Title page – In press (January 2016) in *Global Environmental Change*
http://dx.doi.org/10.1016/j.gloenvcha.2016.01.003

Drivers, constraints and trade-offs associated with recultivating abandoned cropland in Russia, Ukraine and Kazakhstan

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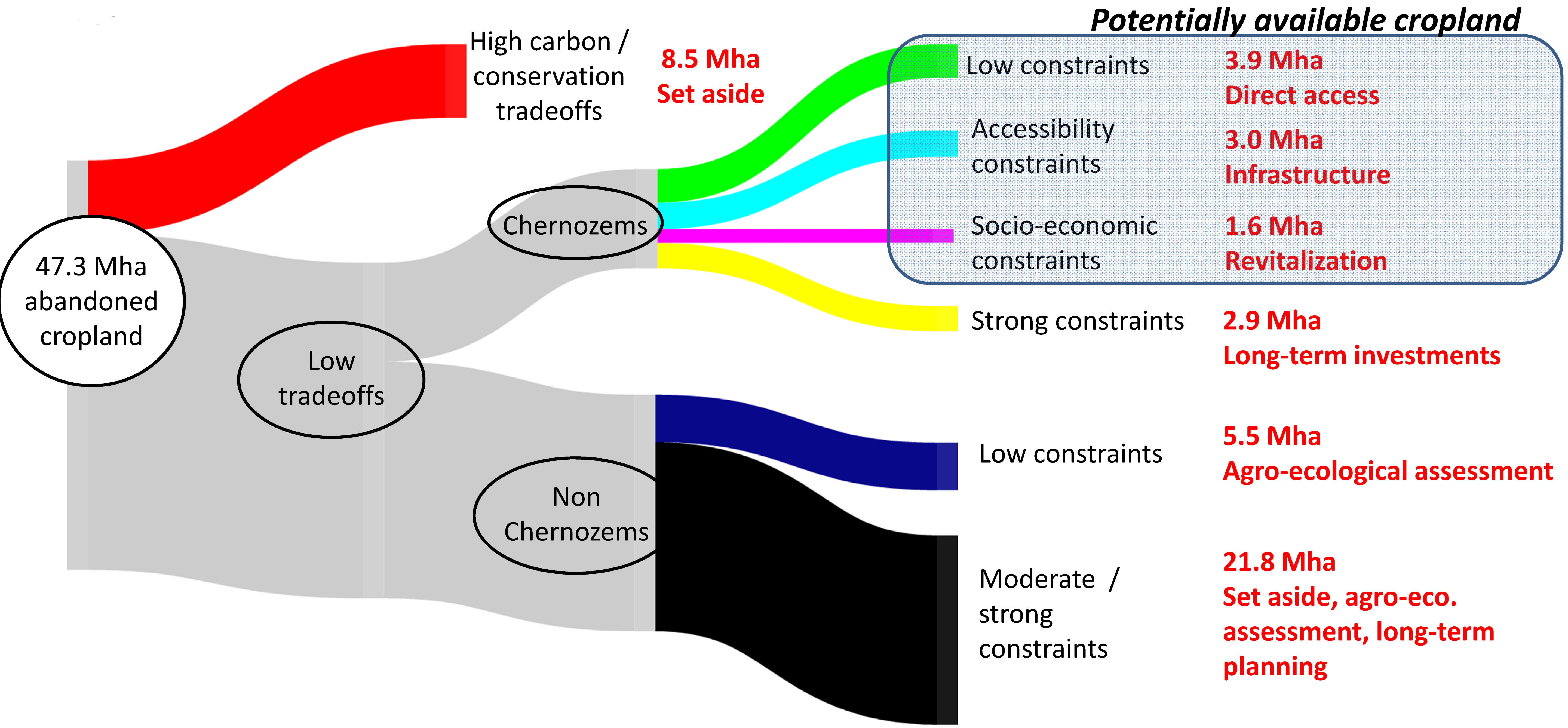
Acknowledgments

We gratefully acknowledge financial support provided by the Einstein Foundation Berlin (Germany), the German Federal Ministry of Food and Agriculture and the Federal Office for Agriculture and Food (project GERUKA), the Leibniz Foundation (project EPIKUR), the German Ministry for Research and Education (project KULUNDA), the Volkswagen Foundation (BALTRAK), Russian Federation Program on Basic Research by Research Institutions 2013-2020 № 01201351529 and № 01201351530 and the NASA Land-Cover/Land-Use Change (LCLUC) Program under award NNX13AC66G. These funding sources had no involvement in the design, analysis, or writing of this study or the decision to publish it. Many thanks to Giovanni Millo for his dynamic support with the R splm package and spatial panel regressions. This study contributes to the Global Land Project http://www.globallandproject.org/ .

Citation:

Meyfroidt P, Schierhorn F, Prishchepov AV, Müller D, Kuemmerle T (2016). Drivers, constraints and trade-offs associated with recultivating abandoned cropland in Russia, Ukraine and Kazakhstan. *Global Environmental Change*, in press, http://dx.doi.org/10.1016/j.gloenvcha.2016.01.003

Graphical Abstract



*Highlights ((without author details, acknowledgements or affiliations)

Highlights

- Ongoing recultivation in areas with young, increasing rural population and higher yields
- 8.5 Mha of potentially available cropland among 47.3 Mha of abandoned cropland
- Potential contribution to global grain production, but socio-economic constraints
- Environmental trade-offs are relatively low compared with tropical frontiers
- Idle croplands not a silver bullet for the global food – carbon – biodiversity nexus

Drivers, constraints and trade-offs associated with recultivating abandoned cropland in Russia, Ukraine and Kazakhstan

Abstract

Further cropland expansion might be unavoidable to satisfy the growing demand for land-based products and ecosystem services. A crucial issue is thus to assess the trade-offs between social and ecological impacts and the benefits of converting additional land to cropland. In the former Soviet Union countries, where the transition from state-command to market-driven economies resulted in widespread agricultural land abandonment, cropland expansion may incur relatively low costs, especially compared with tropical regions.

Our objectives were to quantify the drivers, constraints and trade-offs associated with recultivating abandoned cropland to assess the potentially available cropland in European Russia, western Siberia, Ukraine and Kazakhstan—the region where the vast majority of post-Soviet cropland abandonment took place. Using spatial panel regressions, we characterized the socio-economic determinants of cropland abandonment and recultivation. We then used recent maps of changes in cropland to (i) spatially characterize the socio-economic, accessibility and soil constraints associated with the recultivation of abandoned croplands and (ii) investigate the environmental trade-offs regarding carbon stocks and habitat for biodiversity.

Less cropland abandonment and more recultivation after 2000 occurred in areas with an increasing rural population and a younger labor force, but also improved yields. Synergies were observed between cropland recultivation and intensification over the 2000s. From 47.3 million hectares (Mha) of cropland abandoned in 2009, we identified only 8.5 (7.1-17.4) Mha of potentially available cropland with low environmental trade-offs and low to moderate socio-economic or accessibility constraints that were located on high-quality soils (Chernozems). These areas represented an annual wheat production potential of ~14.3 (9.6-19.5) million tons (Mt). Conversely, 8.5 (4.2-12.4) Mha had high carbon or biodiversity trade-offs, of which ~10% might be attractive for cropland expansion and thus would require protection from recultivation. Agro-environmental, accessibility, and socio-economic constraints suggested that the remaining 30.6 (25.7-30.6) Mha of abandoned croplands were unlikely to provide important contributions to future crop production at current wheat prices but could provide various ecosystem services, and some could support extensive livestock production. Political and institutional support could foster recultivation by supporting investments in agriculture and rural demographic revitalization. Reclaiming potentially available cropland in the study region could provide a notable contribution to global grain production, with relatively low environmental trade-offs compared with tropical frontiers, but is not a panacea to address global issues of food security or reduce land-use pressure on tropical ecosystems.

Keywords: Land use; Cropland reclamation; rewilding; food production; carbon; biodiversity

1. Introduction

With a growing population and increasing affluence, the world is facing a surging demand for food, fiber and bioenergy. In addition, land demands have increased for non-provisioning ecosystem services, including carbon sequestration and safeguarding of biodiversity. Although intensification will have to provide for most of the additional production, some further agricultural expansion will likely be unavoidable (Lambin and Meyfroidt 2011). Land scarcity, the 2007-2008 spikes in food prices (Piesse and Thirtle 2009, Godfray et al. 2010) and the aftermath of the 2008 financial crisis led to a growing interest in identifying regions with unused or underused land reserves, and to large-scale land acquisitions (Deininger et al. 2011, Visser and Spoor 2011, Byerlee and Deininger 2013). However, most of the land suitable for additional cropland is covered by natural areas with high environmental value, particularly in the tropics, where multiple policies and instruments now seek to limit conversion (Lambin et al. 2014, Gibbs et al. 2015, Gasparri et al. 2015, Lehmann 2010). Moreover, land suitable for market-oriented agriculture is often already used by smallholders or livestock herders (Lambin et al. 2013), and converting this land could incur high social costs and trigger conflicts, as highlighted through the recent debate on "land grabbing" (Borras Jr et al. 2011). Further, various agro-environmental, socio-economic and political factors can constrain cropland expansion. A crucial issue is thus to assess the constraints and trade-offs associated with the conversion of additional land to cropland and to identify "potentially available cropland" for cropland expansion at a low social and ecological cost (Lambin et al. 2013, Eitelberg et al. 2015).

While land-use pressure has been increasing in the tropics, it has been relaxing in other world regions (Cramer et al. 2008; Meyfroidt and Lambin 2011, Ramankutty et al. 2010). This is particularly true across temperate developed countries, where agricultural abandonment and reforestation have become widespread due to agricultural intensification (e.g., adoption of new technologies, higher input levels), land-use policies, a larger reliance on traded agricultural commodities, and structural changes in agriculture (MacDonald et al. 2015). For example, Eastern North America underwent major reforestation trends during the 20th century (Ramankutty et al. 2010). Similarly, abandonment has been a major land-use trend in Europe, mostly over the recent decades (Hatna and Bakker 2011; Navarro and Pereira 2012, Estel et al. 2015). Abandonment has been particularly widespread in regions that are marginal for farming, including mountains (Gellrich et al. 2007; MacDonald et al. 2000), dry areas in the Mediterranean (Piquer-Rodríguez et al. 2012; Stellmes et al. 2013) and Scandinavia (Ericsson et al. 2000). However, abandonment has also occurred in areas favorable for farming due to multiple socio-economic and political dynamics (Baumann et al. 2014, van der Sluis et al. 2015).

Abandonment and natural vegetation regrowth can have mixed outcomes, depending on the context and dynamics (Meyfroidt and Lambin 2011). Abandonment provides potential for ecological restoration, e.g., by benefiting carbon sequestration (Schierhorn et al. 2013, Kuemmerle et al. 2015, Kurganova et al. 2014) and species sensitive to land management (Cramer et al. 2008, Queiroz et al. 2014, Kamp et al. 2011). However, abandonment can also reduce water availability (Rey Benayas 2007) and induce wildfire risk (Moreira and Russo 2007) and salinization (Penov 2004), and has contrasting effects on soil erosion (Ruiz-Flaño et al. 1992; Stanchi et al. 2012). Agricultural abandonment can also threaten farmland biodiversity (Plieninger et al. 2014; Queiroz et al. 2014) and cultural heritage landscapes (Fischer et al. 2012), and may amplify the geographic displacement of agriculture and its environmental impacts in more sensitive regions (Meyfroidt et al. 2010, Kastner et al. 2015). Thus, under certain conditions, recultivating parts of the abandoned agricultural land in temperate regions could be an attractive option to increase agricultural production while mitigating some of the unwanted outcomes of abandonment and of agricultural expansion in other regions.

One of the global hotspots of currently unused agricultural land is Eastern Europe and the former Soviet Union, in particular Russia, Ukraine and Kazakhstan (RUK) (Prishchepov et al. 2012, Ioffe et al. 2014, Estel et al. 2015, Kraemer et al. 2015), which held 90% of all cropland of the Soviet Union in 1991 (FAO 2015). The dissolution of the Soviet Union and the subsequent transition from state-command to market-driven economies drastically affected agriculture (Ioffe et al. 2004). Incomplete or inadequate land reforms, loss of guaranteed markets, a dramatic decline in subsidies for inputs and the collapse of the livestock sector resulted in the widespread cropland abandonment (Ioffe et al. 2012, Prishchepov et al. 2013, Rozelle and Swinnen 2004). From 1991 to 2000, approximately 31% or 57 million hectares (Mha) of croplands were abandoned across RUK (ROSSTAT 2014, UKRSTAT 2014, KAZSTAT 2014), mainly but not exclusively in socio-economically and agro-environmentally marginal areas (Ioffe et al. 2004, Prishchepov et al. 2013). After 2000, abandonment has continued outside the Chernozem regions, especially in northern and temperate Russia (Schierhorn et al. 2013). The socio-economic mechanisms underlying post-Soviet agricultural abandonment remain weakly understood though, as most existing studies have focused on factors explaining the spatial patterns of abandonment in local contexts (but see Ioffe et al. 2004). Moreover, while yields or agro-environmental suitability, accessibility and demography have been shown to drive abandonment patterns, the importance and sign of the influence of these factors varied spatially and temporally (Baumann et al. 2011, Vanwambeke et al. 2012, Müller et al. 2013, Prischchepov et al. 2013).

With the economic recovery and increasing domestic and foreign investments in agriculture after 2000, recultivation of some abandoned croplands started, particularly in the agriculturally favorable Chernozem (Black Earth) regions in the south of European Russia, Ukraine and northern Kazakhstan. RUK have recently resurfaced as important players in the world grain market (Schierhorn et al. 2014a, Petrick et al. 2013), mainly through increases in yields, increased concentration on grain production and the offshoring of livestock production—mainly to Brazil (Prishchepov et al., 2013, Schierhorn et al. forthcoming). Recultivation of suitable, yet currently abandoned croplands could further increase the role of RUK as major grain suppliers. However, little is known about the environmental and socio-economic implications of recultivation. As approximately 10-15% of abandoned croplands have already been reverted to young forest, particularly in the temperate region (Potapov et al. 2015, Sieber et al. 2013), and a notable soil carbon sink has developed since 1991 (Kurganova et al. 2014; Schierhorn et al. 2013), the environmental and economic costs of recultivation could be substantial.

The objectives of this study were to quantify the drivers, constraints and trade-offs associated with recultivating abandoned cropland in Russia, Ukraine and Kazakhstan. We aimed to characterize the potentially available cropland, which we defined as moderately to highly productive land that could be used in the coming years for rainfed farming with low to moderate capital investments that is not under intensive use, legally protected or covered by mature forest (Lambin et al. 2013). We started with an econometric analysis of the socio-economic drivers of cropland abandonment and recultivation, which allowed us to characterize the constraints on recultivation (see a flowchart of the methodology in Figure S1). We then combined this analysis with recent maps of cropland dynamics and carbon budgets for the region as well as ancillary data on the biodiversity value and suitability for crop production. Specifically, we spatially characterized (i) the socio-economic and agro-environmental constraints on recultivating abandoned croplands, including infrastructure requirements, market access, labor force and soil quality, and (ii) the environmental trade-offs in terms of carbon stocks and habitat for biodiversity.

2. Data and Methods

2.1 Mapping abandoned and recultivated land

Our study area covered Ukraine, Kazakhstan, European Russia, and the western part of Asian Russia, from the Urals to Altai Krai (hereafter: western Siberia). We excluded three provinces due to data gaps, the two large areas of Moscow and Saint Petersburg, and northern provinces which did not contain cropland. For Russia, the study area included 31.4 Mha of abandoned cropland, from the ~41 Mha recorded for the whole country. The remaining 10 Mha of abandoned cropland in eastern Siberia and the Russian Far East were thus not assessed here due to lack of consistent data. The cropland area in the Soviet Union peaked in the 1970s and already started slowly to decline in the 1980s (Nefedova 2011). In this study, we only considered the cropland abandoned after 1991 as the initial pool of potentially available cropland, because lands abandoned before 1991 were generally very marginal for cropping or were degraded and had reverted back to natural forests or steppes with likely large carbon accumulation and biodiversity restoration.

All analyses were carried out in Albers equal area cartographic projection. To map cropland abandonment and recultivation, we relied on the methodology from Schierhorn et al. (2013). That study used a disaggregation approach to spatially allocate annual sown area statistics reported at the provincial (i.e., *oblast*) level based on a cropland suitability map at a 1-km^2 spatial resolution. Cropland suitability was estimated using a spatial regression that related grain yields to biophysical characteristics and accessibility at the district level (i.e., *rayons*) in European Russia, Ukraine and Belarus. The resulting maps of annual cropland extent allowed us to calculate the years of abandonment and recultivation per pixel from 1991 until 2009. The maps were thus consistent with official provincial-level sown area statistics, the most reliable source for characterizing cropland extent (Ioffe et al. 2004, Schierhorn et al. 2013). The 2003 cropland map had an overall accuracy of 65% on a per pixel basis (Schierhorn et al. 2013), and hotspots of cropland abandonment corresponded well with those mapped from MODIS satellite images (Estel et al. 2015). Here, we expanded the disaggregation approach to Kazakhstan and western Siberia.

2.2 Assessing constraints on recultivation

Statistical analyses of socio-economic drivers of cropland abandonment and recultivation.

We first compiled a set of socio-economic variables for the three countries at the provincial level, based on official statistics (Supplementary Information). Using the splm package in R (Millo and Piras 2012), we performed spatial panel, fixed effects regressions to identify the socio-economic factors explaining cropland abandonment during the peak abandonment over the period 1991-1996, and cropland recultivation over the period 2006-2009, with the assumption that the latter factors would continue to foster or hinder recultivation in the short to medium-term. The fixed-effects approach allowed assessing the importance of socio-economic dynamics while controlling for time-invariant or slowly changing factors, such as biophysical factors (e.g., soils and climate), accessibility, and other location-specific effects. The two periods corresponded to the most dynamic periods for abandonment and recultivation, where 47% of the total abandonment and 59% of the total recultivation between 1991 and 2009 occurred over 1991-1996 and 2006-2009, respectively. We also considered the availability of consistent socio-economic variables across the three countries to select study periods. Due to boundary changes, some provinces were merged to obtain consistent units for the whole period (e.g., in northern Kazakhstan). In total, we used 94 spatial units: 60 in Russia, 25 in Ukraine, and 9 in Kazakhstan. The dependent variables (Table 1) were (i) the yearly rate of cropland abandonment over the period 1991-1996, calculated for each year as the ratio of abandoned land (cumulative abandoned area minus recultivated area) to the total cropland area in 1991, and (ii) the yearly rate of recultivation over the period 2006-2009, calculated as the ratio of the cumulative area recultivated after abandonment to the cumulative area of cropland abandoned.

Our main hypotheses about the socio-economic causes of agricultural abandonment dwelled on the idea of "Black holes", which proposes that land abandonment is concentrated in areas which, beyond having marginal agro-environmental conditions, also have a declining, ageing, poor and unskilled labor force, and low and declining yields (Ioffe et al. 2004). Reflecting this idea, our set of explanatory variables contained four demographic indicators: the crude birth rate, rural life expectancy (unavailable for Ukraine for 1991-1996, thus used only for 2006-2009), population density and ethnic population, i.e., the percentage of the population belonging to an ethnic group other than the majority group in the country (e.g., non-ethnic Russians in the Russian Federation). We used crude birth rates and rural life expectancy as proxies for the age structure of the population and its demographic activity, and its socio-economic status, respectively. We expected that provinces with an older, less demographically active population would have less skilled labor, which would increase abandonment and hinder recultivation (Wegren 2014a). In addition, temporal variations in grain yields were used as an indicator of agricultural intensification or dis-intensification dynamics. Controlling for yield changes allowed for the characterization of the interactions between the changes in intensity and land use, acknowledging that the causality of such relationships could go in both directions.

To accommodate for various sizes and spatial configurations of observation units, the matrix of spatial interaction weights was based on the five nearest neighbors of each unit. Alternative formulations based on contiguity or a different number of neighbors produced qualitatively similar results. We used Conditional Lagrange Multiplier tests to assess the presence of random effects and spatial correlation effects (Baltagi et al. 2003, Millo and Piras 2012). Spatial lag terms capture spillover effects (i.e., spatial interactions due to effects of changes in the dependent variable in one province on changes in a neighboring province, such as through diffusion, imitation, or agglomeration economies effects), while spatial error terms correct for other sources of spatial autocorrelation, such as due to omitted explanatory variables affecting neighboring provinces. We implemented four models for cropland abandonment: one aggregate model using observations from all three countries, as well as one model for each country. Because recultivation was absent in many provinces, we present only the aggregate model for all three countries for recultivation.

Traditional measures of goodness of fit are inappropriate for spatial panel models with fixed effects and both spatial lag and spatial error components (Elhorst 2014). We thus recalculated each model using non-spatial panels, maintaining all other specifications, and assessed the goodness of fit of these models by calculating the adjusted R^2. Given that at least one spatial component was significant in each model, and often both were, adding the spatial components should have improved the performance.

Mapping socio-economic, accessibility and agro-environmental constraints on recultivation.

We then mapped the constraints on recultivation for each pixel of abandoned cropland in three dimensions. We first used the recultivation rate for 2009 (the latest year available) predicted by the aggregate statistical model as a proxy for the level of socio-economic barriers to recultivation. Based on natural breaks in the histogram, we classified this indicator into three categories: strong (negative fitted value or no recultivation), moderate (0-25% of abandoned land predicted to be recultivated), and low constraints (>25%).

Second, poor accessibility, i.e., high distance to potential markets and transportation costs, is a strong determinant of abandonment in post-Soviet countries (Ioffe et al. 2004, Prishchepov et al. 2013) and was thus considered a strong constraint on recultivation (Visser and Spoor 2011). We used the unitless market accessibility index from Verburg et al. (2011), with lower values reflecting less favorable accessibility to national and international markets (large cities and ports). Following Verburg et al. (2011), we devised three accessibility constraint categories: strong (index ranging between 0-0.1, i.e., more than 6 hours (h) of travel to a major city), moderate (0.1-0.3 = 3-6 h) and low (0.3-1 = less than 3 h).

Third, agro-environmental suitability is an important driver of land abandonment (Ioffe et al. 2004, Prishchepov et al. 2013, Kraemer et al., 2015), and unfavorable agro-environmental conditions should thus constrain recultivation. Suitability for cropping is strongly influenced by soil quality and precipitation, though the latter has very heterogeneous effects across biomes (Schierhorn et al. 2013). We thus used the presence of Chernozem soils, which have the highest quality for agriculture (Schierhorn et al. 2013, Lioubimtseva et al. 2013), as an indicator of cropland suitability. Soil data were obtained from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC 2012). In an alternative scenario, we also used two climatic indicators: Selyaninov’s hydrothermal coefficient (HTC) (Dronin and Kirilenko 2008, 2011) as an indicator of aridity in the Southeastern margins of the study area, and the number of degree-days for days above 10°C (data from Afonin et al. 2008). HTC is calculated as the ratio of total precipitation and average daily air temperature during the growing season (days with an average temperature >5 °C).

2.3 Accounting for potential environmental costs of recultivation

To spatially assess the possible trade-offs involved in recultivation, we analyzed the ratio between carbon stocks and expected grain yield (Searchinger et al. 2015), and biodiversity patterns. Schierhorn et al. (2013) used the dynamic vegetation model LPJmL on 0.5°-grid cells to calculate carbon accumulation in abandoned cropland in European Russia up to 2009 and Ukraine up to 2008, which we used to derive the average annual carbon accumulation rate per hectare for each 0.5°-grid cell. The figures obtained for the eastern part of the study area were very low, and we used ordinary kriging to spatially interpolate and extrapolate this dataset to estimate the carbon accumulation rates throughout Kazakhstan and western Siberia. Based on the carbon accumulation rate and the abandonment year, we calculated the carbon stored per pixel of abandoned cropland. The carbon versus yields trade-off was calculated, per pixel, as the ratio between carbon stocks in Mg C ha^{-1} and the average grain yield over 2004-2009 in the province in Mg ha^{-1} y^{-1}. We used a threshold of 2.5 Mg C/Mg grain y^{-1} to identify areas with relatively high carbon trade-off, where recultivation would thus entail high carbon emissions. We also identified areas with a potentially high conservation value that could be negatively affected by the reclamation of former cropland as areas located inside or within a 5-km buffer of (i) protected areas from the World Database of Protected Areas (IUCN/UNEP 2013); (ii) intact forest landscapes (Potapov et al. 2008); and (iii) Global 200 priority ecoregions (Olson and Dinerstein 1998).

2.4 Combining constraints and trade-offs, and estimating potential agricultural production on abandoned cropland

We combined the above maps to identify seven categories of combinations of constraints and trade-offs: (i) land with high carbon and/or conservation trade-offs (all other categories having low environmental trade-offs), (ii) land with low constraints or a single moderate constraint (socio-economic or accessibility), on Chernozem soil, (iii) land on Chernozems with strong accessibility constraint and low socio-economic constraints, (iv) land on Chernozems with strong socio-economic constraint and low accessibility constraint, or moderate constraints on both indicators, (v) land on Chernozems with one strong and one moderate constraint, (vi) land outside of Chernozems, with only low constraints, and (vii) land outside of Chernozems with moderate or strong constraints. We constructed two decision trees to illustrate how our approach could be used to reflect different ways to prioritize constraints and trade-offs to allocate abandoned cropland to different uses. We identified hotspots of the major categories of combinations of constraints and trade-offs associated with abandoned cropland using a moving window, which calculated the majority category of abandoned cropland in a circular radius of 25 km around each pixel. We converted this result to polygons and all polygons smaller than 5,000 km^2 were then removed. Sensitivity analyses using other window sizes and minimum size thresholds provided similar results. Based on this approach, a hotspot reflected the dominance of a certain category among areas of abandoned cropland, but a hotspot did not necessarily contain large areas of abandoned cropland. Further, not all abandoned croplands within a hotspot were characterized identically.

To assess the uncertainties on all constraints and trade-offs and their combinations, we calculated two alternative estimates of the different categories of abandoned cropland. A first scenario used more conservative thresholds for the constraints and trade-offs, thus resulting in a lower estimate of potentially available cropland. Thresholds for this scenario were 5% and 30% of predicted recultivation for the socio-economic constraints, 0.15 and 0.35 for the categories of accessibility constraints, and a 10 km buffer around areas of conservation value. The threshold for carbon, being already very low, was not changed. A second scenario used more relaxed thresholds for the constraints and trade-offs, thus resulting in a higher amount of potentially available cropland. Thresholds for this scenario were -5% and 20% of predicted recultivation for the thresholds of socio-economic constraints, 0.05 and 0.25 for the categories of accessibility constraints, a 1 km buffer around areas of conservation value, and a 5 Mg C/Mg grain y^{-1} threshold for the carbon trade-off. In addition, for the second scenario, areas outside of Chernozems with HTC > 0.6 and accumulated degree days for days above 10°C > 1600 (based on Ioffe and Nefedova (2004) and Ioffe et al. (2004)) were considered as having moderate agro-environmental constraints for wheat production. Areas located on Chernozems and above these climatic constraints were considered as having low agro-environmental constraints. Areas outside of Chernozems and below these climatic thresholds were considered as having strong agro-environmental constraints. An HTC index below 0.7 is generally considered as indicating droughts (Dronin and Kirilenko 2008, 2011), but in Kazakhstan croplands in some regions were found to have an HTC index close to 0.5, as a legacy of the Virgin Lands campaign (Kraemer et al. 2015). Based on these scenarios, we assessed the range of uncertainty for each of the seven categories of abandoned cropland listed above by selecting the lowest and highest value of all possible scenarios.

Finally, we multiplied the areas of different categories of abandoned cropland with the observed wheat yields by province to calculate the wheat production potentials. To account for the large annual fluctuations in yields due to climate variation, we used low, medium and high yields from 2004 to 2013 (Schierhorn et al. 2014b). We used wheat as a representative crop for RUK because it is well adapted to various climate and biophysical conditions and is the most important export crop of RUK for the world market (Schierhorn et al. 2014a). We did not multiply the uncertainties on constraints and trade-offs on abandoned cropland with uncertainties in yields, as they partly reflect similar sources of uncertainties.

3. Results

3.1 Abandoned cropland

A total of 59.3 Mha of cropland had been abandoned between 1991 and 2009 in the study area, of which 35.9 Mha were located in the studied part of Russia, 2.9 Mha in Ukraine, and 20.6 Mha in Kazakhstan. Of that, 12.0 Mha or 20% had already been recultivated by 2009, mainly in the Chernozem belt, and most of it (81%) was recultivated after 2003 (4.5 Mha in Russia, 0.3 Mha in Ukraine, and 7.2 Mha in Kazakhstan). In 2009, a total of 47.3 Mha were thus still abandoned within our study area, of which 31.4 Mha were in Russia, 2.6 Mha were in Ukraine, and 13.4 Mha were in Kazakhstan (Fig. 1). In terms of area, this equaled 40.3%, 9.6%, and 62.4% of the total cropland cultivated in these three countries, respectively, in 2009. The 47.3 Mha constituted the pool of abandoned cropland that we investigated further.

3.2 Determinants of abandonment and recultivation

The general performance of our abandonment models was satisfactory; the adjusted R^2 of the corresponding non-spatial panel models ranged between 0.32 and 0.64 (Table 2). The performance of the non-spatial recultivation model was lower (0.18), but the performance of the spatial model was likely higher with the two highly significant spatial variables. For the aggregate model (all countries together), abandonment was positively associated with declining crude birth rates, corresponding to older and less reproductively active populations. Greater cropland abandonment was also associated with lower population densities, more ethnic minority populations (i.e., non-Russians in Russia, non-Kazakhs in Kazakhstan, and non-Ukrainians in Ukraine) and lower grain yields. The spatial lag parameter was highly significant and positive. Therefore, abandonment in one province was positively associated with abandonment in neighboring provinces, showing the presence of spillover effects.

The results of the country models were broadly consistent with the findings for the aggregate model across RUK. The country models provided some nuances on the aggregate results, but given the lower number of spatial units and the smaller heterogeneity for each variable, the relationships were generally weaker than in the general model. Population density was a significant factor in the Ukraine, but not in the Kazakhstan and Russia country models. By contrast, the significant negative effect of yields on abandonment was only observed in Russia. In all models, the spatial lag parameters were highly significant, and always positive except for Ukraine. Thus, cropland abandonment in Ukraine tended to be lower in provinces whose neighbors had larger abandonment and vice versa. The spatial error parameter was not significant for the aggregate model but was significant for several country-level models, i.e., positive for Ukraine, and negative for Kazakhstan.

The results for the recultivation model (all countries together) were broadly consistent with those for abandonment. The spatial lag parameter was significant and positive, suggesting clustered spatial patterns with spillover effects of recultivation in one province on recultivation in neighboring provinces. Increased crude birth rates, ethnic minority populations and grain yields were associated with greater rates of recultivation.

3.3 Spatial pattern of constraints and trade-offs

The different constraints showed contrasting spatial patterns across RUK (Fig. 2). Places with major socio-economic constraints on recultivation, broadly characterized by a demographically less active population and declining yields, were spread mainly across central European Russia and the Volga region (Fig. 2a). Accessibility constraints dominated in the central-eastern RUK area, stretching from the eastern Volga region to western Siberia and Kazakhstan, as well as some areas of European Russia (Fig. 2b). Abandoned cropland under Chernozem soils formed a belt starting from Ukraine, going through southwestern European Russia, and the Volga region, and across the Russian-Kazakh border, covering parts of the Urals and western Siberia (Fig. 2c). Regarding trade-offs, areas with important carbon accumulation and carbon to yield ratio were concentrated mainly in western European Russia, where the earliest cropland abandonment occurred and where woody vegetation regrowth was relatively advanced (Fig. 2d). Areas with a potential biodiversity value that could be adversely affected by cropland recultivation were spread throughout the three countries (Fig. 2e).

3.4 Hotspots of constraints and trade-off combinations and potential grain production

A scattered pattern of combinations of constraints and trade-offs emerged from our analyses (Fig. 3). However, some hotspots (i.e., concentrations) of specific types of potentially available cropland appeared (Fig. 2f). The two decision trees reflected the potential priorities of certain actors, such as public authorities, environmental organizations or private land investors, concerned with balancing environmental conservation with agricultural production (Fig. 4a), or alternatively, the priorities of actors placing emphasis on identifying land with high potential for relatively rapid agricultural development (Fig. 4b). Following the first tree (Fig. 4a, corresponding to the categories displayed in Fig. 1, 3 and 5, full results with uncertainties ranges are in Table S1), abandoned cropland with high carbon trade-off and/or high conservation concerns covered 8.5 (4.2-12.2) Mha scattered across the study area. Hotspots corresponded occasionally to areas where early abandonment led to a large carbon accumulation (mainly in northern and temperate Russia), but frequently to areas of high conservation value (e.g., in northern and western Ukraine, the Ural and North Caucasus Mountains, and southern Kazakhstan steppes). A total of 11.5 (10.6-18.6) Mha had relatively good agricultural potential and potentially low environmental trade-offs. Of these, 3.9 (2.6-7.2) Mha had low constraints in terms of accessibility and socio-economic characteristics and thus constituted low-hanging fruits that could be reclaimed relatively easily (displayed in green). These lands were concentrated in eastern Ukraine, southwestern European Russia, the south-central parts of European Russia and the Volga regions, and the westernmost part of Siberia. In southern European Russia and Kazakhstan, large tracts of land had already been reclaimed after 2000 (Fig. 3), and abandoned fields most suitable for recultivation were located in their proximity. Areas affected by a single constraint, either accessibility or socio-economic conditions, and located on Chernozems or areas with suitable climatic conditions, covered 4.6 (4.4-10.2) Mha (Fig. 4a, light blue and magenta). Concentrations of areas with socio-economic constraints were located in eastern Ukraine and the northern part of the Chernozem belt, while concentrations of accessibility constraints were in central European Russia, northern Kazakhstan, and western Siberia (Fig. 3). These 8.5 (7.1-17.4) Mha with low environmental trade-offs, low or moderate constraints, and which were located on Chernozem soils, constituted the pool of potentially available cropland according to our above definition. The recultivation of these 8.5 Mha would increase wheat production by approximately 14.3 (9.6-19.5) Mt (Fig. 5).

The remaining 2.9 (1.2-3.5) Mha with suitable agro-environmental conditions, located mainly in the Volga region and northeastern Kazakhstan, had several moderate to strong socioeconomic or accessibility constraints on recultivation (yellow). These lands could eventually be reclaimed to contribute to agricultural production, but this would require substantial long-term investments in both infrastructure and socio-economic revitalization. Approximately 27.7 (24.5-27.7) Mha of abandoned cropland with low environmental trade-offs occurred on land with moderate or strong agro-environmental constraints. Of these, 5.4 (2.7-9.6) Mha, located mainly in southeastern and central European Russia and the Volga region (Fig. 3), had relatively low socio-economic or accessibility constraints on recultivation (dark blue). Additional reclamation of these 5.4 Mha could yield 10.4 (7.3-13.6) Mt of wheat (Fig. 5). The remaining 21.8 (14.9-21.8) Mha, mainly in the north-central European Russia and the Volga and Urals regions, were identified as having multiple strong or moderate constraints (black). These lands would be very difficult to reclaim, for little economic gain, and were thus likely to remain uncultivated.

In a second tree (Fig. 4b), 9.3 Mha were identified with expectations of good suitability for agricultural production and low to moderate constraints on recultivation, which represents the land most attractive to investors. Of these, 0.7 Mha were identified as having a relatively high environmental value. Given the high attractiveness of these lands, focused conservation efforts would be required to safeguard these lands. The remaining 38.0 Mha were characterized by either strong constraints or less fertile soils, and thus would likely be less attractive to investors, at least in the short-term.

4. Discussion

4.1 Cropland abandonment and recultivation dynamics

In this analysis, we went further than previous studies that focused on the spatial determinants of abandonment at a local scale by covering a large study area, focusing on the effects of socio-economic dynamics that cause land-use changes, and providing the first statistical analysis of the determinants of recultivation in RUK. Our assessment of the socio-economic factors that affect abandonment and recultivation confirmed that cropland abandonment was more widespread and persistent in socially marginal areas with declining yields and a diminishing and less demographically active population, the so-called “Black Holes*”* (Ioffe et al. 2004*)*. The collapse of the state-driven socialist economy resulted in the deterioration of rural livelihoods, a decline in life expectancy and lowered crude birth rates (Kontorovich 2001, Gerry et al. 2008). The association of greater cropland abandonment with declining birth rates was indeed significant in all three countries. Decreasing rural population density was also associated with land abandonment in the aggregate model, as shown elsewhere with cross-section data (Van Doorn and Bakker 2007, Kristensen et al. 2004, Ioffe et al. 2004, 2014). One explanation for the lack of statistical association between population density and cropland abandonment in the Russia and Kazakhstan country models is that this effect was difficult to capture, given the low population density already before 1991 in many Russian and Kazakhstan regions.

The lowest cropland area was observed in 2006, and most recultivation happened thereafter. Foreign and domestic investments, among others encouraged by agricultural price spikes since 2007, improved agricultural profitability and stimulated recultivation (Visser and Spoor 2011). In addition, government support increased after 2000 and contributed to the partial revival of agricultural production, especially in areas where favorable agronomic conditions allowed for profitable farming, i.e., outside the “Black Holes” described above (Ioffe et al. 2012, 2014). Recent developments in Russia, including the 2014 ban on the import of agricultural products from the E.U. and other countries to Russia, and the ruble devaluation against the U.S. dollar and euro, contributed to strengthen the government’s willingness to support agricultural renewal (Wegren 2014b). On the other hand, the ruble devaluation and repeated taxes and restrictions on wheat exports since 2007 may affect the integration of Russia into the global grain markets, and the risks and profitability of wheat cultivation, and thus deteriorate the incentives for investment and long-term progresses of the agricultural sector (Götz et al. 2013). The significant and positive spatial lag indicated that there were positive spatial externalities associated with recultivation, such as attraction of agricultural expertise, improved market conditions and diffusion of successful practices, which may have contributed to support recultivation in the provinces neighboring the pioneering provinces. In addition, the highly significant positive influence of increasing grain yields on recultivation showed that there were synergies or agglomeration economies between intensification and cropland expansion, as reported elsewhere (Garrett et al. 2013).

The effects of the ethnic population seemed mixed. The effect on abandonment was positive for the aggregate model but was not apparent in the country models. The actual effect might vary between regions. For example, in Russia, some clusters of the non-ethnic Russian population were associated with cropland abandonment, e.g., in the Caucasus, where conflicts among ethnic groups may have contributed to abandonment (Baumann et al. 2014). However, other provinces with a higher share of non-ethnic Russians, such as the Muslim-dominated southern and Volga regions of Russia, often maintained important rural populations with high birth rates, differing starkly from neighboring Russian-dominated regions that were undergoing population decline (ROSSTAT 2014). In territories dominated by non-Russian ethnicities, agriculture is often considered a backbone for the ethnic identity, resulting in formal and informal arrangements regarding agricultural production and land, which may have reduced cropland abandonment and fostered recultivation (Hale 2003, Ioffe et al. 2012).

Kazakhstan experienced the most widespread recultivation. Similar to Russia, increasing investments and government support into agricultural production since 2000 contributed to rising yields and recultivation (OECD 2013). The implementation of a new land code in 2003 is another major cause (Petrick et al. 2013). A total of 81% of all recultivation in Kazakhstan over 2006-2009 was concentrated in the northern Kazakhstan steppe region, the country’s major breadbasket. Large-scale corporate farms and agro-holdings dominate wheat production in this region, leading to continued structural and technological changes towards mechanization over the last decade. As a result, labor quantity has not been a limiting factor, although the skilled workforce is becoming scarce (Wegren 2014a).

The post-Soviet cropland extent in Ukraine was the most stable in the three countries, with the lowest abandonment and the lowest recultivation rates: 10% of the 1991 cropland was recultivated by 2009, mainly in the eastern and northern provinces. This relatively low abandonment compared with Russia and Kazakhstan is consistent with the generally better agro-environmental and accessibility conditions in Ukraine.

Our statistical analyses were restricted to the set of variables available for the three countries consistently over the study periods, and thus capture only some of the socio-economic dynamics underlying cropland abandonment and recultivation. Other processes and variables, such as direct measures of poverty rates, external investments in agriculture or governance indicators deserve to be explored, and likely explain part of the remaining variability in cropland dynamics.

In summary, our results confirmed that large-scale socio-political changes contributed to massive cropland abandonment, particularly on socio-economically marginal lands. The causes of cropland abandonment are complex and spatially diverse, suggesting that multiple measures would be needed to maintain farming and foster recultivation. The significance of the effects of birth rates rather than population density showed that the quality of the labor force, i.e., the presence of young, skilled, and motivated people with an entrepreneurial spirit, was crucial, more so than the sheer number of people (see also Ioffe et al. 2004, Wegren 2014a). While recultivation patterns are strongly determined by agro-environmental suitability, they can also be influenced by socio-economic dynamics. Political and institutional support can enhance recultivation trends, although indirectly, by improving the demographic and socio-economic trends and supporting investments in agriculture.

4.2 Hotspots of potentially available cropland

Our total area of potentially available cropland with low environmental trade-offs and low to moderate constraints was consistent with another preliminary estimate for Russia realized using simpler data and methods (Lambin et al. 2013) but provides considerably more details and nuances. Hotspots of potentially available cropland with low constraints and trade-offs were identified in eastern Ukraine, south-central and southwestern European Russia and the Volga region. These areas have a sufficient workforce, good connections with international markets and potentially high internal food demand due to positive demographic trends (Nefedova 2014, de Beurs and Ioffe 2014). However, with climate change, agricultural potentials may decrease in much of the Chernozem belt, especially in southern European Russia and Kazakhstan, where extreme events such as drought may become more frequent and lead to production shortfalls and temporary fallowing of land (de Beurs and Ioffe 2014). By construction, not all of these hotspots corresponded to places with large areas of potentially available cropland, but rather to places where most abandoned cropland fell within this category. For example, eastern Ukraine possesses a small area of abandoned cropland and reclamation by large agroholdings has already started (Visser and Spoor 2011), although the agricultural sector has been affected by the ongoing armed conflict (Iwanski 2014). Hotspots of accessibility constraints have been identified in western Siberia, northern Kazakhstan and a part of southern European Russia. However, improved data on local food demand and infrastructures, including wheat-processing facilities, may show that the constraints on accessibility in these regions are less severe than in our assessment.

Very little potentially available cropland was found in temperate European Russia due to combinations of low soil suitability and socio-economic and accessibility constraints, although this region hosts massive areas of abandoned croplands. Certain areas outside of the Chernozems may exhibit good yields, but identifying them would require a very fine-grained agro-ecological assessment, and many of them would require substantial investments to be reclaimed. Indeed, independent estimates based on remote sensing showed that agricultural abandonment has continued in these areas (de Beurs and Ioffe 2014, Sieber et al. 2013, Potapov et al. 2015, Estel et al. 2015). Climate change may relax the agro-environmental constraints in temperate and northern Russia, and these regions could serve to buffer agricultural production when droughts hit the southern regions (Lioubimtseva et al. 2013). However, because socio-economic and accessibility constraints will remain, rapid reclaiming of abandoned cropland is unlikely in this area. The 8.5 Mha of potentially available cropland identified correspond to ~5-10% of the global additional cropland demand of 81-147 Mha projected between 2000 and 2030 (excluding biofuels) (Lambin et al. 2011).

In the uncertainty analyses, the major source of variation in the categories of abandoned cropland is the relaxation of climatic constraints, which is mainly affecting Russia (Fig. 1, Tab. S1). The “high” scenario suggests that an additional 2.6 Mha in Russia shift to the category with low or a single moderate socioeconomic or accessibility constraint and good agro-environmental conditions. These are mainly lands located in southeastern European Russia, such as in Volgograd province, in the southern Volga and East Siberia regions, which are outside of the Chernozems belt but have an HTC > 0.6. Further, this scenario also suggests that in Russia, an additional 4.7 Mha of land outside of Chernozems shift to the category with suitable agro-environmental conditions but with socio-economic constraints. These are mainly land in northern European Russia falling within the range of 1,600 to 2,200 accumulated degree-days, which is considered as “submarginal” for wheat production, and which in many places are still experiencing cropland abandonment (Ioffe and Nefedova 2004, Ioffe et al. 2004). The area with conservation trade-offs also notably increases in the "low" scenario, increasing from 8.5 to 12.4 Mha due mainly to increasing buffer sizes around protected areas in Russia.

4.3 Potential environmental impacts of recultivation

Most abandoned cropland in European Russia, Ukraine and Kazakhstan would result in similar carbon emissions should this land be recultivated, with few areas exceeding 5 Mg C ha^{-1} stored since 1991, i.e., mainly land already encroached by forest. Carbon accumulation has been relatively slow due to environmental conditions, occasional fires and other disturbances (Shorohova et al. 2009), and soils have been important components of carbon storage (Kuemmerle et al. 2015, Schierhorn et al. 2013, Kurganova et al. 2014). Carbon stocks are typically higher in the western part of the study area, but yields of winter wheat cultivated in this area are typically higher than those of spring wheat cultivated in the eastern part. Carbon trade-offs are thus relatively small compared with those in other world regions, mainly the tropics (e.g., an average of approximately 90-110 Mg C/ha across all tropical forests, and typically higher than that in humid tropical forests, Saatchi et al. 2011), which constitute major fronts of commodity crop expansion (Meyfroidt et al. 2014). Globally, the average carbon / yield ratio for land cultivated with maize and soybean were estimated at 20.8 and 44.5 Mg C / Mg grain y^{-1}, respectively (Searchinger et al. 2015). Our thresholds at 2.5 and 5 Mg C / Mg grain y^{-1} are thus much lower, but they account only for current carbon stocks. Substantial carbon sequestration could still occur over the long-term if abandoned cropland would revert back to natural forests or steppes (e.g., carbon storage in mature boreal forests is similar to that of tropical forests, Pan et al. 2011, Malhi et al. 1999). Thus, although post-Soviet agricultural abandonment has resulted in considerable carbon storage due to the massive cropland abandonment (approximately 470 Tg C for European Russia, Ukraine and Belarus, according to Schierhorn et al. 2013), the area, rather than the location of land recultivated seems to matter most in terms of carbon trade-offs. Moreover, mitigation schemes (e.g., protection of land where future sequestration can be expected) could be designed to offset carbon emission due to recultivation.

A relatively small share (14%) of abandoned cropland was close to protected areas, inside intact forest landscapes and or inside the Global 200 priority regions (Fig. 2e). Moreover, the priority sites for conservation were often relatively marginal in their agricultural production potential (e.g., southern Kazakhstan, Caucasus, Urals). This partly reflects the establishment of protected areas in regions that are less valuable for agriculture (Joppa and Pfaff 2009). In contrast, agricultural production potentials were highest in the temperate and steppe biomes, which extend across large parts of Eurasia where relatively few endemic species occur and where most species have large ranges. Collectively, this suggests that the local biodiversity impacts of reclaiming cropland may be lower than in other world regions, particularly in the tropics. However, our assessment also highlighted large areas with a very sparse protected area network (e.g., northern Kazakhstan, see also Kamp et al. 2011).

While the impact of post-Soviet agricultural abandonment on wildlife remains poorly understood (Henle et al. 2008, Plieninger et al. 2014, Queiroz et al. 2014, Bragina et al. 2015), biodiversity benefits of abandonment and rewilding, or extensive grazing systems across large areas are likely. For example, the study area harbors sizeable populations of large-bodied carnivores and herbivores of conservation concern (e.g., brown bear, grey wolf, lynx, red deer, European bison, saiga) that require large tracts of habitat. The biodiversity effects of recultivation are thus likely to depend on the spatial pattern of reclamation, emphasizing the need for regional-scale planning. Some potentially available croplands may constitute important wildlife corridors, and identifying those while considering the co-benefits of carbon storage in corridors could be an important strategy to mitigate negative biodiversity outcomes (Jantz et al. 2014). Finally, it is important to note that this assessment lacked a comprehensive spatial biodiversity dataset, requiring us to rely on proxy variables.

Regional land-use and conservation planning should thus seek to include a broader set of biodiversity measures (Kamp et al. 2011).

Recultivation has been ongoing in some of the hotspots with high environmental trade-offs, for instance, in western Ukraine (Griffiths et al. 2013, Stefanski et al. 2014), and proactive land-use planning is thus needed to avoid detrimental environmental impacts. However, one important result is that only approximately 10% (0.8 Mha) of the 8.2 Mha identified as having relatively high environmental trade-offs had a notable interest for cropping actors by combining low socio-economic and accessibility constraints and good soil quality. Beyond these 10%, the remaining land with high environmental trade-offs could be largely protected passively by being unattractive for recultivation, although these lands may be attractive for livestock grazing.

4.4 Potential agricultural production on potentially available cropland and distant implications

RUK accounted for 15%-23% of the world's total grain exports between 2006 and 2011 (FAO 2015), and the scope for increasing production and exports has been widely highlighted. However, the relative additional wheat production that could realistically be expected from recultivation versus intensification on existing cropland remains debatable. In European Russia alone, Schierhorn et al. (2014a) calculated that increasing yields on existing cropland to 80-100% of their potential could generate an additional 23-44 Mt of wheat under rainfed conditions, and 60-90 Mt under irrigated conditions on an annual basis. The scope for increasing wheat production by reclaiming potentially available cropland, which to 14.3 (9.6-19.5) Mt in this study, is thus notable but much smaller than what could be achieved by intensifying already cultivated land, and would represent ~6% of the 244 Mt of additional global wheat demand between 2005 and 2050 projected by the FAO (Alexandratos and Bruinsma 2012).

Within RUK, Russia has the largest potential for increasing wheat production, holding the largest land reserve and being dominated by winter wheat, which has higher yields compared with spring wheat that dominates in Kazakhstan. The wheat production potential on potentially available cropland in Russia amounted to 9.9 (6.6-12.4) Mt. Land with low constraints or with moderate accessibility constraints, being concentrated in southern and southeastern Russia, has a higher yield variation because crop shortfalls due to drought are more frequent (Lioubimtseva et al. 2013) (Fig. 5). By contrast, land with moderate socio-economic constraints, located mainly in the northern part of the Chernozem region where droughts are less severe, has lower yield variation. Some high-yielding regions have especially high potential. For example, potentially available cropland in Rostov amounted to only 0.5 Mha, but could produce approximately 1.3 Mt of wheat annually due to higher yields than in other regions of RUK (Schierhorn et al. 2014a). In Kazakhstan, much of the land had high trade-offs or moderate and strong constraints and lay outside of the Chernozems and thus would be ecologically or economically costly to reclaim. In northern Kazakhstan, reclaiming all the lands with low and moderate constraints could provide up to 5.9 (3.3-10.9) Mt of wheat. Given the low average yields (0.8 t/ha), achieving such amounts of additional production would require reclaiming large tracts of land. Further, the variability in yield is very high in Kazakhstan, mainly due to frequent and severe droughts. In Ukraine, the scope for increasing wheat production from reclaiming abandoned cropland is relatively low (2.5 (1.8-3.4) Mt on Chernozem lands with low to moderate constraints) despite relatively high wheat yields because little cropland was abandoned.

With the growing international trade of agricultural products, understanding the distant effects of land use dynamics in one region becomes increasingly crucial (MacDonald et al. 2015). The reclamation of abandoned cropland and agricultural intensification could have important implications beyond the RUK region. During the transition, RUK have largely switched from livestock to grain production, leading to large insufficiencies in domestic meat production. During the 2000s, Russia became one of the largest importer of meat globally, and in particular the largest importer of Brazilian beef, thus contributing indirectly to a sizeable portion of deforestation for pasture expansion in the Amazon (Prishchepov et al., 2013; Schierhorn et al. forthcoming).

Therefore, reclaiming cropland in RUK, including for the production of livestock fodder, would decrease the reliance on imports from the tropics, mitigating the environmental impacts of agricultural expansion there. Fluctuations in grain exports from RUK could strongly affect the world market prices and thus food security (Fellman et al. 2014). In particular, RUK are the major suppliers of grain for the Middle East. Over 2009-2011, 78% of the wheat exports from RUK were shipped to Middle East countries, with the major buyers being Egypt, Turkey, Israel, Syria and Tunisia (FAO 2015). The Middle East is highly dependent on this supply, with, e.g., 42.5% and 61.6% of the 2010-2011 wheat imports of Egypt and Syria, respectively, being supplied by RUK. With increasing evidence linking conflicts and geopolitical crises in the Middle East to disruptions in food prices and supply (Kelley et al. 2015), the stability and abundance of grain supply from RUK to the Middle East also affects geopolitical tensions.

5. Conclusions

Our results showed that low rates of recultivation and continued abandonment were more prevalent in areas with declining yields, deteriorating socio-economic conditions, and a declining and ageing population. These areas were typically characterized by self-reinforcing feedbacks of impoverishment, outmigration, erosion of social capital and declining investments in agriculture that constituted rural development traps (Ioffe et al. 2004, Mikulcak et al. 2015). Cropland recultivation and intensification appeared to be synergistically linked. The quality of the labor force, i.e., the presence of young, skilled, and motivated people with entrepreneurial spirit, appeared to be a stronger determinant for recultivation than the total amount of labor force. Political and institutional support could enhance recultivation trends, although indirectly, by improving the demographic and socio-economic conditions and supporting investments in agriculture. However, overcoming constraints on recultivation would not necessarily result in socio-economic improvements. Large farms (agroholdings) investing in labor-saving technologies have been reclaiming and cultivating large areas with little labor force, and thus contributing little to overall employment and livelihood opportunities in rural areas, although they have been relying on a functioning rural society to attract skilled agricultural labor (Wegren 2014). The slow decline in rural poverty mainly affects the working population (Gerry et al. 2008), and thus to a large extent, could be attributed to stagnating labor markets in rural areas. Measures to revitalize rural areas should therefore be a priority.

Our assessment of potentially available cropland in Russia, Ukraine and Kazakhstan was an initial, broad-scale exercise. Limitations included the use of a global dataset of market accessibility due to the lack of up-to-date, publicly available and consistent infrastructure datasets for the study area. However, this assessment represents a useful benchmark for finer-scale assessments and land-use planning. We showed that the land potentially available for recultivation in Russia, Ukraine and Kazakhstan was only a relatively small fraction of the total abandoned cropland in these countries. Reclaiming this land could provide a notable contribution to global grain production and food security in different regions, with relatively low environmental trade-offs compared with tropical frontiers, but is not the panacea to address global food security and reduce land-use pressure on tropical ecosystems. An in-depth investigation of the full chain of distant environmental and societal implications of reclaiming cropland in RUK was beyond the scope of the study, but we showed the global relevance of an improved understanding of the dynamics and prospects for recultivating abandoned cropland in the post-Soviet countries. The approach developed here is flexible, allows categories of land to be prioritized in different ways based on the objectives and strategies of different agents, and can be used to assess the social and environmental constraints and trade-offs associated with using potentially available cropland in other regions.

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FIGURES

Figure 1. Trade-offs and constraints of abandoned cropland in million hectares (Mha), by country. Error bars correspond to the uncertainties in area based on the low and high scenarios (Table S1). The orange error bars correspond to the uncertainties on the total potentially available cropland with low constraints and trade-offs (sum of the three bottom categories in green, light blue and magenta). The white error bars correspond to the category with high environmental trade-offs (in red).

Figure 2. Constraints and environmental trade-offs of recultivating abandoned croplands. For clarity of display in panels A-E, the pixels of abandoned cropland were resampled at a 10-km resolution using a majority filter. A: Socio-economic constraints, based on the fixed-effects panel regressions. B: Accessibility constraints. C: Location of Chernozem soils. D: Carbon versus yield trade-off on abandoned cropland. E: Potential conservation value of abandoned cropland. F: Hotspots of the main categories of combinations of constraints and trade-offs associated with abandoned cropland. For clarity, this panel displays only the hotspots with high environmental trade-offs (in red) and the categories that constitute the pool of potentially available cropland with low (in green) or a single moderate constraint (in light blue and magenta).

Figure 3. Combined constraints and trade-offs associated with abandoned cropland in Russia, Ukraine and Kazakhstan. The map identifies seven categories of abandoned cropland. In addition, cropland that has been continuously cultivated since 1990 and cropland abandoned after 1990 but already recultivated in 2009 are shown. The map uses a 3-km resolution (instead of the native 1-km resolution) to filter some noises.

Figure 4. Minard/Sankey charts displaying two decision trees with different ways to prioritize constraints and trade-offs associated with abandoned cropland. A: This tree starts by prioritizing environmental conservation, excluding areas with high environmental costs. Colors correspond to the categories displayed in Figures 1, 2F and 3. Abandoned croplands with low carbon and biodiversity trade-offs, on Chernozems, and having low or a single moderate constraint constitute the pool of potentially available cropland. B: This alternative tree starts by prioritizing favorable cost/benefit ratios for agricultural production, notwithstanding environmental costs.

Figure 5. Potential wheat production in different categories of abandoned cropland, in million tons (Mt). The uncertainty bars correspond to low and high estimates of yields from Schierhorn et al. (2014b).

Table 1

Table 1: Description of variables for the analysis of determinants of abandonment and recultivation.

		1991-1996			2006-2009		
Variable	Units	Mean (Sd)	Min.	Max.	Mean (Sd)	Min.	Max.
All three countries (n=94)							
Rate of net abandoned area relative to total maximum cropland area	%	6.23 (7.44)	0.00	45.27	27.3 (20.9)	-5.66	77.98
Rate of cumulative recultivated area relative to total abandoned area	%	0.00 (0.00)	0.00	0.00	15.7 (28.5)	0.00	193.98
Crude birth rate	births / '000 hab.	11.5 (4.24)	0.00	29.35	12.4 (4.3)	7.90	32.02
Rural life expectancy	Years	-	-	-	66.3 (3.0)	57.60	77.56
Rural population density	p/km2	16.7 (13.7)	0.18	66.33	15.8 (13.6)	0.24	65.39
Share of population with ethnicity different from the national majority group	%	25.4 (23.6)	2.62	93.21	27.0 (25.5)	2.19	98.19
Yields of all grain types per hectare of sown grain	t / ha	1.94 (0.92)	0.00	4.96	2.18 (0.92)	0.00	5.22

Notes: all variables were measured in the same year as the land use change (abandonment or recultivation). Data were available from 1990 to 2009; thus, the first year for which land use change figures were calculated is 1991.

Table 2

Table 2: Determinants of cropland abandonment from 1991-1996 and recultivation from 2006-2009.

	Abandonment (1991-1996)								Recultivation (2006-2009)	
Estimate	All countries		Ukraine		Kazakhstan		Russia		All countries	
Spatial lag (lambda)	0.79	***	-0.96	***	0.79	***	0.80	***	0.74	***
Spatial error (rho)	-0.11		0.71	***	-1.28	**	-0.08		-0.85	***
Crude birth rate	-0.49	***	-0.57	***	-1.82	***	-0.46	***	0.84	*
Rural life expectancy	-	-	-	-	2.04		-0.02		-0.03	
Population density	-0.91	***	-0.69	***	-6.46		-0.46		1.50	
Ethnic population	0.76	***	-0.07		-0.27		-0.53		1.25	*
Yields of grains	-1.11	***	-0.04		-0.97		-1.35	***	1.85	*
Adjusted R2 of corresponding non-spatial model	0.42		0.38		0.64		0.37		0.18	
Observations	564		150		54		360		282	

Notes: Significance levels of raw coefficients are shown as: *: 0.05; **: 0.01; ***: <0.001

Figure 1

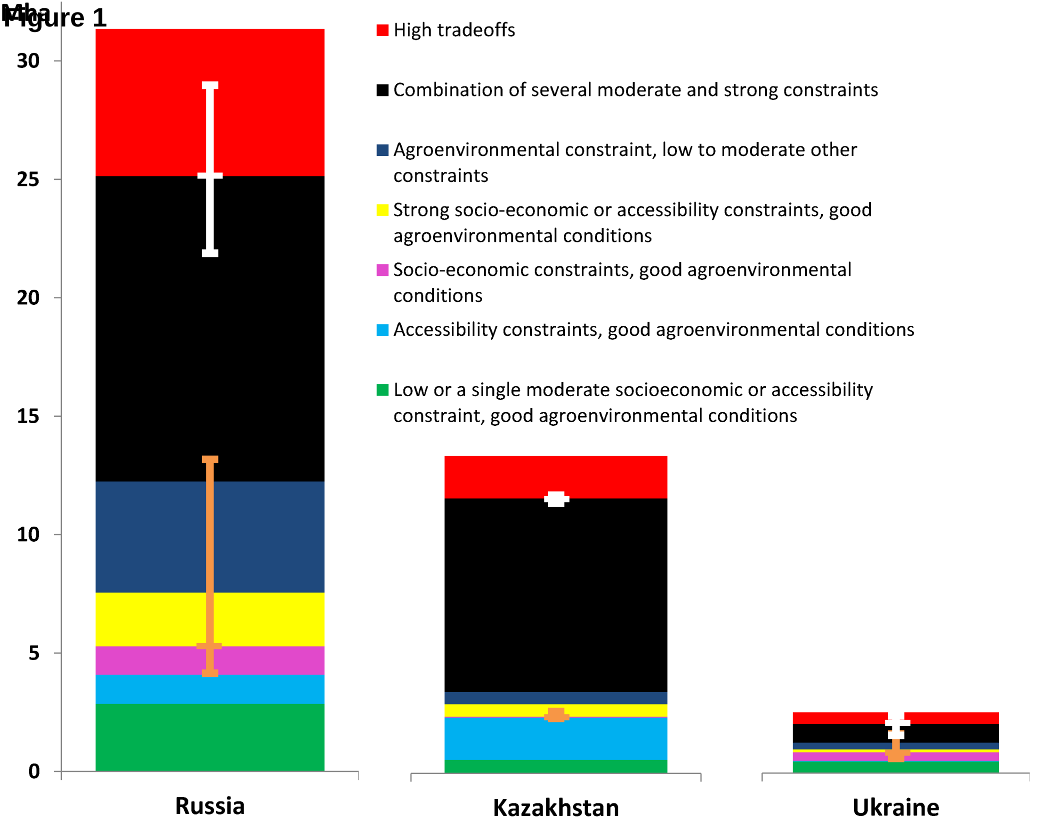
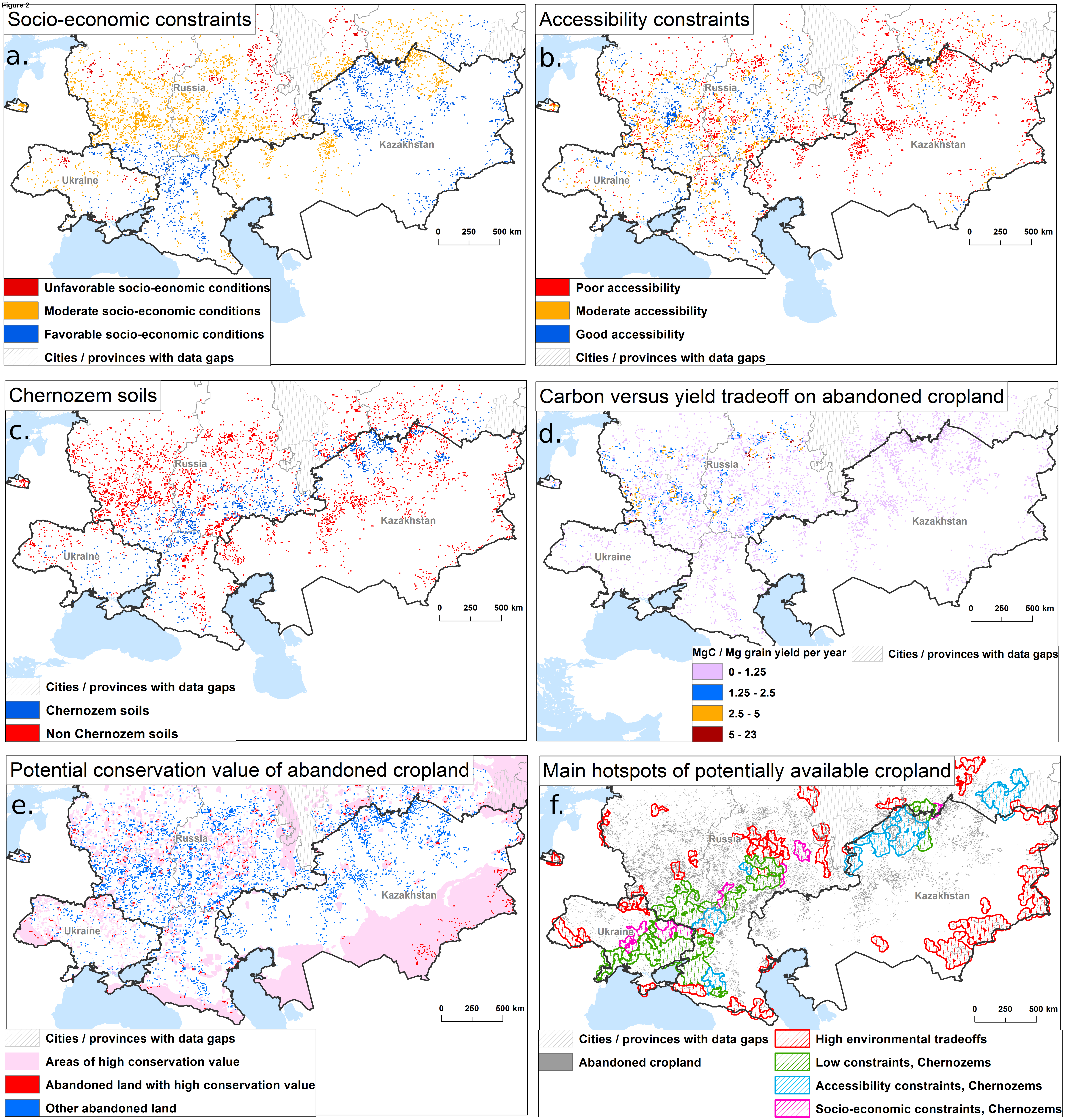
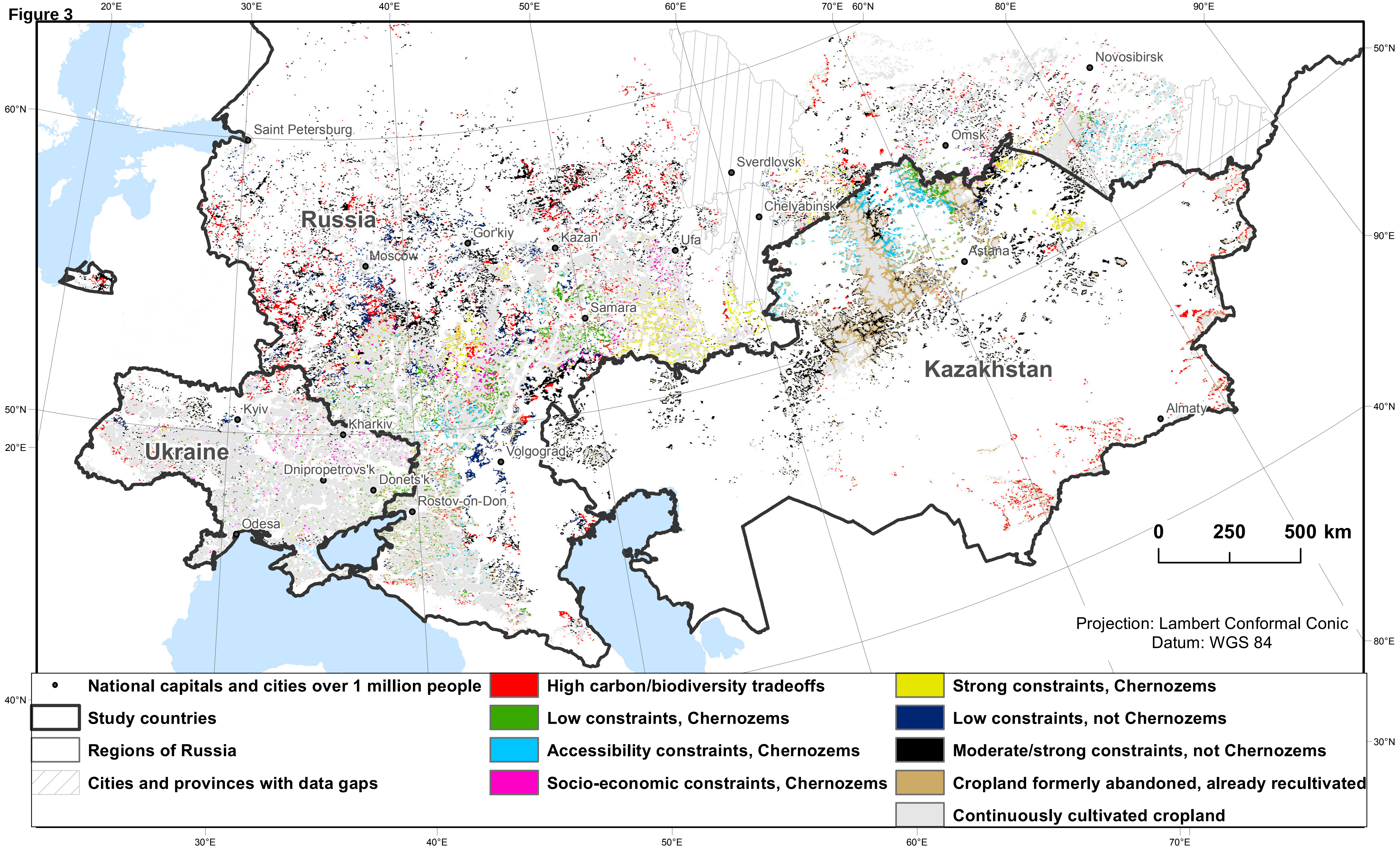

Mha
30
25
20
15
10
5
0
High tradeoffs
Combination of several moderate and strong constraints
Agroenvironmental constraint, low to moderate other constraints
Strong socio-economic or accessibility constraints, good agroenvironmental conditions
Socio-economic constraints, good agroenvironmental conditions
Accessibility constraints, good agroenvironmental conditions
Low or a single moderate socioeconomic or accessibility constraint, good agroenvironmental conditions
Russia
Kazakhstan
Ukraine

Figure 2



Socio-economic constraints
a.
Russia
Kazakhstan
Ukraine
0 250 500 km
Unfavorable socio-eonomic conditions
Moderate socio-economic conditions
Favorable socio-economic conditions
Cities / provinces with data gaps
Accessibility constraints
b.
Russia
Kazakhstan
Ukraine
0 250 500 km
Poor accessibility
Moderate accessibility
Good accessibility
Cities / provinces with data gaps
Chernozem soils
c.
Russia
Kazakhstan
Ukraine
0 250 500 km
Cities / provinces with data gaps
Chernozem soils
Non Chernozem soils
Carbon versus yield tradeoff on abandoned cropland
d.
Russia
Kazakhstan
Ukraine
0 250 500 km
MgC / Mg grain yield per year
0 - 1.25
1.25 - 2.5
2.5 - 5
5 - 23
Cities / provinces with data gaps
Potential conservation value of abandoned cropland
e.
Russia
Kazakhstan
Ukraine
0 250 500 km
Cities / provinces with data gaps
Areas of high conservation value
Abandoned land with high conservation value
Other abandoned land
Main hotspots of potentially available cropland
f.
Russia
Kazakhstan
Ukraine
0 250 500 km
Cities / provinces with data gaps
Abandoned cropland
High environmental tradeoffs
Low constraints, Chernozems
Accessibility constraints, Chernozems
Socio-economic constraints, Chernozems

Figure 3



Russia
Ukraine
Kazakhstan
Saint Petersburg
Moscow
Gor'kiy
Kazan'
Ufa
Sverdlovsk
Chelyabinsk
Omsk
Novosibirsk
Astana
Almaty
Samara
Kyiv
Kharkiv
Volgograd
Dnipropetrovs'k
Donets'k
Rostov-on-Don
Odesa
0 250 500 km
Projection: Lambert Conformal Conic
Datum: WGS 84
National capitals and cities over 1 million people
Study countries
Regions of Russia
Cities and provinces with data gaps
High carbon/biodiversity tradeoffs
Low constraints, Chernozems
Accessibility constraints, Chernozems
Socio-economic constraints, Chernozems
Strong constraints, Chernozems
Low constraints, not Chernozems
Moderate/strong constraints, not Chernozems
Cropland formerly abandoned, already recultivated
Continuously cultivated cropland

Figure 4

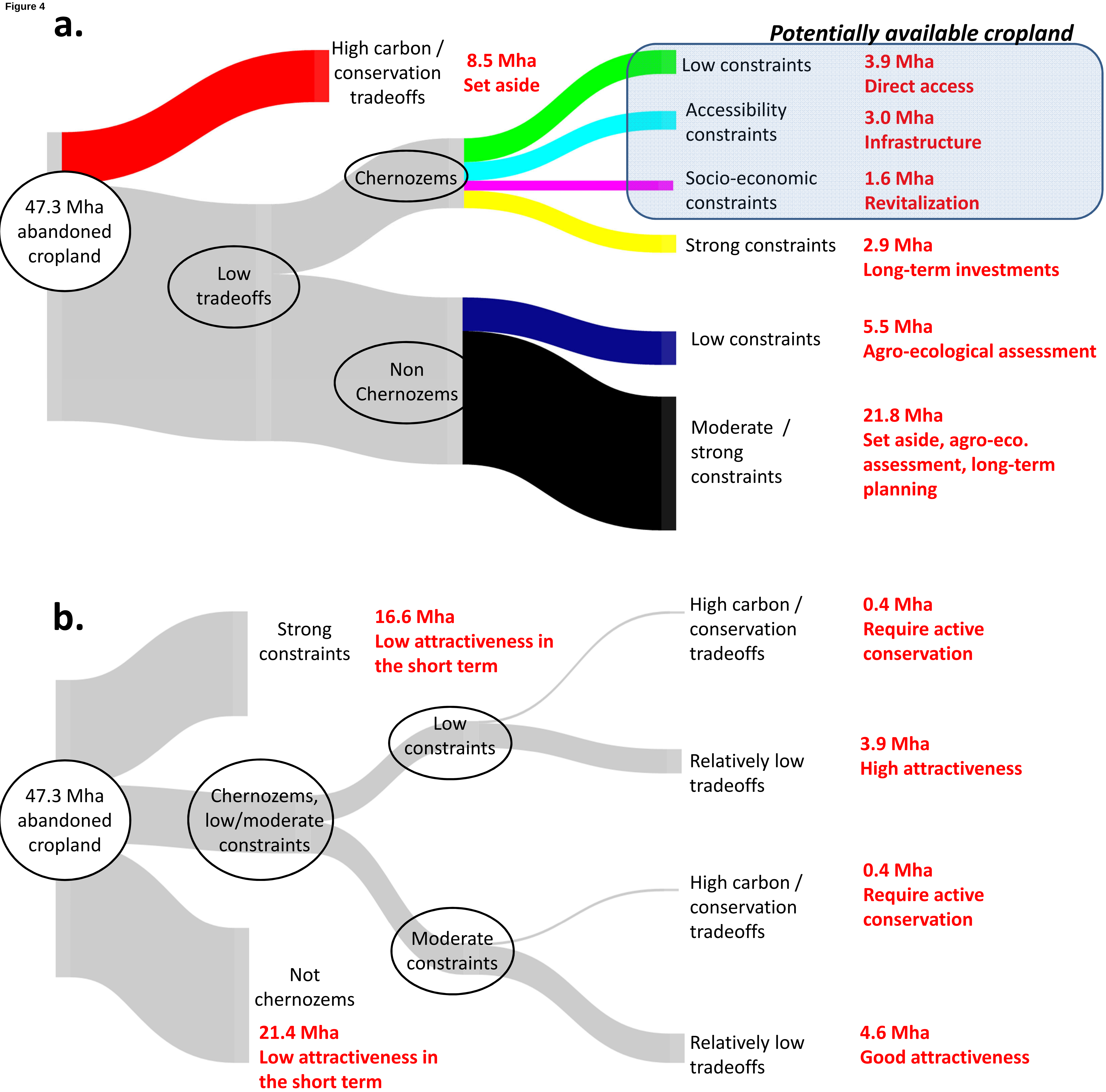
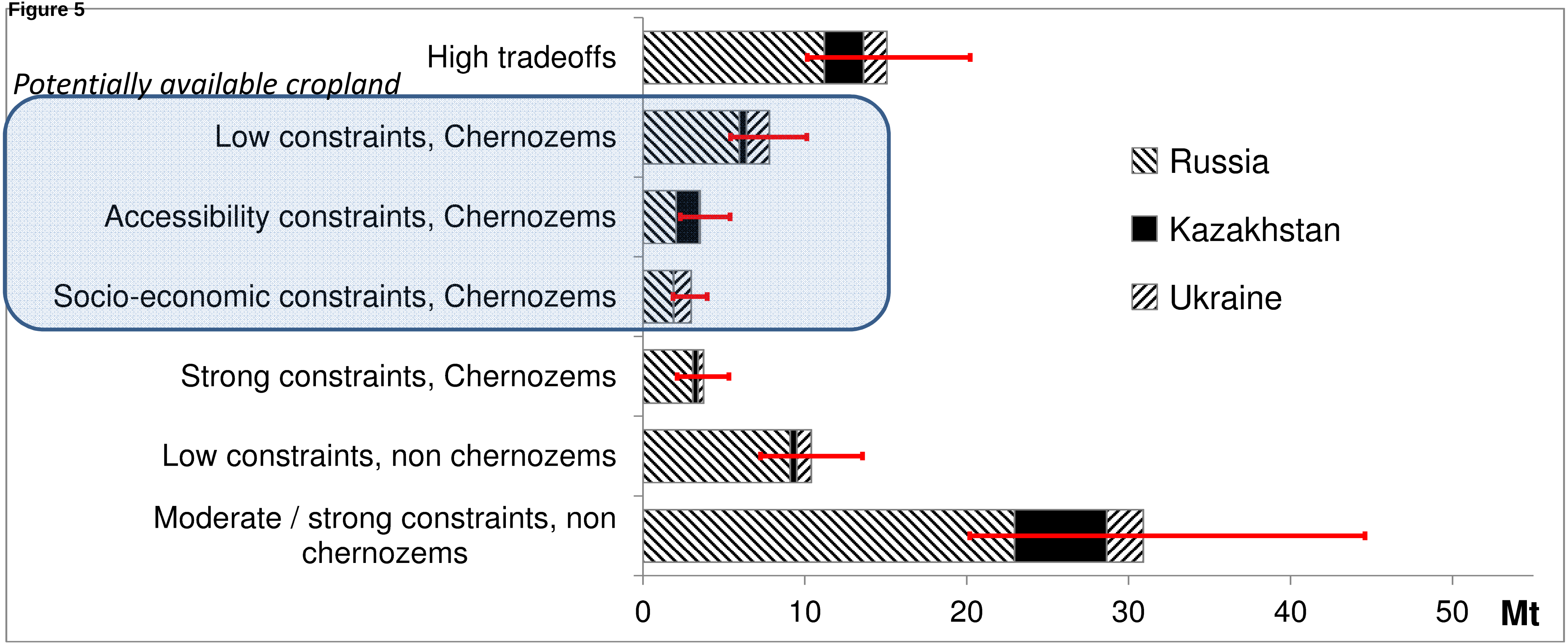

a.
Potentially available cropland
47.3 Mha abandoned cropland
High carbon / conservation tradeoffs
8.5 Mha
Set aside
Low tradeoffs
Chernozems
Low constraints
3.9 Mha
Direct access
Accessibility constraints
3.0 Mha
Infrastructure
Socio-economic constraints
1.6 Mha
Revitalization
Strong constraints
2.9 Mha
Long-term investments
Non Chernozems
Low constraints
5.5 Mha
Agro-ecological assessment
Moderate / strong constraints
21.8 Mha
Set aside, agro-eco. assessment, long-term planning
b.
47.3 Mha abandoned cropland
Strong constraints
16.6 Mha
Low attractiveness in the short term
Chernozems, low/moderate constraints
Low constraints
High carbon / conservation tradeoffs
0.4 Mha
Require active conservation
Relatively low tradeoffs
3.9 Mha
High attractiveness
Moderate constraints
High carbon / conservation tradeoffs
0.4 Mha
Require active conservation
Relatively low tradeoffs
4.6 Mha
Good attractiveness
Not chernozems
21.4 Mha
Low attractiveness in the short term

Figure 5


High tradeoffs
Potentially available cropland
Low constraints, Chernozems
Accessibility constraints, Chernozems
Socio-economic constraints, Chernozems
Strong constraints, Chernozems
Low constraints, non chernozems
Moderate / strong constraints, non chernozems
Russia
Kazakhstan
Ukraine
0
10
20
30
40
50
Mt

Supplementary Figure S1 : Flowchart of the methodology.

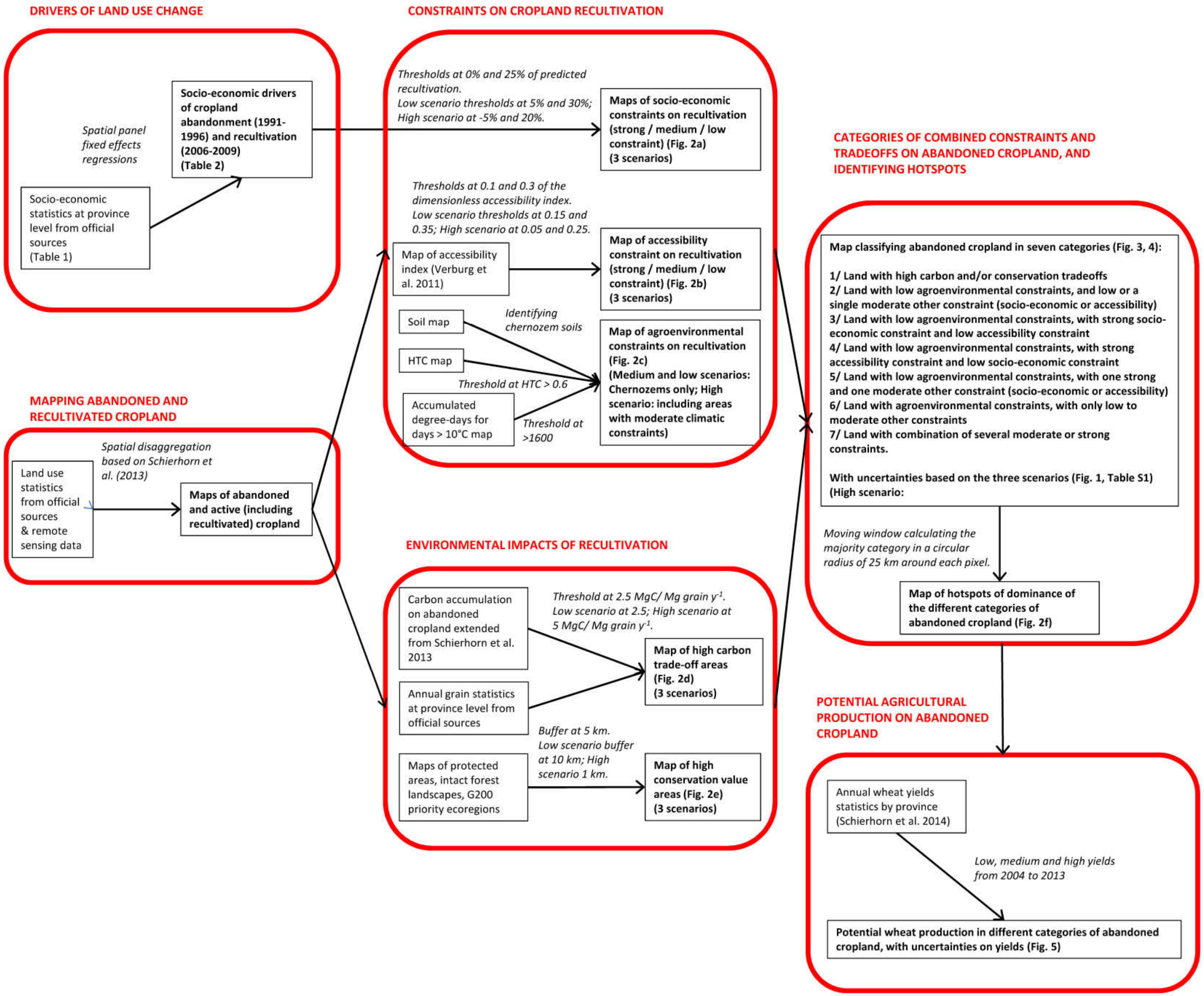


Figure legend : Red outlines identify the main steps of the method. Boxes identify datasets or outputs. Arrows indicate the use of a box as input for a further step, with the methods indicated in italics. Bold identify the major outputs, displayed in the tables and figures.

Supplementary Table S1: Categories of abandoned cropland with low and high estimates. Uncertainties ranges correspond to the lowest and highest value obtained in the three scenarios. As the total abandoned cropland does not vary, changes in one category correspond to changes in other categories, so that the low and high values for different categories cannot be directly summed up.

Categories of abandoned cropland, '000 hectares	Russia	Kazakhstan	Ukraine	Total
Low or a single moderate socioeconomic or accessibility constraint, good agro-environmental conditions	2851 (1948-5468)	560 (364-999)	488 (335-782)	3899 (2647-7249)
Accessibility constraints, good agro-environmental conditions	1229 (1229-1776)	1783 (1523-1947)	22 (8-32)	3034 (3034-3380)
Socio-economic constraints, good agro-environmental conditions	1197 (801-5927)	41 (5-78)	367 (245-855)	1605 (1051-6859)
Total potentially available cropland	5276 (4149-13172)	2384 (2316-2599)	877 (613-1645)	8537 (7079-17415)
Strong socio-economic or accessibility constraints, good agro-environmental conditions	2275 (885-2697)	519 (236-555)	117 (35-236)	2912 (1156-3488)
Agro-environmental constraint, low to moderate other constraints	4687 (2224-8300)	512 (390-748)	287 (103-559)	5485 (2717-9606)
Combination of several moderate and strong constraints	12900 (6615-12810)	8152 (8106-8152)	784 (164-785)	21836 (14907-21836)
High tradeoffs	6219 (2386-9477)	1794 (1650-1994)	497 (159-972)	8510 (4195-12442)

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