioeconomic factors was larger on the restored areas as compared to the permanent steppe. In the periods of 1990–2000 and 2000–2010, restoration occurred more frequently far from the roads and settlement areas. An exception was the fragmented patches of restored steppe that recorded opposite impacts of the proximity of settlement and roads on the location of restored patches. The restoration from 2000 to 2010 was also significantly associated with the proximity of grain storage facilities (distance to the sillage), but was less likely influenced by the biophysical conditions (e.g., soil quality) as in the other periods. The location of recent restoration from 2010 to 2018 was largely related to natural conditions (soils, HPC) but contrary to the previous period the restoration occurred most likely close to the paved road network.

Assessing land-use intensities

Exploring district-level annual statistics from 1995 to 2018 showed a clear change in agricultural land use within the Orenburg province (Fig. 5). Comparing agricultural production in 2018 and 1995 reveals a decrease in sown areas, livestock numbers and the number of agricultural organisations. For instance, the number of sheep and goats decreased by 60% from 1995 to 2018. Different trends through were observed for the number of cattle, which increased from 1995 to 2005 but decreased later, reaching out only 72% of the 1995 level by 2018. For the early 2000s, we also observed a continuous decrease in the overall sown area within districts, decreasing to 48% of the 1995 level by 2018. In contrast, yields of grain and sunflowers were increasing sharply despite high variation in the average annual values (to some extent caused by reporting bias), i.e., by 2014 twofold for grain and threefold for sunflower compared to the initial levels in 1995.

Combining the spatial configuration of the restored steppe with the selected statistical indicators (sown

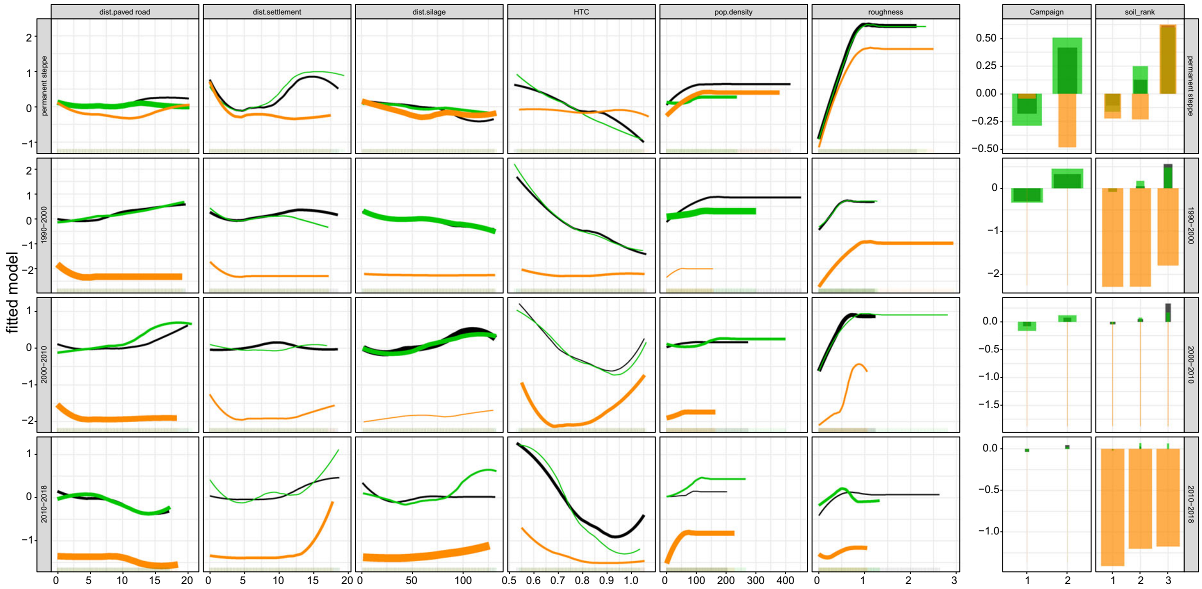

Fig. 4 An overview of factors explaining permanent and restored steppe location in different periods. Each plot represents the modelled responses in the measured range of values of a particular variable (x-axis) and its fitted influence on the overall model (y-axis). Lines indicate the modelled dependences of either the overall model (black), or the submodels model of compact (green) and isolated patches (orange) on particular variables (columns in the plot). Line thickness in each case illustrates the relative importance of particular variables within the model. The figure plots represent the dependences of continuous variables (columns 1–6, *on left*), a binary variable (presence in the Campaign district—column 7, *on right*) and an ordinal variable (ranked soil quality—column 8, *on right*)

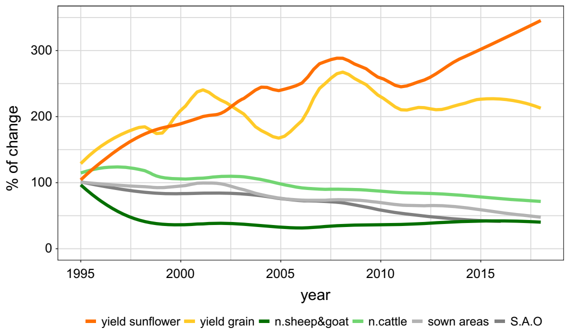

Fig. 5 Relative change of selected indicators of agricultural productivity in Orenburg province (average district values per year) compared to the year 1995. S.O.C stands for the share of agricultural organisations on the total number of companies in the districts

area, grain yield and sunflower yield) via cumulative change rates from 1995 to 2018, revealed that the proportion of isolated restored steppe patches on the overall size of the restored steppe highly correlated with the cumulative rates of grain and sunflower yields (R = 0.75,0.70, respectively) (Fig. 6). A positive correlation was also found between the rates of isolated areas and the proportion of sown areas. An opposite, strong negative correlation was found between the increase of isolated areas and the growth of number of sheep and goat rates in Orenburg's districts. The strenght and direction of the relationship, implies that the restoration patterns differed among the districts in Orenburg. The restoration developed in a fragmented habitat in the districts intensively used for crop production and steppe became more continuous in districts where the grasslands were grazed.

Discussion

Steppe restoration dynamics

Our study reveals that agricultural land abandonment in the Orenburg province, an area that is highly representative for the Russian steppe belt, resulted in an increase in steppe landscape from 40% of the province's total area in 1990 to 57% in 2018. As documented by classification of multi-seasonal Landsat imagery, steppe areas have been restored, as ecologically valuable ecosystems, due to agricultural land abandonment over the past 35 years. As several

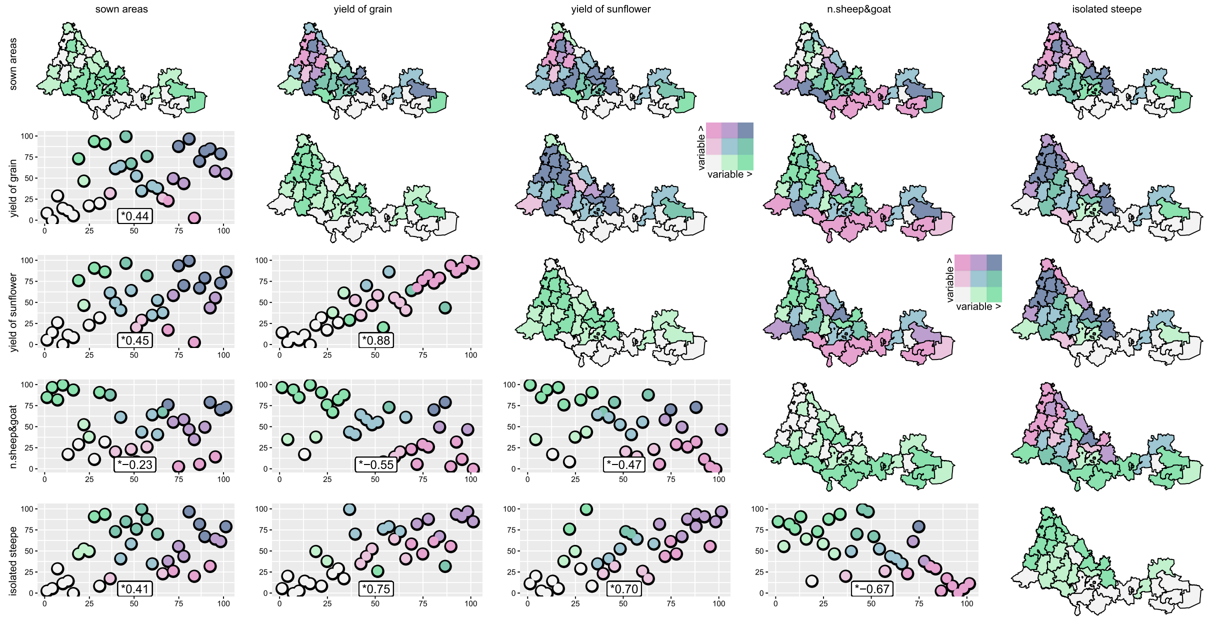

Fig. 6 Rates of change of selected indicators of agricultural productivity in Orenburg province (cumulative change values for the period 1995–2018) and their pair-wise mutual relationship expressed by scatterplot (non-spatial agreement) and bivariate maps (spatial agreement)). The comparison also includes a spatial configuration ratio that represents the change of proportion of isolated patches in the total restored steppe area. The pair-wise relationship expresses the correlation coefficient (indicated with "*" and value in the rectangle) and colors on the bivariate map

studies showed, it may take at least 20 years for abandoned croplands to develop into ecologically valuable restored steppes that display ecosystem functions that are typical for pristine steppes, such as the accumulation of carbon stocks and the composition of typical plant and animal species (Kurganova et al. 2015; Wertebach et al. 2017). Our work went beyond documenting agricultural land abandonment patterns in the steppe belt (Klein et al. 2012; Kraemer et al. 2015; Dara et al. 2018; Nguyen et al. 2018). For instance, we revealed the differences in rates of abandonment in different periods and illustrated the configurational consequences of agricultural abandonment with high relevance for steppe landscape restoration.

Even though abandonment rates and patterns vary across space and time, the overall pattern of the steppe restoration was more compact and defragmented, supplemented by rather isolated steppe patches ("branches") surrounded by agricultural land in predominantly agricultural landscapes. The more compact steppe landscapes were located in the south and south-west of Orenburg Province, which are areas with high aridity and low soil quality. Considering the marginal agro-environmental conditions, it is not surprising that these areas also coincided with districts that were once subject to the Virgin Lands Campaign. Within these districts, the Soviet Virgin Lands Campaign entailed the ploughing of virgin steppe and the establishment of new farms in the remaining idle agricultural frontier (AVLC 2004). Once socioeconomic and political conditions changed after the collapse of the Soviet Union, these marginal areas, which were subsidized during the Soviet era, became abandoned. Similar abandonment patterns have also been reported in former Campaign districts in the Kostanay Province in Kazakhstan (Kraemer et al. 2015). In the Kostanay Province (Kazakhstan), however, the abandonment on Campaign districts was more pronounced than in Orenburg, which likely relates to the different institutional conditions and accessibility of the market. The markable differences between areas being in neighbourhood and share similar climate conditions but belong to different countries underlaying the necessity of conducting land-use change assessment studies in different parts of steppes. In other parts of the Orenburg province, the steppe landscape is dominated by smaller, compact forms and isolated patches of permanent and restored steppes. This pattern appears close to the border areas between cropland and non-agricultural zones. The ecological quality of such isolated and fragmented patches lies in their role as elements in the connectivity network being used for different plant and bird species in areas otherwise dominated by intensive agriculture and other land cover types, including oil and gas production (Mjachina et al. 2018).

Explaining the spatial pattern of steppe restoration

In general, steppe has persisted or has been restored in areas further away from infrastructure (roads, settlements), in areas with complex terrain and areas with harsh climatic conditions. This is in line with other studies that showed that human drivers such as a shrinking and ageing population and the great distances between markets and settlements are highly relevant (Rey Benayas 2007; van Vliet et al. 2015; Sheludkov et al. 2020). The positive relationship between crop abandonment and remoteness from settlements and infrastructure has also been found across Russia, Ukraine and Kazakhstan (Meyfroidt et al. 2016), as well as in the neighbouring states of Western Siberia (Nguyen et al. 2018). This relationship emphasizes the importance of profit maximization in the allocation of agricultural production determined by the land quality and transportation costs (Prishchepov et al. 2013; Nguyen et al. 2018). Yet, we should bear in mind that the interaction between human and natural factors is also shown by the lower population densities often found in areas less suitable for farming. However, the influences of both natural and human factors were found to vary over time. Overlaps were found between the allocation of permanent steppe and restoration in the postsocialist period, as well as between the period of late socialism and the beginning of the twentieth century. Permanent steppe and restored patches during postsocialism were mostly found in the Campaign districts and in areas of high marginality (natural and socioeconomic) as consequences of poor soil quality, raw terrain and greater distances from settlements (all characteristics of poor suitability for crop production). Areas of permanent steppe and steppes that were restored during postsocialism mostly contributed to or developed new compact steppe patches that make them ecologically valuable. The explanation of steppe restoration by spatial marginality was not valid for isolated restored areas, as these cases were often located close to settlements, contradicting utility maximisation behaviour. Considering the beginning of twenty-first century as the start of recovery of Russian agriculture (since 2002–2003 Kudrin and Gurvich 2015; Nguyen et al. 2018)), may explain the strong likelihood of increase of restoration within the period of 2000–2010, accentuated with an increasing distance to silos which are considered as the nodes of storage and transportation of agricultural production. A poor or even opposite relationship with the other factors determining the relationship with socioeconomic marginality of the restored areas from 2000 to 2018 suggests that the restoration pattern in these periods was largely driven by economy-oriented crop production, which is more dependent on natural conditions than on socio-economic constraints. For example, the most recent steppe restoration pattern related to aridity and the sharp drop of likelihood of restoration on areas with less arid climate conditions (HTC index equalling or higher 0.9). Such relationship implies that restoration of the steppe due to the abandonment of crop production occurred in areas that experience insufficient humidity and high drought stress. Considering the importance of climate on the restoration pattern over the studied period (also including the recovery of Russian agriculture) such climatically challenging zones could, in general, be designated as priority areas for steppe restoration given their unsuitable conditions for crop production. This might even become more pressing in the future, as progressing aridity due to climate change (Roshydromet 2014) will become one of the major drivers of agricultural abandonment, an effect already observed in the Russian steppe belt (Ray et al. 2019). The future adaptation of farmers to climate change manifestations, such as extreme drought events, is even foreseen for the whole of southern Russia (de Beurs and Ioffe 2014; Groisman et al. 2017).

Besides the patterns and determinants of steppe restoration, we also evaluated the annual dynamics of agricultural management within the districts of the Orenburg province. While remote sensing data allowed for a detailed analysis of land cover, official district-level statistics facilitated the assessment of land-use intensity, including yields, livestock counts and the number of farms. Although we could not fully correct for the effects of the economy and legislation transformations on the quality of official statistics, we believe that the results obtained reveal plausible dynamics of the agricultural sector over the period from 1995 to 2018.

As revealed by the maps capturing cumulative changes in district-level statistics, sown areas ratios increased mostly in the central and eastern part of Orenburg Province at the expense of abandoned lands with only a slight increase of grain and sunflower yields, while yields grew more in the north without much increase in sown areas. Such a different pattern indicates that in areas of low yield, farmers likely extend the size of sown areas instead of intensifying production. In contrast, some agricultural areas with increased yields especially in the most productive regions showed decrease in cultivated area size, which is a pattern also found in other parts of European Russia (Prishchepov et al. 2013; Meyfroidt et al. 2016). Such an increase in the intensity is in line with the Boserupian theory of innovation and intensification (intensification as result of land scarcity) (Erb et al. 2014). Schierhorn et al. (2019) indicates that yield gaps exist in the area, therefore, there is potential for future intensification to free up more land for steppe restoration. Alternatively, areas can be used less intensively, such as for haymaking or grazing of livestock, which may also have a positive environmental impact. Throughout the district, we observed such tendencies mostly in the southern part of Orenburg Province with an increasing numbers of sheep and goats. These areas do not exhibited the increase of sown areas in the last 35 years, which is likely a sign of farmers strategies of avoiding farming in the areas with low yields. In the context of grazing, however, it is important to consider alternating of grazing and haymaking to avoid the risk of decline in soil organic carbon stock, which goes along with intensive grazing on steppes (Cremone et al. 2005; Schönbach et al. 2012; Ren et al. 2015; Garcia-Franco et al. 2018). Overall effects on greenhouse gas emissions, including methane, must be carefully considered when determining best practices for grazing on steppe landscapes (Zhang et al. 2015).

The findings of our study have implications for ecological quality assessment in the area. Overall, a high proportion of isolated patches was found in areas of high-intensity agricultural land use (as indicated by yield statistics). It implies that in intensively used areas, the steppe was restored only to a mosaic of isolated patches which do not allow for the essential

Table 2 Summary of district-level statistics (Online Appendix A) used to identify land-use intensity

Data type		Mean	Min	Max	Standard deviation
Sown area*	1000 × hectares	96.2	21.8	232.6	42.6
Grain yield*	Centners per hectare	9.3	0.2	21.6	4.0
Sunflower yield*	Centners per hectare	6.5	0.1	18.7	3.0
Sheep and goats	1000s	9.2	0.7	69.7	8.2
Cattle	1000s	21.6	4.4	51.2	9.3
Number of organisations active in agriculture (*includes both corporate and family farms but excludes households*)		183.3	26	672	111.67

*Statistics used to compare with the spatial configuration of steppe restoration patches

migration and re-population of flora and fauna species, thus bearing the risk of local extinction of isolated populations (Sluis et al. 2009). Considering the connectivity (spatial configuration) policies that address abandonment and restoration, programs may considerably increase the steppe network's ecological quality in those regions. Keeping in mind the ongoing recultivation of abandoned lands and restored steppes due to rebounding agriculture in Russia since 2000 (Estel et al. 2015; Schierhorn et al. 2019), we consider this to be a crucial moment for the development of environmentally sound agriculture and alternative land use in restored steppe landscapes (Table 2).

Conclusions

Our study has shown that permanent and restored steppe (as a consequence of agricultural abandonment) have appeared across the whole Orenburg province. Restoration dynamics have varied across different periods in terms of extent and factors that influenced the restoration process. The allocation of the permanent steppe was found to be determined by similar factors to those involved in the process of steppe restoration during postsocialism. This was found mostly in the Campaign districts and on areas of high marginality (natural and socioeconomic), indicating that restoration in this period appeared in unsuitable areas for crop production. Similarities were also found in the pattern of steppe restoration within the most recent (economically driven) periods when the restoration patterns negatively correlated with the distance to crop storage, transportation facilities and natural conditions.

Over time, the restored pattern defragmented the patches of permanent steppe or formed isolated patches of steppe surrounded by cropland production areas. Such a spatial configuration was determined by agricultural land-use intensities dynamics, as districts with increasing intensities overlap with districts with high proportions of isolated forms of the restored steppe. This indicates that the restored steppe in intensive cropland production areas may have different functions, as restored steppe on areas of lower cropland intensities such as those used for extensive grazing. Thus, the spatial pattern of restoration and its dynamics needs to be reflected in future restoration programs.

Acknowledgements Open Access funding provided by WSL - Swiss Federal Institute for Forest, Snow and Landscape Research. We acknowledge funding of EU FP7 ERA.Net Russia Plus (Grant Number: 449 CLIMASTEPPE), funding for the Scientific Research of the OFRC UrB RAS - Institute of Steppe UrB RAS No. AAAA-A19-119080190044-5), DFF-Danish ERC Support Program (Grant Numbers: 116491, 9127-00001B). We also thank Alexander Tsypin for statistical data preparation and Dr. Alexander Chibilyev for the project's overall support and advice. We thank Curtis Gautschi for professional language editing and the two anonymous reviewers whose comments considerably improved the manuscript.

Author contributions Conceptualization: [RP, AVP, PHV, MB], Methodology: [RP, AVP, PHV, MB], Formal analysis and investigation: [RP, AVP, KM, PHV, MB], Writing—original draft preparation: [RP, AVP, KM, SL, MB]; Writing—review and editing: [RP, AVP, PHV, EVP, MB], Data resources: [AVP, KM, EVP, GK, IY, RA, NR].

Funding Open Access funding provided by WSL - Swiss Federal Institute for Forest, Snow and Landscape Research.

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