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IOP Publishing   *Environ. Res. Lett.* **10** (2015) 054012   doi:10.1088/1748-9326/10/5/054012

Environmental Research Letters

OPEN ACCESS

RECEIVED
11 August 2014

REVISED
30 March 2015

ACCEPTED FOR PUBLICATION
16 April 2015

PUBLISHED
14 May 2015

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LETTER

Long-term agricultural land-cover change and potential for cropland expansion in the former Virgin Lands area of Kazakhstan

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Keywords: agricultural abandonment, re-cultivation, Kazakhstan, Soviet Union, remote sensing, change detection, Virgin Lands Campaign

Supplementary material for this article is available online

Abstract

During the Soviet Virgin Lands Campaign, approximately 23 million hectares (Mha) of Eurasian steppe grassland were converted into cropland in Northern Kazakhstan from 1954 to 1963. As a result Kazakhstan became an important breadbasket of the former Soviet Union. However, the collapse of the Soviet Union in 1991 triggered widespread agricultural abandonment, and much cropland reverted to grasslands. Our goal in this study was to reconstruct and analyze agricultural land-cover change since the eve of the Virgin Lands Campaign, from 1953 to 2010 in Kostanay Province, a region that is representative of Northern Kazakhstan. Further, we assessed the potential of currently idle cropland for re-cultivation. We reconstructed the cropland extent before and after the Virgin Lands Campaign using archival maps, and we mapped the agricultural land cover in the late Soviet and post-Soviet period using multi-seasonal Landsat TM/ETM+ images from circa 1990, 2000 and 2010. Cropland extent peaked at approximately 3.1 Mha in our study area in 1990, 38% of which had been converted from grasslands from 1954 to 1961. After the collapse of the Soviet Union, 45% of the Soviet cropland was abandoned and had reverted to grassland by 2000. After 2000, cropland contraction and re-cultivation were balanced. Using spatial logistic regressions we found that cropland expansion during the Virgin Lands Campaign was significantly associated with favorable agro-environmental conditions. In contrast, cropland expansion after the Campaign until 1990, as well as cropland contraction after 1990, occurred mainly in areas that were less favorable for agriculture. Cropland re-cultivation after 2000 was occurring on lands with relatively favorable agro-environmental conditions in comparison to remaining idle croplands, albeit with much lower agro-environmental endowment compared to stable croplands from 1990 to 2010. In sum, we found that cropland production potentials of the currently uncultivated areas are much lower than commonly believed, and further cropland expansion is only possible at the expense of marginal lands. Our results suggest if increasing production is a goal, improving crop yields in currently cultivated lands should be a focus, whereas extensive livestock grazing as well as the conservation of non-provisioning ecosystem services and biodiversity should be priority on more marginal lands.

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1. Introduction

Global agricultural production will need to supply substantially more feed, food, and bioenergy in the coming decades, but crop yields are stagnating, soil degradation is widespread (Godfray *et al* 2010, FAO 2011, Foley *et al* 2011), and available fertile lands for further cropland expansion are becoming increasingly scarce (Ramankutty *et al* 2002, Fischer *et al* 2011, Lambin and Meyfroidt 2011). Past agricultural expansion has been particularly widespread in the steppe and savanna biomes, due to abundant fertile soils and the low costs of land conversion (Ramankutty *et al* 2006, Ellis *et al* 2010, Müller *et al* 2015). Approximately 400 million hectares (Mha) of these biomes were converted in the 20th century alone (Ramankutty and Foley 1999, Goldewijk 2001).

The former Soviet Union is a prime example of a region with rapid agricultural expansion into the steppes. After the Second World War, due to an acute grain supply shortage, the general secretary of the Communist party of the USSR, Nikita Khrushchev, initiated a unique cropland expansion project called the *Virgin Lands Campaign* (McCauley 1976, Wein 1980). From 1954 to 1963, approximately 45 Mha of the Eurasian steppe grasslands, an area nearly the size of Spain, were converted into cropland, roughly half each in the Russian and Kazakh territory of the USSR (McCauley 1976). This rapid land conversion boosted Soviet agricultural production, particularly of wheat, but also resulted in negative environmental and socio-economic outcomes, such as massive soil degradation that reduced soil organic matter, and promoted widespread salinization and dust storms (Hahn 1964, Amerguzhin 2003, Funakawa *et al* 2007, Josephson *et al* 2013).

Recently, cropland abandonment has become a common phenomenon in many parts of northern Eurasia, including the steppe region of Kazakhstan in Central Asia (Ioffe *et al* 2004, Wright *et al* 2012, Schierhorn *et al* 2013). Cropland abandonment in Kazakhstan reflects the socio- political and structural changes in agriculture that followed the breakup of the Soviet Union, and the subsequent transition from a state-commanded to a market-driven economy ('transition' hereafter) (Smith 1999, Lioubimtseva 2010, Prishchepov *et al* 2013). From 1990 to 2000, Kazakhstan's grain production dropped from 23.4 to 10.7 million tons, and livestock numbers declined from 48.6 to 14.5 million heads (World Bank 2004, ASK 2014). As a result, nearly 19 Mha of areas cultivated with grain and fodder crops in 1990 were withdrawn from cropland production by 2000, which is a decline of 54% (ASK 2003).

After 2000, Kazakhstan's crop and livestock production started to recover, largely in response to policy reforms and increasing governmental support for agriculture (Dudwick *et al* 2007, Belaya and Mykhaylenko 2010, OECD 2013). As a result, idle cropland was partially re-cultivated and livestock numbers increased. Yet, 14 Mha of Kazakhstan's rain-fed croplands cultivated in 1990 remained idle in 2010 (ASK 2014). Some of these abandoned croplands may represent a valuable land resource for future cropland expansion (Liefert *et al* 2010, FAO 2011, Lambin *et al* 2013).

Satellite remote sensing is a powerful tool for mapping trajectories and patterns of agricultural land-cover change, including agricultural land abandonment in the post-socialist countries (Prishchepov *et al* 2012a, Alcantara *et al* 2013, de Beurs and Ioffe 2013, Kuemmerle *et al* 2013). However, prior studies of post-socialist agricultural land-cover change focused largely on Eastern and Central Europe, and only a few studies have examined Central Asia (e.g., Klein *et al* 2012, Chen *et al* 2013, Dubovyk *et al* 2013). Existing evidence about land-use and land-cover change in Central Asia mainly stems from coarse-scale satellite imagery, showing biomass and land-surface phenology dynamics, which are likely related to post-Soviet agricultural change (de Beurs and Henebry 2004, Propastin *et al* 2008, de Beurs *et al* 2009, Zhou *et al* 2015). Unfortunately, the resolution of coarse-scale satellite imagery can limit understanding of the spatial patterns of land change.

Multispectral Landsat TM/ETM+ satellite imagery may be well suited to map the dynamics of land cover in the steppe region of Central Asia. Landsat images have been previously used to map broad land-cover classes, such as cropland, grassland, shrubs and trees, in sparse vegetation environments (Guerschman *et al* 2003, Estes *et al* 2012, Müller *et al* 2015, Senf *et al* 2015), and also to monitor land-cover change in northern Kazakhstan (Terekhov 2010). Moreover, the Landsat TM/ETM+ resolution (30 m) suits well to the average size of agricultural fields in our study area, which is approximately 4 km^2 (Kazakh Space Research Institute 2013b). Finally, cost-free access to historical archives with multi-date Landsat TM/ETM+ satellite images that date to the mid-1980s allows the reconstruction of agricultural land-cover change back to the Soviet period.

Our major goal was to assess available idle croplands and their suitability for future cropland expansion in northern Kazakhstan by analyzing long-term agricultural land-cover change, and the biophysical characteristics of idle cropland. Detailed maps were available from the peak time of the Virgin Lands Campaign (Moscow State University 1964), which allow us, in combination with Landsat TM/ETM+ satellite images, to reconstruct the trajectories of agricultural land-cover change from shortly before the beginning of the Virgin Lands Campaign in 1953 to 2010.

Our first objective was to reveal the rates and patterns of agricultural land-cover change from 1953 until 2010. Our second objective was to assess whether statistical relationships exist between observed patterns of agricultural land-cover change and

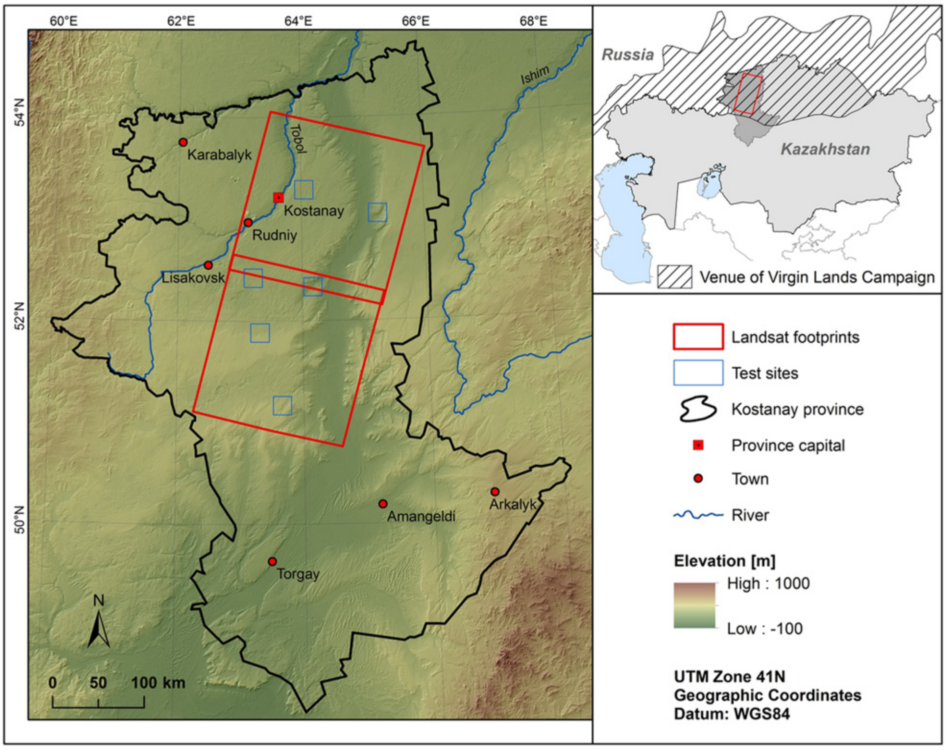

Figure 1. Overview of Kostanay Province, Northern Kazakhstan, study area (Landsat footprints) and test sites for collection of validation data.

biophysical conditions (namely, elevation, soil types and degree of aridity). Finally, we assessed suitability for idle cropland re-cultivation and contrasted them with ongoing increase of livestock numbers in order to assess the remaining idle croplands under different agro-environmental conditions and the competition of land-use.

2. Materials and methods

2.1. Study area

We chose Kostanay Province (*oblast*) as our study area because it is representative of the northern Kazakh steppe region, the core area for rain-fed crop production in Kazakhstan (figure 1, table A1). Within Kostanay Province, we analyzed two Landsat footprints that cover approximately 5.8 Mha, or 30% of the province area (figure 1). The elevation in our study area ranges from 90 to 300 m, with an increase in elevation toward the south. The climate of Kostanay Province is dry-continental, with a mean annual precipitation ranging from 400 mm in the north to 200 mm in the south (Afonin *et al* 2008). The potential annual evaporation ranges from 600 to 700 mm (Hahn 1964, Wein 1980) and frequently results in drought conditions, especially in the south (Iijima *et al* 2008). Severe droughts and dry storms (*Sukhovey*) occur every three to four years. The average number of frost-free days in Kostanay Province is 131, and decreases toward the north (Afonin *et al* 2008). Croplands are prevalent in the north, while grasslands dominate in the south. Numerous seasonal lakes and wetlands, which are mostly drainless and salty, are scattered throughout the area (DIK and Feorija 2011).

The semi-arid climate also produces a high mineral content in the soils and increases the risk of salinization, particularly in lowlands (Hahn 1964, Florinsky *et al* 2000). The most common and most fertile soil type in our study area is *Chernozem* (black earth), followed by *Kastanozem* (chestnut soils). The least fertile soils are the wet and salty *Solonetz*. Overall, the environmental conditions in the study area are not ideal for agricultural production (Lioubimtseva and Henebry 2012, Pavlova *et al* 2014). In particular, recurring droughts cause yield shortfalls, and average wheat yields from 2000 to 2010 were 1 ton ha^{-1}, with high inter-annual fluctuations (ASK 2003, 2014).

The steppes of northern Kazakhstan were traditionally used as pastures by nomadic herders (Olcott 1995, Robinson *et al* 2003). Initial efforts to plough the steppes date back to the late 19th and early 20th century. However, official statistics suggest, the main expansion of cropland area occurred during the Virgin Lands Campaign (the Campaign hereafter) in the 1950s and 1960s, when croplands in Kostanay Province increased from 1.0 to 6.4 Mha (ASK 2003). After 1963, cropland expansion slowed, and croplands reached a maximum extent (8.5 Mha) in the early 1980s. Toward the end of the Soviet era, the cropland area in Kostanay Province started to decline, and after

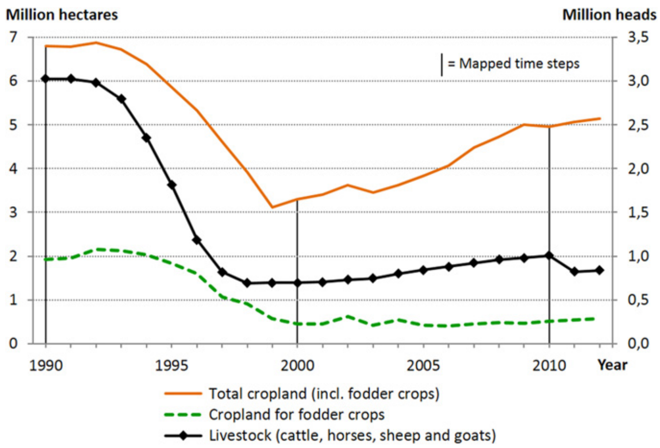

Figure 2. Agricultural development in Kostanay Province, 1990–2012 (left axis: cropland area, right axis: number of livestock), source: ASK 2003, KDS 2011, 2013.

the dissolution of the Soviet Union in 1991, the cropland area decreased from 6.8 to 3.1 Mha until 1999, and has only slightly rebounded since 2000 (KDS 2011, 2013) (figure 2). Similarly, livestock numbers decreased from 3.0 to 0.7 million head between 1990 and 1999, with a moderate recovery since 2000 (KDS 2011, 2013) (figure 2).

In 2010, the agricultural sector of Kazakhstan comprised three main types of producers: corporate enterprises, which are successors of Soviet collective farms (*kolkhoz*) or state farms (*sovkhoz*), registered and commercially-oriented individual farms, and small, partly subsistence-oriented household farms (Dudwick *et al* 2007, OECD 2013, Petrick *et al* 2013). The large-scale corporate enterprises constitute the backbone of the Kazakh crop production, controlling about three fourths of the total cropland in northern Kazakhstan (ASK 2014). The main crop grown in Kostanay Province is spring wheat, which accounts for over 90% of the total crop production (KDS 2012). After 1991, livestock production shifted largely from corporate farms to individual and household farms (OECD 2013). In 2010, household farms owned 83% of the livestock in Kostanay Province (KDS 2012). From 1990 to 2000, Kostanay Province experienced a drastic population decline, from 1.24 million to 995,000 inhabitants (KDS 2011), which coincided with socio-economic and agricultural decline. Population totaled 881,000 inhabitants in 2010 (KDS 2011).

2.2. Archival land use data and satellite imagery

To estimate the cropland extent during the 1950s and 1960s, we digitized a 1:3,000,000 map from the Atlas of Virgin Territory (Moscow State University 1964) (for a generalized subset of the scanned map, see figure S1). This map contains information about cropland areas by 1953, the year before the start of the Campaign, and by 1961, which represented the peak of cropland expansion during the Campaign. The atlas was produced based on the results of two in-depth field campaigns running from 1953 to 1961, conducted by the Geography Department of Moscow State University in Northern Kazakhstan, which aimed to scientifically support the cropland allocation during the Campaign. Detailed cropland expansion plans, updated land-use maps of newly established *kolhozes* and *sovkhozes* in Kazakhstan and information from the local cadaster offices were also used to complete the Atlas (Moscow State University 1964). We scanned the cropland expansion map from the atlas, georeferenced it and digitized (vectorized) two thematic classes: the cropland extent by 1953 (‘pre-Campaign cropland’ hereafter), and the grassland converted into cropland during the peak of the Campaign, from 1954 to 1961 (‘Campaign cropland’ hereafter).

To assess agricultural land-cover change from 1990 to 2010, we analyzed 30 m resolution Landsat TM/ETM+ satellite imagery from two Landsat footprints (WRS-2 path/row 160/23 and 160/24, figure 1). To account for crop phenology (Prishchepov *et al* 2012b), we acquired multi-seasonal images from the U.S. Geological Survey (USGS) circa 1990, 2000 and 2010. We then selected suitable multi-seasonal satellite images based on cropping schedules (table 1, figure S2). In total, we analyzed 11 images for footprint 160/23 and 12 images for footprint 160/24 (table 1).

For our satellite data analysis, we acquired orthorectified Landsat satellite images (USGS 2013). Due to the flat terrain in our study area, additional topographic correction was not necessary as we used systematically terrain-corrected Landsat images (Level 1T product). We also did not apply an additional atmospheric correction because we used a classification change detection approach based on all (stacked) satellite images (Coppin *et al* 2004, Jensen 2005, Chen *et al* 2012). Since the training dataset is derived from this multi-temporal composite (stack) (Jensen 2005, Prishchepov *et al* 2012b), an atmospheric correction would have no effect on such an image classification (Song *et al* 2001). For each image date, 30 m resolution

Table 1. Landsat TM/ETM+ images used for land-cover change analysis with acquisition date and cloud contamination.

	WRS-2 path/row			
	160/23		160/24	
Time step	Date	Clouds (%)	Date	Clouds (%)
Circa 1990	1986-06-22	8	1986-06-06	13
	1986-10-28	7	1986-06-22	2
	1987-09-13	2	1986-07-24	5
	1988-10-09	0	1987-09-13	1
			1988-10-09	0
Circa 2000	2000-09-08	0	2000-09-08	19
	2000-11-11	0	2000-11-11	0
	2001-06-07	48	2001-06-07	4
	2001-07-25	22		
Circa 2010	2009-06-05	0	2009-06-05	0
	2009-09-09	5	2009-06-21	2
	2009-10-11	0	2009-09-09	0
			2009-10-11	0

Table 2. Classification scheme with number of training pixels per footprint (WRS-2 path/row) and validation pixels for entire map.

		No. of training pixels		
Class name	Acronym	160/23	160/24	No. of validation pixels
Stable cropland in 1990, 2000, 2010	C-C-C	488	440	85
Stable grassland in 1990, 2000, 2010	G-G-G	212	521	135
Cropland in 1990, grassland in 2000, 2010	C-G-G	217	519	133
Cropland in 1990, 2000, grassland in 2010	C-C-G	120	211	52
Cropland in 1990, grassland in 2000, cropland in 2010	C-G-C	152	231	56
Grassland in 1990, 2000, cropland in 2010	G-G-C	36	Not observed	13
Forest	F	399	557	58
Wetland	W	348	383	45
Other (water, bare soil, impervious surfaces)	Other	162	269	28

spectral bands 1–5 and 7 of the TM/ETM+ sensors were stacked to one multi-spectral image. Clouds and associated shadows were masked using 'Fmask' (Zhu and Woodcock 2012).

2.3. Classification of satellite images

Our classification scheme focused on agricultural land-cover change for 1990, 2000 and 2010 (table 2). We defined 'cropland' as agricultural land that was ploughed prior to sowing in either spring or fall or that was kept temporarily fallow as a part of a crop rotation. Initial tests to separate grasslands with different management regimes and degrees of degradation indicated high spectral collinearity among these classes. Therefore, we mapped all grassland types as one single class ('grassland') that included pastures, hay cutting areas and natural grasslands. In total, we mapped six classes of cropland and grassland, and three non-agricultural classes (forest, wetland and 'other', which included water bodies, bare soil and impervious surfaces) (table 2).

Utilized multi-spectral images (table 1, six spectral bands each) were assembled into multi-temporal image composites, which comprised a total of 66 and 72 bands for footprint 160/23 and footprint 160/24, respectively. This depth of spectral information of each pixel over all time steps helps the classifier to group pixels into thematic classes. For the classification, we utilized semi- automatic non-parametric support vector machines (SVM) (Vapnik 1995, Huang *et al* 2002), which have been successfully used to map post-socialist agricultural land-cover change elsewhere (e.g., Kuemmerle *et al* 2008, Prishchepov *et al* 2012b). We used the SVM implementation in the EnMAP-Box (version 1.4) (Rabe *et al* 2010) based on LIBSVM (Chang and Lin 2011), which iteratively selects optimal SVM parameters (for details, please refer to text S1 available at stacks.iop.org/ERL/10/054012/mmedia).

2.4. Collection of training data

To facilitate the collection of training and validation data, we stratified the multi-temporal image stacks into 50 classes using iterative automatic clustering (ISODATA, k-means), which we grouped into nine thematic classes to separate all trajectories of agricultural land-cover change and predominant non-agricultural land-cover classes (table 2). Based on this stratification, we sampled between 2000 and 3000 random training points (single pixels) per Landsat TM/ETM+ footprint, with a minimum distance of 500 m between points to reduce potential spatial autocorrelation (table 2). We assigned a thematic class to each training point using expert-based visual interpretation of the dense stacks of Landsat images available from the USGS archive along with very high-resolution images (e.g., QuickBird™ and WorldView™ images) from Bing™ and GoogleEarth™ online mapping services (table S1) and from digitized agricultural plots from the 1980s (Kazakh Space Research Institute 2013a). We selected at least 200 training points in classes that were common and at least 100 in rare classes (table 2). The only exception was the new cultivation class after 2000 (G-G-C), for which we could allocate only 36 training points (table 2). Using these points, we trained the SVM to classify the multi-temporal Landsat stacks into our land-cover change classes. Finally, we applied a 3 × 3 majority filter to reduce the salt-and-pepper effect in the initial classifications.

2.5. Collection of reference data and accuracy assessment

For our accuracy assessment of the land-cover change map, we collected validation data, using a stratified clustered random sample (Edwards *et al* 1998, Prishchepov *et al* 2012b). Points were then labeled during a field campaign in 2013, and using very high-resolution QuickBird™ and WorldView™ images available via Bing™ and GoogleEarth™ (table S1). We selected six 20 × 20 km blocks in our study area, which matched footprints of the high-resolution satellite images (figure 1). Then, we digitized all roads and randomly selected points that were at least 60 meters and at most 360 meters (i.e., 12 Landsat pixels) away from these roads (to ensure accessibility in the field), while maintaining a minimum distance of 500 meters between validation and training points. During the field campaign, we located validation points and recorded additional points with a non-differential GPS.

Field surveying, however, was sometimes difficult due to poor road conditions. Thus, we had to assign the land-cover classes for non-visited points manually based on their spectral similarity to known, non-random points nearby. To reconstruct land use for 1990 and 2000, we interviewed local farmers and officials of farm enterprises using semi-structured questionnaires, and we obtained information such as detailed land-use plans for each plot. To validate the 'forest', 'wetland' and 'other' classes, we used high-resolution images and spectral profiles for validation points derived from dense stacks of Landsat images (Baumann *et al* 2012, Griffiths *et al* 2013).

To assess the map accuracy, we calculated contingency matrices, producer's and user's accuracies and the overall accuracy (Congalton *et al* 1983, Olofsson *et al* 2013). We derived area estimates, which we adjusted for possible sampling bias, and we calculated 95% confidence intervals around these estimates (Olofsson *et al* 2013).

2.6. Combination of archival and satellite-derived maps and comparison of land-cover change with biophysical conditions

The combination of the satellite-derived map and the digitized Virgin Lands Campaign atlas for 1953 to 1961 allowed us to identify cropland expansion after the peak of the Campaign from 1962 to 1990 ('post-Campaign cropland' hereafter), as well as the abandonment of pre- Campaign cropland and Campaign cropland from 1962 to 1990. We also assessed the biophysical characteristics of each agricultural land-cover change class, such as elevation (CGIAR–CSI 2014), Selyaninov's hydrothermal coefficient (HTC) (Selyaninov 1928, Afonin *et al* 2008) and soil quality (COGC 1976) (figure 3). The HTC represents the ratio of total precipitation and average daily air temperature during the growing season (days with an average temperature >5 °C). Areas with insufficient humidity are defined by values below one (Gathara *et al* 2006, Voropay *et al* 2011). We digitized the soil types from the 1:2 500 000 Soil Map of Kazakhstan (COGC 1976), grouped them into three classes and ranked them according to the suitability for crop production into pure Chernozem and Kastanozem (highest crop production suitability, and rank 1), Chernozem Solonetz and Kastanozem Solonetz (medium crop production suitability, and rank 2) and Solonetz and meadow soils (lowest crop production suitability, and rank 3). For further spatial analysis, all data were rasterized, including the Virgin Lands Campaign map, resampled to a 30 m resolution to match the satellite-derived agricultural land-cover-change map, and analyzed using GRASS GIS (GRASS Development Team 2014), where we summarized each land-cover change class and its association with elevation, HTC and soil rank.

2.7. Biophysical determinants of agricultural land-cover change and suitability for cropland expansion

In addition to summary statistics, we also analyzed the relationships between the spatial patterns of the agricultural land-cover change from 1953 to 2010 and the biophysical variables (figure 3). We expected that cropland expansion would be more common in areas with better soils, higher HTC and at higher elevation, while abandonment would dominate marginal plots with lower HTC, lower soil quality and at lower elevations. Similarly, we expected re-cultivation of abandoned plots would be most common in areas with better agro-environmental conditions. However, we were unable to analyze other socio-economic variables

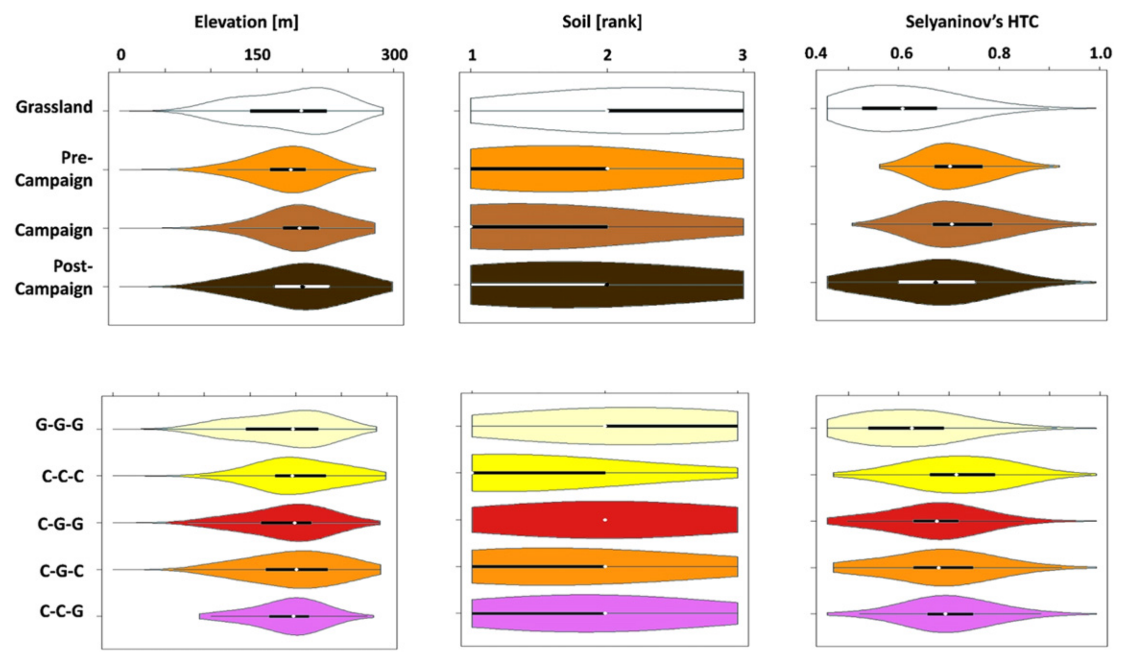

Figure 3. Violin plots for selected biophysical parameters for major agricultural land-cover change classes 1953–2010. Note: the violin plots contain boxplots with median and interquartile range (Hintze and Nelson 1998). Acronyms for land-cover classes introduced in table 2. The G-G-C class was not assessed due to rare occurrence.

because no fine-scale data were available for the study period.

For our statistical analysis, we conducted several binary logistic regressions separately for two periods (1953–1990 and 1990–2010) (table 3). For instance, for the period 1953–1990, 'pre-Campaign cropland' was coded as '1', while the 'stable grassland in 1953, 1961 and 1990' class was coded as '0' (table 3, model 1–3). For the period 1990–2010, we set the agricultural land-cover changes equal to one and stable cropland (C-C-C) to zero (table 3, model 4–6). Finally, we constructed one additional model to map suitability for potential cropland expansion at the expense of abandoned croplands (table 3, model 7).

We selected observations with a distance of at least 1 km among them, as this helped us to reduce spatial autocorrelation of Moran's I to 0.1–0.2, which we measured in ENVI™ package for five randomly selected 10 × 10 km blocks. All bivariate Pearson's correlation coefficients between predictors were below 0.5, indicating little multi-collinearity. We assessed the goodness-of-fit using the log-likelihood, the deviance for the residuals of the null and fitted models and the area under the receiver operating characteristics curve (AUC; Pontius and Schneider 2001). We checked robustness of models to balanced and unbalanced sampling, as often numbers of absence (0s) were more frequent than numbers of presence (1s). For model interpretation, we used odds ratios. Finally, using the statistically significant coefficients ($p < 0.05$) from model 7 (table 3), we calculated the relative suitability for cropland expansion at the expense of formerly abandoned croplands. For comparison, we also summarized recent trends of livestock increase in our study area using detailed population statistics available at the settlement level (ASK 2001b, 2011b) as well as district-level livestock dynamics for Kostanay Province (ASK 2001a, 2011a, KDS 2001 and 2012). For details on our methodology to disaggregate the livestock data please refer to text S2. We used *R* software for all statistical analysis (R Development Core Team 2011).

Table 3. Logistic regression models[a].

	Coding	
Model	'1' (presence)	'0' (absence)
1	'pre-Campaign cropland'	'Stable grassland in 1953, 1961, 1990'
2	'Campaign cropland'	'Stable grassland in 1953, 1961, 1990'
3	'post-Campaign cropland'	'Stable grassland in 1953, 1961, 1990'
4	C-G-G	C-C-C
5	C-G-C	C-C-C
6	C-C-G	C-C-C
7	C-G-C	G-G-G + C-G-G + C-C-G

[a] Acronyms for land-cover classes in model 4–7 introduced in table 2.

3. Results

3.1. Land-cover change from 1953 to 2010

Our classifications had an area adjusted overall accuracy of 78% (table 4). Among the agricultural

Table 4. Confusion matrix with user´s (UA), producer´s (PA) and area adjusted producer´s accuracy (aPA), and conditional Kappa for the satellite-derived change map[a].

	Reference											
Classification	Other	Water	Forest	G-G-G	C-C-C	C-G-G	C-G-C	C-C-G	G-G-C	Total	UA (%)	Kappa
Other	24	2		2	2	1		1		32	75.0	72.9
Water	3	28	5	4	1	3	1	1	1	47	59.6	54.0
Forest			46	1						47	97.9	93.9
G-G-G		13	6	105		9	1	3		137	76.6	70.4
C-C-C	1			1	73	3	3	5	1	87	83.9	78.3
C-G-G		2	1	15	1	103	4	4		130	79.2	74.2
C-G-C					5	4	46		3	58	79.3	77.2
C-C-G				6	2	10		38		56	67.9	64.0
G-G-C				1	1		1		8	11	72.7	79.0
Total	28	45	58	135	85	133	56	52	13	605		
PA (%)	85.7	62.2	79.3	77.8	85.9	77.4	82.1	73.1	61.5		77.9	
aPA (%)	70.7	63.1	55.6	86.0	94.9	73.4	70.3	48.8	35.4		77.8	

[a] Acronyms for land-cover classes introduced in table 2.

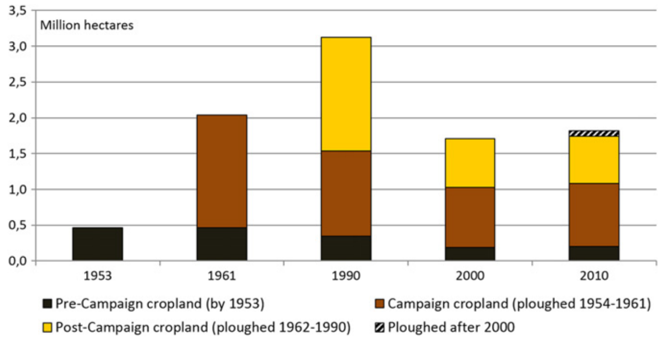

Figure 4. Changes in cropland area from 1953 to 2010 by period and with proportions of first documented conversion of grassland into cropland.

land-cover classes, the 'stable cropland in 1990, 2000, 2010' class (C-C-C) had the highest user's accuracy (84%) and area adjusted producer's accuracy (95%), followed by 'stable grassland in 1990, 2000, 2010' (G-G-G), with 77% and 86%, respectively (table 4). Among the change classes, the user's and area adjusted producer's accuracies varied from 68% to 79%, though with lower producer's accuracies for 'cropland in 1990, 2000, grassland in 2010' (C-C-G, 49%) and 'grassland in 1990, 2000, cropland in 2010' (G-G-C, 35%).

We observed high rates of cropland expansion since the beginning of the Campaign, and substantial cropland contraction after 1990, followed by a minor rebound of cropland area after 2000 (figure 4). There was an almost seven-fold increase in cropland from 1953 to 1990 (figures 4 and 5(A)). The cropland area was 465,000 ha in 1953, then expanded by 1.57 Mha through 1961 and by another 1.08 Mha through 1990 (figures 4 and 5(A)). At the same time, 120,000 ha of pre-Campaign cropland (by 1953) and 380,000 ha of Campaign cropland (ploughed 1954–1961) were already converted back to grassland by 1990 (figure 4).

The highest rates of cropland abandonment occurred between 1990 and 2000 (figures 4 and 5(B)). The cropland area was 3.12 ± 0.45 Mha (54 ± 7.7% of the study area) in 1990, but it decreased by 1.41 ± 0.21 Mha (~45%, class C-G-G and C-G-C) by 2000 (figures 4 and 5(B)). By 2010, 373,000 ± 84,000 ha (~26%) of prior abandoned cropland (i.e., from 1990 to 2000) was ploughed again (class C-G-C, 6.4 ± 1.5% of the study area), while another 341,000 ± 102,000 ha of earlier cultivated cropland was abandoned (class C-C-G, 5.9 ± 1.8% of the study area) (figures 4, 5(B) and 6). We also observed a minor expansion of cropland from 2000 to 2010 at the expense of virgin grasslands (class G-G-C: 72,000 ± 48,000 ha, 1.2 ± 0.8% of the study area, ~2% of the 2010 cropland) (figures 4, 5(B) and 6). In total, cultivated cropland comprised 1.81 ± 0.26 Mha by 2010 (class C-C-C, C-G-C and G-G-C) or approximately 58% of the cropland extent of 1990 (figures 4, 5(B) and 6).

From 1990 to 2000, 64% of cropland abandonment (C-G-G) occurred in areas cultivated after the peak of the Campaign (1962–1990) (figures 4 and 5). This post-Campaign cropland alone decreased by 57% (from 1.59 to 0.91 Mha) during the first decade of transition. By 2010, 58% (0.93 Mha) of total post-Campaign croplands were still grasslands (part of C-G-G and C-C-G), despite efforts to re-cultivate grasslands starting in 2000. In contrast, the cropland that was ploughed during the peak of the Campaign (1954–1961) decreased by only 29% (from 1.19 to 0.84 Mha) from 1990 to 2000 (part of C-G-G and C-G-C), with rare re-cultivation events until 2010 (38,000 ha) (figures 4, 5 and 6). Interestingly, about 44% (203,000 ha) of the oldest pre-Campaign croplands were still cultivated in 2010 (part of class C-C-C or C-G-C) (figures 4, 5 and 6).

3.2. Comparison of land-cover changes with biophysical conditions

From 1953 to 1990, the cropland area gradually expanded toward the southern edge of our study area (i.e., the vicinity of Burevestnik settlement, which was established in 1965) (figure 5(A)). The Landsat satellite images revealed that stable cropland (C-C-C) was dominant in the north, whereas stable grassland (G-G-G) and early cropland abandonment and reversion to grassland (C-G-G) predominantly occurred in the central and the southern parts of our study area (figure 5(B)).

Descriptive statistics showed both Campaign and post-Campaign croplands were more common at higher elevations (a mean of 197 m for both classes) compared to pre-Campaign cropland (a mean of 181 m) (figure 3). Pre-Campaign and Campaign croplands ploughed by 1990 were located at slightly higher elevations compared to croplands that were abandoned prior to 1990. The post-Campaign croplands had a lower HTC (0.68 mean) compared to pre-Campaign cropland and Campaign cropland (means of

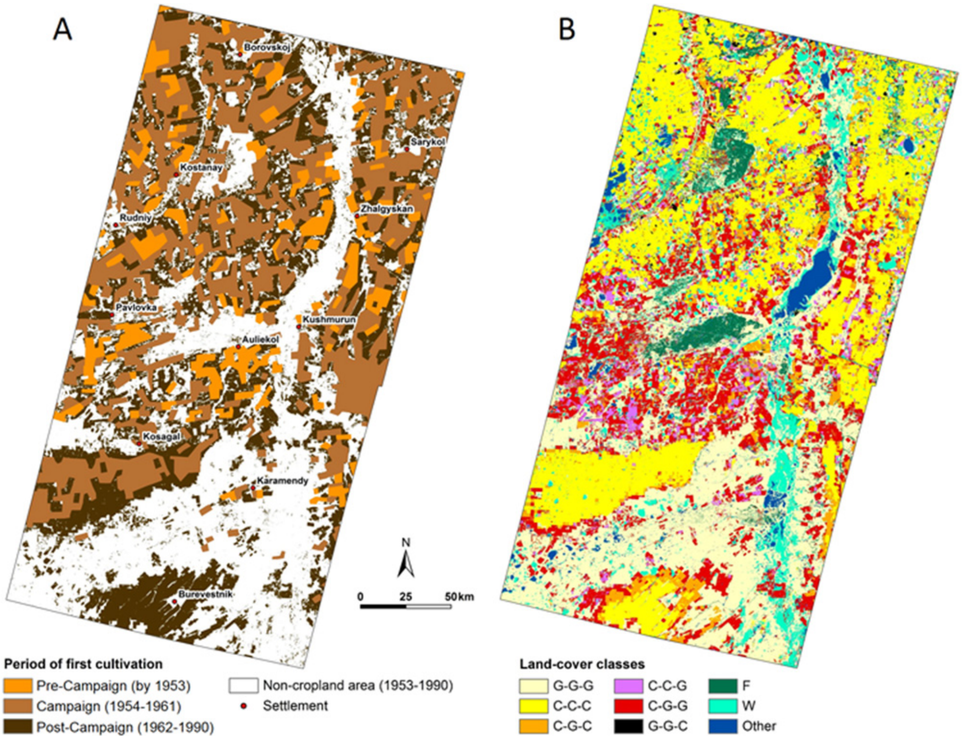

Figure 5. Agricultural land-cover change in the study area. (A) Cropland in 1990 by period of first documented conversion of grassland into cropland. (B) Classified land-cover map for post-Soviet period (1990–2000–2010). Acronyms for land-cover classes introduced in table 2.

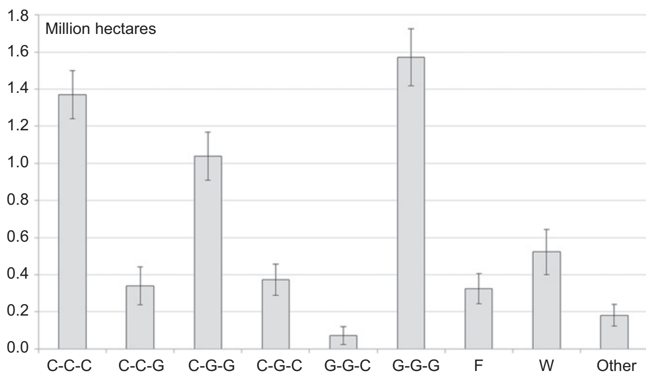

Figure 6. Error-adjusted area estimates for mapped agricultural land-cover classes of post-Soviet period (error bars indicate the error margins with 95% confidence interval). Acronyms for land-cover classes introduced in table 2.

0.72 and 0.73, respectively) (figure 3). Pre-Campaign cropland had the lowest variation in HTC compared to the Campaign and post-Campaign cropland, which occurred largely in very dry areas with an HTC of approximately 0.5 (figure 3).

From 1990 to 2010, stable cropland (C-C-C) occurred on average at higher elevations (203 m mean) than all other agricultural classes (figure 3). Among the change classes, cropland re-cultivation (C-G-C) tended to occur at higher elevations than the other classes. Stable grassland (G-G-G) existed at lower elevations and in areas with distinct lower HTC values than all the classes that were croplands in 1990 (figure 3). Furthermore, we found that stable cropland (C-C-C) and recent conversion of grasslands for crop production (G-G-C) had the best hydrothermal conditions, with a mean and median HTC above 0.7 (figure 3).

In terms of soil types, pre-Campaign cropland primarily occurred on soils with the highest or medium suitability for crop production (43% of pure Chernozem or Kastanozem, and 50% of Chernozem or Kastanozem Solonetz) (figures 3 and 7(B)). Cropland expansion during the Campaign largely occurred on the most suitable soils (by ~58%), while nearly 60% of the expansion after the Campaign, from 1962 to 1990,

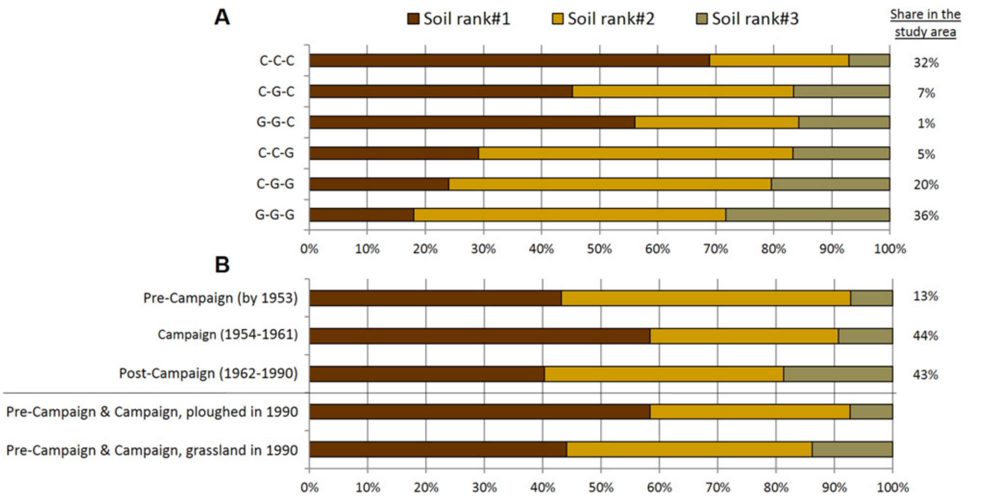

Figure 7. (A) Distribution of soil classes per agricultural land-cover class for post-Soviet period. (B) Distribution of soil classes for 1990´s cropland by period of first documented conversion into cropland (soil rank no. 1 = highest suitability for crop production: *Chernozem and Kastanozem;* soil rank no. 2 = medium suitability: *Chernozem and Kastanozem Solonetz*; Soil rank no. 3 = lowest suitability: *Solonetz and meadow soils*). Acronyms for land-cover classes introduced in table 2.

were found on soils of lower suitability (figure 7(B)). Moreover, 19% of post-Campaign cropland expansion occurred on the least suitable soils. In the post-Soviet period, 69% of the stable cropland (C-C-C), and 45% of the abandoned cropland re-cultivation (C-G-C), occurred on the most suitable soils, whereas 76% of the early reversion of cropland to grassland, and 71% of the late reversion, occurred on soils with medium or lowest suitability (figure 7(A)).

3.3. Biophysical determinants of land-cover change and suitability for cropland expansion

We found a statistically significant association of land-cover changes with elevation, soil types and Selyaninov's HTC (table 5). Our models were robust to equal and unequal sampling of '0s' and '1s' with very marginal change of the coefficients, and models largely confirmed the results in section 3.2. For instance, an increase of soil rank by one unit increased the chances of land to be converted into cropland by 62% in the pre-Campaign period (model 1, table 5) and by 61% during the Campaign (model 2, table 5), while the chance of conversion was only 38% in the post-Campaign period (model 3, table 5). The higher odds ratio for the pre-Campaign and Campaign periods, compared to the post-Campaign cropland expansion model, suggest that cropland expansion during these periods primarily occurred on lands with better agro-environmental conditions relative to post-Campaign cropland expansion. Similarly, after 1990 a decrease of soil rank by one unit increased the likelihood of abandonment until 2000 (C-G-G) by a factor of three (model 4, table 5). After 2000, a decrease of soil rank by one unit increased the likelihood of abandonment until 2010 (C-C-G) by a factor of 2.4 (model 6, table 5).

Agricultural land abandonment primarily took place on marginal lands from 1990 to 2000. Once socio-economic conditions changed, re-cultivation took place at the expense of these marginal lands. The likelihood to observe re-cultivation of such plots by 2010 on soils with low suitability (rank) was high (76%), albeit much lower compared to the likelihood of agricultural abandonment from 1990 to 2000 and from 2000 to 2010. This suggests, recent re-cultivation efforts focused on the best soils available, and least suitable soils for crop production remained abandoned.

We used the results from the logistic regression model (model 7, table 5) and assessed the suitability for future re-cultivation of currently abandoned croplands (figure B1 (1)). The comparison of the likelihood for re-cultivation with ongoing livestock expansion (figures B1 (2) and (3)) revealed that only few idle cropland plots with good agro-environmental characteristics remained available for cultivation due to competition of land use. Often, expansion of livestock grazing and associated provision of hay as fodder for subsistence farms was taking place on abandoned croplands.

4. Discussion

We conducted the first assessment of agricultural land-cover change in the northern Kazakh grain region during sixty years of Soviet and post-Soviet cropland development. Our results revealed high spatial and temporal dynamics in cropland extent from 1953 to 2010. Because of the importance of wheat procurement in the post-WWII Soviet Union, croplands substantially expanded in our study area, from only 8% of the total area in 1953 to 54% in 1990. At the same time, our results showed that the conversion of virgin steppe into croplands during the peak of the

Table 5. Odds ratios[a] for agricultural land-cover change models from 1953 to 1990 and from 1990 to 2010.

	1953–1990			1990–2010[b]			
'1' (presence)	Model 1: pre-Campaign cropland	Model 2: Campaign cropland expansion	Model 3: post-Campaign cropland expansion	Model 4: C-G-G	Model 5: C-G-C	Model 6: C-C-G	Model 7: C-G-C
Variable/'0' (absence)		Stable grassland in 1953, 1961, 1990			C-C-C		G-G-G + C-G-G + C-C-G
Elevation (100 m)	1.041	1.170	1.108	0.887	0.932	0.930	1.090
Soil type (rank)	0.377	0.393	0.621	3.072	1.761	2.451	0.561
Selyaninov's HTC (unit * 100)	3.435	4.984	2.185	0.398	0.543	0.634	1.635
Number of presence observations ('1')	3095	10 495	10 236	6387	2192	1632	2192
Number of absence observations ('0')	9929	9929	9929	10 320	10 320	10 320	18 151
Adjusted R^2	0.371	0.519	0.221	0.319	0.103	0.136	0.093
AUC	0.85	0.875	0.746	0.796	0.68	0.729	0.686

[a] All odds ratios are statistically significant at $p < 0.001$.

[b] Acronyms for land-cover classes introduced in table 2.

Virgin Lands Campaign (1954–1961) was concentrated in areas most suitable for agriculture. After 1961, cropland cultivation gradually expanded southward, irrespective of lower agricultural suitability there (figures 5(A) and 7(B)). Expansion in these marginal areas often led to rapid land degradation and subsequent cropland abandonment after only a few years of cultivation (Geipel 1964, OECD 2013). Thus, our results show that the majority of highly suitable lands had already been converted to cropland by 1961 in the course of the Campaign (Wein 1980).

The dissolution of the Soviet Union and the transition to a market economy were the underlying causes of the drastic decline in agricultural land use in Kazakhstan in the 1990s (World Bank 2004, Lioubimtseva 2010). The loss of guaranteed markets, disintegration of value chain supplies and deteriorating price relationships between inputs and outputs during the transition, promoted the decline in agricultural production and the agricultural land abandonment in post-Soviet times (Smith 1999, Ioffe *et al* 2004, Prishchepov *et al* 2013). In northern Kazakhstan, particularly, the decline of livestock and associated fodder crop production after 1990 notably contributed to the abandonment of cultivated croplands (Dudwick *et al* 2007, Suleimenov and Oram 2000), as confirmed by our interviews in the field.

Overall, the proportion of cropland in our study area decreased from 54% in 1990 to 30% in 2000, a relative reduction of 45%. Interestingly, most of the cropland that reverted to grassland after 1990 was only marginally suitable for agriculture and was, for the first time, ploughed only after the peak of the Campaign. In general, we observed higher rates of cropland abandonment from 1990 to 2000 compared to the subsequent decade, similar to other regions in post-Soviet Eastern Europe (Baumann *et al* 2011, Prishchepov *et* al 2012a, Griffiths *et al* 2013). Economic changes, such as economic adjustment toward open-market conditions, and the increase of world wheat prices after 2000 (FAO 2014) fostered re-cultivation of 6% of the idle cropland in our study region from 2000 to 2010. Similar re-cultivation rates of abandoned lands have also been observed in Romania and post-Soviet Ukraine (Griffiths *et al* 2013). Together, these findings suggest that comparable underlying drivers of land-cover change operated across former socialist countries after 1990.

Cropland abandonment and reversion to grasslands continues in our study area, partly due to incomplete land reforms, termination of agricultural production by bankrupt enterprises and ongoing structural change in the agricultural sector (OECD 2013, Petrick *et al* 2013, Glauben *et al* 2014). Although the overall amounts of re-cultivation and abandonment from 2000 to 2010 were almost equal, the two processes resulted in distinct spatial patterns of agricultural land-cover change because cropland abandonment primarily affected marginal areas (table 4, figure 5(B)). Conversely, the re-cultivation from 2000 to 2010 primarily occurred on lands with relatively favorable agro-environmental conditions compared to remaining idle croplands, albeit with much lower agro-environmental endowment in contrast to stable croplands from 1990 to 2010 (table 5, figure 7(A)).

Overall, we observed that 80%, or approximately 1.2 Mha, of the previously used cropland on the best soils was still under cultivation in 2010 (figure 7(A)). In contrast to optimistic expectations about untapped agricultural potentials on the abandoned agricultural lands in Kazakhstan (Liefert *et al* 2010, FAO 2011, Lambin *et al* 2013), our analysis of land-cover change and the increase of livestock density since 2000 (figures B1 (2) and (3)) showed that not much suitable land remains for future cropland expansion. In our study area, just about approximately 300,000 ha out of 1.7 Mha of idle croplands in 2010 have a high suitability for agricultural production. Any further cropland expansion would only be possible in marginal lands that originally were ploughed during and after the Campaign, but were quickly abandoned, especially after 1990. Moreover, strong competition for available idle croplands is expected from other land uses, for instance, due to implementation of governmental programs on agricultural diversification, and to support livestock production, including the development of the livestock fodder base (OECD 2013).

The fit of our model to map suitability for re-cultivation is adequate (table 5, model 7, AUC 0.68), given that we only used biophysical parameters as explanatory variables. Accounting for socio-economic parameters (e.g., proximity to grain processing facilities and markets) would have potentially improved the model fit. To proxy the spatial pattern of livestock dynamics (figures B1 (2) and (3)), we used data for subsistence livestock that we disaggregated by the aid of population census data (text S2). Maps of grassland productivity would also potentially corroborate the representation of livestock density, and thus the analysis of competition between crop and livestock production. However, such data were not available for our study. Nevertheless, our results support the recent findings about limited potential for cropland expansion on abandoned agricultural lands in post-Soviet Russia, where cropland abandonment is widespread (Schierhorn *et al* 2014). Ultimately, our results underscore the need to increase crop yields in existing fields and to use land that is currently uncultivated for extensive livestock grazing and the preservation of non-provisioning ecosystem services, such as carbon sequestration, as well as for biodiversity conservation (Kamp *et al* 2011, Kurganova *et al* 2014, Schierhorn *et al* 2013).

The remote sensing classifications had high accuracies for the stable land-cover classes, such as stable croplands and grasslands, whereas accuracies for the change classes were somewhat lower, despite the selection of multi-seasonal images, and the use of a non-parametric machine- learning classifier. Difficulties experienced in separating the change classes can be mainly attributed to the spectral similarities of more or less intensively managed and unmanaged grasslands in dry environments, and the limited spectral and temporal resolutions of the Landsat TM/ETM+ imagery (Klein *et al* 2012, Gong *et al* 2013). This is why we mapped broad agricultural land-cover change classes and complemented with spatial modeling of livestock density (text S2, figures B2 and B3).

Our cropland area estimates, using remote sensing data, were fairly close to the late Soviet official statistics (1990), and recent agricultural statistics (2010), but differed from official reports during the transition period (2000) (table C1). Given that official estimates lie well outside the error margins we calculated for our cropland area estimates, the possible difference between our and the official estimates can be largely attributed to uncertainties in official statistics, which were common during the early transition period across post-Soviet countries (Rumer and Zhukov 1998, Ioffe *et al* 2004). This accentuates the importance of monitoring land-cover change with remote sensing data, when official statistics remain uncertain.

Our remote sensing approach is well suited to map land-cover change in grassland and savanna ecosystems, and this approach could be used throughout the steppes of Central Asia. Furthermore, the increase in image availability after the launch of Landsat 8 in 2013 and, potentially, of Sentinel-2 in 2015, may offer new research opportunities at higher temporal and spatial resolutions, especially when used with imagery of higher temporal frequencies, such as MODIS.

5. Conclusion

Abandoned croplands may offer opportunities for cropland expansion, and re-cultivation of currently unused cropland may contribute to regional and global food security. Our study area, which is representative of the northern Kazakh rain-fed grain region, encompasses a substantial amount of abandoned cropland. However, we found that the potential for cropland expansion is limited in northern Kazakhstan, because the remaining idle croplands are mainly located in areas that are little suitable for crop production. In addition, given that recent agricultural policies in Kazakhstan are targeting an increase in livestock production and the diversification of crop production, increasing competition between different land uses can be expected. Increasing grain production may thus be more easily achieved by improving yields on existing croplands, rather than through additional cropland expansion. The remaining abandoned croplands in less suitable areas of northern Kazakhstan are likely more apt for grazing, and for conserving biodiversity and non-provisioning ecosystem services.

Acknowledgments

We gratefully acknowledge the support of the GERUKA project, which is funded by the German Federal Ministry of Food and Agriculture (BMEL), the Federal Office for Agriculture and Food (BLE) and the EPIKUR project, which is funded by the Leibniz Association's 'Joint Initiative for Research and Innovation' ('Pakt für Forschung und Innovation'). We also acknowledge the financial support of the German Ministry for Research and Education (BMBF, project KULUNDA), the NASA Land-Cover/Land-Use Change Program (LCLUC), and the Volkswagen Foundation (project BALTRAK). We thank our colleagues from the Analytical Centre of the Economic Policy in the Agricultural Sector (ACEPAS) in Astana, and Dauren and Rakhim Oshakbaev for their support in the field. We are grateful to Martin Petrick, Florian Schierhorn, Friedrich Koch and Brett Hankerson from IAMO for constructive discussions, and also to Achim Zetek and Alexander Mizgirev for their technical assistance. Two anonymous reviewers and an anonymous editorial board member provided valuable comments that greatly improved our manuscript.

Appendix A

Table A1. Comparison of Northern Kazakhstan[a] and Kostanay Province using selected socio-economic and agro-environmental indicators.

Group	Indicator	Northern Kazakhstan[a]	Kostanay province
Socio-economic[b]	Cropland area (Mha) (share in the total area)	15.4 (26.8%)	5.0 (24.9%)
	Area under grain crops (Mha) (share in the cropland area)	13.2 (85.6%)	4.4 (86.9%)
	Share of agricultural sector in the total gross regional product	16.1%	20.2%
	Share of crop production in the gross output of the agricultural sector	65.3%	73.3%
Agro-environmental[c]	Annual frost free days, mean (min, max)	118.6 (89, 159)	130.8 (109, 159)
	HTC, mean (min, max)	0.73 (0.28, 1.15)	0.62 (0.28, 1.15)
	Share of pure Chernozem and Kastanozem over all soils	45.0%	41.8%

[a] Northern Kazakhstan = provinces Akmola, Kostanay, North Kazakhstan, Pavlodar.
[b] 2009–2011 average, source: ASK (2014).
[c] Source: Afonin *et al* (2008).

Appendix B

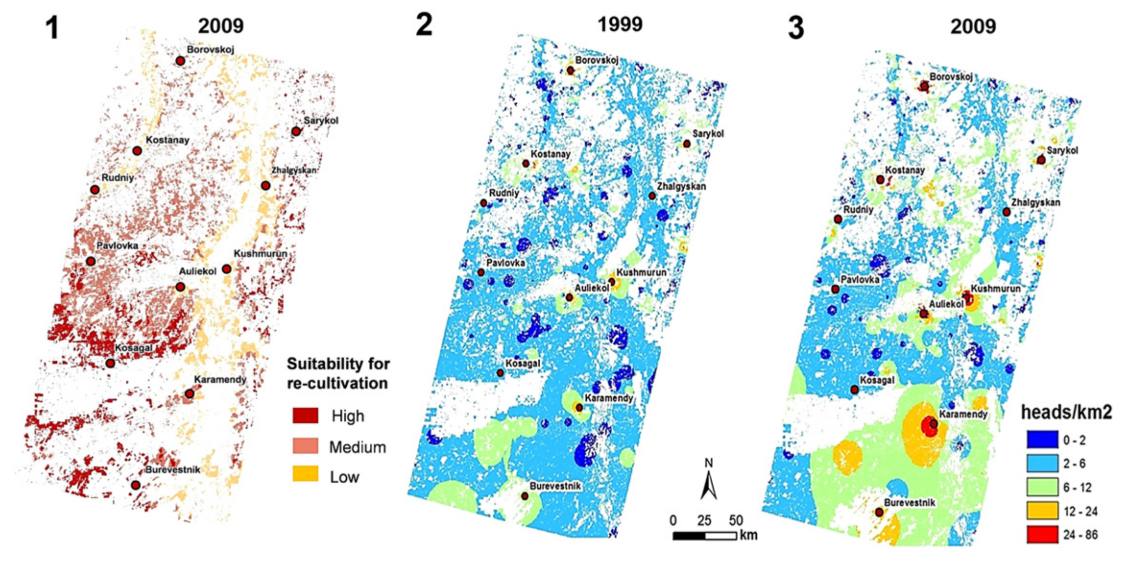

Figure B1. (1) Tertiles of suitability of abandoned cropland re-cultivation by 2009 using results from spatially-explicit logistic regression (model 7, table 5). (2) and (3): livestock density for 1999 and 2009. For computation of livestock density, please refer to text S2.

Appendix C

Table C1. Comparison of cropland area in Altynsarin and Auliekol districts[a] by map estimates and official statistics for time steps 1990, 2000, 2010.

District	Year	Remote-sensing based land-cover change map[b] (thousand ha)	Official statistics[c] (thousand ha)
Altynsarin	1990	328.2 (±25.3)	290.5
	2000	199.9 (±8.0)	161.5
	2010	239.6 (±10.8)	225.1
Auliekol	1990	568.5 (±43.8)	505.6
	2000	264.3 (±10.6)	196.5
	2010	251.4 (±11.4)	293.4

[a] These are the only two districts completely lying within our study area. For location of districts in the study area please refer to figure S3.

[b] Numbers in brackets stand for error margins with 95% confidence interval based on confusion matrix (see table 4).

[c] Source: KDS (2001), (2012).

References

Afonin A N, Greene S L, Dzyubenko N I and Frolov A N (ed) 2008 *Interactive Agricultural Ecological Atlas of Russia and Neighboring Countries. Economic Plants and their Diseases, Pests and Weeds* (www.agroatlas.ru)

Alcantara C *et al* 2013 Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data *Environ. Res. Lett.* **8** 035035

Amerguzhin H A 2003 Agroecological characteristics of soils of Northern Kazakhstan (Aroekologicheskiye haraketirstiki pochv Severnogo Kazakhstana) *PhD Dissertation* Dokuchaev Soil Institute, Moscow

ASK 2001a *Agriculture, forestry and fishery in the Republic of Kazakhstan 1990, 1995-2000 (Sel'skoe, lesnoe i rybnoe hozjajstvo v Respublike Kazahstan 1990, 1995-2000)* (Almaty: Agency of Statistics of the Republic of Kazakhstan)

ASK 2001b *Results of population census in Kostanay province in 1999* vol 1–4 (Almaty: Agency of Statistics of the Republic of Kazakhstan)

ASK 2003 *Republic of Kazakhstan: 50 Years since the Beginning of Virgin Lands Campaign. Statistical digest 1953–2003 (Respublika Kazahstan: 50-let nachala osvoenija celinnyh i zalezhnyh zemel'. Statisticheskij sbornik 1953–2003)* (Almaty: Agency of Statistics of the Republic of Kazakhstan)

ASK 2011a *Agriculture, Forestry and Fishery in the Republic of Kazakhstan 2006–2010 (Sel'skoe, lesnoe i rybnoe hozjajstvo v Respublike Kazahstan 2006-2010)* (Astana: Agency of Statistics of the Republic of Kazakhstan)

ASK 2011b *Population of the republic of Kazakhstan. Results of the National population census of the republic of Kazakhstan* vol 1,2 (Astana: Agency of Statistics of the Republic of Kazakhstan)

ASK 2014 *Agriculture, forestry and fishery in the Republic of Kazakhstan 2009–2013 (Sel'skoe, lesnoe i rybnoe hozjajstvo v Respublike Kazahstan 2009–2013)* (Astana: Agency of Statistics of the Republic of Kazakhstan)

Baumann M, Kuemmerle T, Elbakidze M, Ozdogan M, Radeloff V C, Keuler N S, Prishchepov A V, Kruhlov I and Hostert P 2011 Patterns and drivers of post-socialist farmland abandonment in Western Ukraine *Land Use Policy* **28** 552–62

Baumann M, Ozdogan M, Kuemmerle T, Wendland K J, Esipova E and Radeloff V C 2012 Using the Landsat record to detect forest-cover changes during and after the collapse of the Soviet Union in the temperate zone of European Russia *Remote Sens. Environ.* **124** 174–84

Belaya V and Mykhaylenko M 2010 Agrargigant Kasachstan. Probleme und Perspektiven der landwirtschaftlichen Entwicklung *Zentralasien-Analysen* **27** 2–5

CGIAR–CSI 2014 *NASA Shuttle Radar Topographic Mission (SRTM) Digital Elevation Data* (http://srtm.csi.cgiar.org/)

Chang C-C and Lin C-J 2011 LIBSVM: a library for support vector machines *ACM Trans. Intell. Syst. Technol.* **2** 1–27

Chen X, Giri C P and Vogelmann J E 2012 *Remote Sensing of Land Use and Land Cover. Principles and Applications* (*Remote Sensing Applications Series*) ed C P Giri (Hoboken: CRC Press) pp 153–76

Chen X, Bai J, Li X, Luo G, Li J and Li B L 2013 Changes in land use/land cover and ecosystem services in Central Asia during 1990–2009 *Curr. Opin. Environ. Sustain.* **5** 116–27

COGC 1976 *Soil Map of Kazakhstan* (Moscow: Central Office of Geodesy and Cartography at the Council of Ministers of the USSR) (http://eusoils.jrc.ec.europa.eu/library/maps/country_maps/metadata.cfm?mycountry=KZ)

Congalton R G, Oderwald R G and Mead R A 1983 Assessing Landsat classification accuracy using discrete multivariate analysis statistical techniques *Photogramm. Eng. Remote Sens.* **49** 1671–8

Coppin P, Jonckheere I, Nackaerts K, Muys B and Lambin E 2004 Digital change detection methods in ecosystem monitoring: a review *Int. J. Remote Sens.* **25** 1565–96

de Beurs K M and Henebry G M 2004 Land surface phenology, climatic variation, and institutional change: analyzing agricultural land cover change in Kazakhstan *Remote Sens. Environ.* **89** 497–509

de Beurs K M, Wright C K and Henebry G M 2009 Dual scale trend analysis for evaluating climatic and anthropogenic effects on the vegetated land surface in Russia and Kazakhstan *Environ. Res. Lett.* **4** 045012

de Beurs K M and Ioffe G 2013 Use of Landsat and MODIS data to remotely estimate Russia's sown area *J. Land Use Sci.* **9** 377–401

DIK (Dizajn, Informacija, Kartografija) and Feorija 2011 *Great Atlas of Kazakhstan (Bol'shoj atlas Kazahstana)* (Moscow: Dizain, Informacija, Kartografija)

Dubovyk O, Menz G, Conrad C, Kan E, Machwitz M and Khamzina A 2013 Spatio-temporal analyses of cropland degradation in the irrigated lowlands of Uzbekistan using remote-sensing and logistic regression modeling *Environ. Monit. Assess.* **185** 4775–90

Dudwick N, Sedik D J and Fock K 2007 Land reform and farm restructuring in transition countries *The Experience of Bulgaria, Moldova, Azerbaijan, and Kazakhstan (World Bank working paper 104)* (Washington, DC: World Bank) (http://hdl.handle.net/10986/6685)

Edwards T C Jr, Moisen G G and Cutler D R 1998 Assessing map accuracy in a remotely sensed ecoregion-scale cover map *Remote Sens. Environ.* **63** 73–83

Ellis E C, Klein Goldewijk K, Siebert S, Lightman D and Ramankutty N 2010 Anthropogenic transformation of the biomes, 1700–2000 *Glob. Ecol. Biogeogr.* **19** 589–606

Estes A B, Kuemmerle T, Kushnir H, Radeloff V C and Shugart H H 2012 Land-cover change and human population trends in the greater Serengeti ecosystem from 1984–2003 *Biol. Conserv.* **147** 255–63

FAO 2011 *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW). Managing Systems at Risk* (Rome: FAO) (www.fao.org/docrep/017/i1688e/i1688e.pdf)

FAO 2014 *Economic and Social Development Statistics—Commodity Prices* (www.fao.org/es/esc/prices)

Fischer G, Hizsnyik E, Prieler S and Wiberg D 2011 Scarcity and abundance of land resources: competing uses and the shrinking land resource base *SOLAW Background Thematic Report* TR02 (Rome: FAO) (www.fao.org/fileadmin/templates/solaw/files/ thematic_reports/TR_02_light.pdf)

Florinsky I V, Eilers R G and Lelyk G W 2000 Prediction of soil salinity risk by digital terrain modeling in the Canadian prairies *Can. J. Soil Sci.* **80** 455–63

Foley J A *et al* 2011 Solutions for a cultivated planet *Nature* **478** 337–42

Funakawa S, Yanai J, Takata Y, Karbozova-Saljnikov E, Akshalov K and Kosaki T 2007 *Climate Change and Terrestrial Carbon Sequestration in Central Asia* ed R Lal *et al* (London: Taylor and Francis) pp 279–331

Gathara S T, Gringof L G, Mersha E, Sinha Ray K C and Spasov P 2006 *Impacts of Desertification and Drought and Other Extreme Meteorological Events CAgM Report* 101, WMO/TD 1343 (Geneva, CH: World Meteorological Organization (WMO)) (www.wamis.org/agm/pubs/CAGMRep/CAGM101.pdf)

GRASS Development Team 2014 *Geographic Resources Analysis Support System* (*GRASS*) (v6.4) (http://grass.osgeo.org/)

Geipel R 1964 Die Neulandaktion in Kasachstan *Geogr. Rundsch.* **16** 137–44

Glauben T *et al* 2014 Eastern breadbasket obstructs its market and growth opportunities *IAMO Policy Brief* **16** 1–4 (www.iamo.de/dok/IAMOPolicyBrief16_en.pdf)

Godfray H C J, Beddington J R, Crute I R, Haddad L, Lawrence D, Muir J F, Pretty J, Robinson S, Thomas S M and Toulmin C 2010 Food security: the challenge of feeding 9 billion people *Science* **327** 812–8

Goldewijk K K 2001 Estimating global land use change over the past 300 years: the HYDE database *Glob. Biogeochem. Cycles* **15** 417–33

Gong P *et al* 2013 Finer resolution observation and monitoring of global land cover: first mapping results with Landsat TM and ETM+ data *Int. J. Remote Sens.* **34** 2607–54

Griffiths P, Müller D, Kuemmerle T and Hostert P 2013 Agricultural land change in the Carpathian ecoregion after the breakdown of socialism and expansion of the European Union *Environ. Res. Lett.* **8** 045024

Guerschman J P, Paruelo J M, Di Bella C, Giallorenzi M C and Pacin F 2003 Land cover classification in the argentine pampas using multi-temporal landsat TM data *Int. J. Remote Sens.* **24** 3381–402

Hahn R 1964 Klimatische und bodenkundliche Bedingungen der Neulanderschließung in Kasachstan *Osteuropa* **14** 260–6

Hintze J L and Nelson R D 1998 Violin plots: a box plot-density trace synergism *Am. Stat.* **52** 181–4

Huang C, Davis L S and Townshend J R G 2002 An assessment of support vector machines for land cover classification *Int. J. Remote Sens.* **23** 725–49

Iijima Y, Kawaragi T, Ito T, Akshalov K, Tsunekawa A and Shinoda M 2008 Response of plant growth to surface water balance during a summer dry period in the Kazakhstan steppe *Hydrol. Process.* **22** 2974–81

Ioffe G, Nefedova T and Zaslavsky I 2004 From spatial continuity to fragmentation: the case of russian farming *Ann. Assoc. Am. Geogr.* **94** 913–43

Jensen J R 2005 Introductory digital image processing. A remote sensing perspective (*Prentice Hall Series in Geographic Information Science*) vol 3 (Upper Saddle River, NJ: Pearson)

Josephson P, Dronin N, Cherp A, Mnatsakanian R, Efremenko D and Larin V 2013 An environmental history of Russia *Studies in Environment and History* (Cambridge: Cambridge University Press)

Kamp J, Urazaliev R, Donald P F and Hölzel N 2011 Post-Soviet agricultural change predicts future declines after recent recovery in Eurasian steppe bird populations *Biol. Conserv.* **144** 2607–14

Kazakh Space Research Institute 2013a *Digitized Agricultural Plots with Status of land Use in Circa 1980s* (Almaty: Kazakh Space Research Institute)

Kazakh Space Research Institute 2013b *Digitized Agricultural Plots with Annual Status of Land Use and Date of Harvest for 2006–2013* (Almaty: Kazakh Space Research Institute)

KDS 2001 *Statistical Yearbook of Kostanay Province 1991–2000 (Statisticheskij Ezhegodnik Kostanajskoj Oblasti 1991–2000)* (Kostanay: Kostanay Department of Statistics)

KDS 2011 *Kostanay Province During Independence Time of the Republic of Kazakhstan (Kostanajskaja Oblast'za Gody Nezavisimosti Respubliki Kazahstan)* (Kostanay: Kostanay Department of Statistics)

KDS 2012 *Agriculture, Forestry and Fishery of Kostanay Province in 2007–2011 (Sel'skoe, Lesnoe i rybnoe Hozjajstvo Kostanajskoj Oblasti 2007–2011)* (Kostanay: Kostanay Department of Statistics)

KDS 2013 *Sborniki 2013 god* (www.kostanai.stat.kz/ru/publications/sborniki/sborniki2013.php)

Klein I, Gessner U and Kuenzer C 2012 Regional land cover mapping and change detection in Central Asia using MODIS time-series *Appl. Geogr.* **35** 219–34

Kuemmerle T, Hostert P, Radeloff V C, Linden S, Perzanowski K and Kruhlov I 2008 Cross-border comparison

of post-socialist farmland abandonment in the carpathians *Ecosystems* **11** 614–28
Kuemmerle T *et al* 2013 Challenges and opportunities in mapping land use intensity globally *Curr. Opin. Environ. Sustain.* **5** 484–93
Kurganova I, Lopes de Gerenyu V, Six J and Kuzyakov Y 2014 Carbon cost of collective farming collapse in Russia *Glob. Change Biol.* **20** 938–47
Lambin E F and Meyfroidt P 2011 Global land use change, economic globalization, and the looming land scarcity *Proc. Natl Acad. Sci.* **108** 3465–72
Lambin E, Gibbs H, Ferreira L, Grau R, Mayaux P, Meyfroidt P, Morton D, Rudel T K, Gasparri I and Munger J 2013 Estimating the world's potentially available cropland using a bottom-up approach *Glob. Environ. Change* **23** 892–901
Liefert W, Liefert O, Vocke G and Allen E 2010 Former Soviet Union region to play larger role in meeting world wheat needs *Amber Waves* (www.ers.usda.gov/amber-waves/2010-june/former-soviet-union-region-to-play-larger-role-in-meeting-world-wheat-needs.aspx#.VUJ_GOZNTc)
Lioubimtseva E 2010 Global food security and grain production trends in central eurasia: do models predict a new window of opportunity? *Natl Soc. Sci. J.* **34** 79–92
Lioubimtseva E and Henebry G M 2012 Grain production trends in Russia, Ukraine and Kazakhstan: new opportunities in an increasingly unstable world? *Front. Earth Sci.* **6** 157–66
McCauley M 1976 Khrushchev and the development of Soviet agriculture *The Virgin Land Programme 1953–1964* (New York: Holmes & Meier)
Moscow State University 1964 *Atlas of the Virgin Territory (Atlas Celinnogo Kraja)* (Moscow: Moscow State University, Geography Department)
Müller H, Rufin P, Griffiths P, Barros Siqueira A J and Hostert P 2015 Mining dense Landsat time series for separating cropland and pasture in a heterogeneous Brazilian savanna landscape *Remote Sens. Environ.* **156** 490–9
OECD 2013 *OECD Review of Agricultural Policies: Kazakhstan* 2013 (Paris: OECD Publishing) (doi:10.1787/9789264191761-en)
Olcott M B 1995 *The Kazakhs* vol 2 (Stanford: Hoover Institution Press)
Olofsson P, Foody G M, Stehman S V and Woodcock C E 2013 Making better use of accuracy data in land change studies: estimating accuracy and area and quantifying uncertainty using stratified estimation *Remote Sens. Environ.* **129** 122–31
Pavlova V N, Varcheva S E, Bokusheva R and Calanca P 2014 Modelling the effects of climate variability on spring wheat productivity in the steppe zone of Russia and Kazakhstan *Ecol. Model.* **277** 57–67
Petrick M, Wandel J and Karsten K 2013 Rediscovering the virgin lands: agricultural investment and rural livelihoods in a eurasian frontier *Area World Dev.* **43** 164–79
Pontius R and Schneider L C 2001 Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA *Agric. Ecosyst. Environ.* **85** 239–48
Prishchepov A V, Radeloff V C, Baumann M, Kuemmerle T and Müller D 2012a Effects of institutional changes on land use: agricultural land abandonment during the transition from state-command to market-driven economies in post-Soviet Eastern Europe *Environ. Res. Lett.* **7** 024021
Prishchepov A V, Radeloff V C, Dubinin M and Alcantara C 2012b The effect of Landsat ETM/ETM+ image acquisition dates on the detection of agricultural land abandonment in Eastern Europe *Remote Sens. Environ.* **126** 195–209
Prishchepov A V, Müller D, Dubinin M, Baumann M and Radeloff V C 2013 Determinants of agricultural land abandonment in post-Soviet European Russia *Land Use Policy* **30** 873–84
Propastin P A, Kappas M W and Muratova N R 2008 Inter-annual changes in vegetation activities and their relationship to temperature and precipitation in central Asia from 1982 to 2003 *J. Environ. Inf.* **12** 75–87
R Development Core Team 2011 *R: A Language and Environment for Statistical Computing* (www.r-project.org/)
Rabe A, van der Linden S and Hostert P 2010 *imageSVM* (*v2.1*) (www.imagesvm.net)
Ramankutty N and Foley J A 1999 Estimating historical changes in global land cover: croplands from 1700 to 1992 *Glob. Biogeochem. Cycles* **13** 997–1027
Ramankutty N, Foley J A, Norman J and McSweeney K 2002 The global distribution of cultivable lands: current patterns and sensitivity to possible climate change *Glob. Ecol. Biogeogr.* **11** 377–92
Ramankutty *et al* 2006 *Land-Use and Land-Cover Change* ed E F Lambin and H Geist (Berlin: Springer) pp 9–39
Robinson S, Milner-Gulland E and Alimaev I 2003 Rangeland degradation in Kazakhstan during the Soviet era: re-examining the evidence *J. Arid Environ.* **53** 419–39
Rumer B Z and Zhukov S V 1998 *Central Asia: The Challenges of Independence* (New York: M.E. Sharpe)
Schierhorn F, Müller D, Beringer T, Prishchepov A V, Kuemmerle T and Balmann A 2013 Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus *Glob. Biogeochem. Cycles* **27** 1175–85
Schierhorn F, Müller D, Prishchepov A V, Faramarzi M and Balmann A 2014 The potential of Russia to increase its wheat production through cropland expansion and intensification *Glob. Food Secur.* **3** 133–41
Selyaninov T G 1928 On the agricultural estimation of climate *Proc. Agric. Meteorol.* **20** 165–77
Senf C, Leitão P J, Pflugmacher D, van der Linden S and Hostert P 2015 Mapping land cover in complex Mediterranean landscapes using Landsat: improved classification accuracies from integrating multi-seasonal and synthetic imagery *Remote Sens. Environ.* **156** 527–36
Smith G 1999 *The Post-Soviet States. Mapping the Politics of Transition* (New York: Oxford University Press)
Song C, Woodcock C E, Seto K C, Lenney M P and Macomber S A 2001 Classification and change detection using Landsat TM data *Remote Sens. Environ.* **75** 230–44
Suleimenov M and Oram P 2000 Trends in feed, livestock production, and rangelands during the transition period in three Central Asian countries *Food Policy* **25** 681–700
Terekhov A 2010 *NELDA Test Site Report. Kostanay Site (Kazakhstan)* (www.fsl.orst.edu/nelda/sites/docs/NELDA_site6_final_report_Kazakhstan.pdf)
USGS 2013 *Landsat processing details* (http:// landsat.usgs.gov/Landsat_Processing_Details.php)
Vapnik V N 1995 *The Nature of Statistical Learning Theory* (New York: Springer)
Voropay N N, Maksyutova E V and Balybina A S 2011 Contemporary climatic changes in the Predbaikalie region *Environ. Res. Lett.* **6** 045209
Wein N 1980 Fünfundzwanzig jahre neuland *Geogr. Rundsch.* **32** 32–8
World Bank 2004 *Kazakhstan's Livestock Sector: Supporting its Revival* (Washington, DC: World Bank) (http://documents.worldbank.org/curated/en/2004/06/5584117/kazakhstans-livestock-sector-supporting-revival)
Wright C K, de Beurs K M and Henebry G M 2012 Combined analysis of land cover change and NDVI trends in the Northern Eurasian grain belt *Front. Earth Sci.* **6** 177–87
Zhou Y, Zhang L, Fensholt R, Wang K, Vitkovskaya I and Tian F 2015 Climate contributions to vegetation variations in central asian drylands: pre- and post-USSR collapse *Remote Sens.* **7** 2449–70
Zhu Z and Woodcock C E 2012 Object-based cloud and cloud shadow detection in Landsat imagery *Remote Sens. Environ.* **118** 83–94