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# Mapping the timing of cropland abandonment and recultivation in northern Kazakhstan using annual Landsat time series

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A B S T R A C T

Much of the world's temperate grasslands have been converted to croplands, yet these trends can reverse in some regions. This is the case for the steppes of northern Kazakhstan, where the breakdown of the Soviet Union led to widespread cropland abandonment, creating restoration opportunities. Understanding when abandonment happened and whether it persists is important for making use of these opportunities. We developed a trajectory-based change detection approach to identify cropland abandonment between 1988 and 2013 and recultivation between 1991 and 2013. Our approach is based on annual time series of cropland probabilities derived from Landsat imagery and resulted in reliable maps (89% overall accuracy), with abandonment being detected more accurately (user's accuracy of 93%) than recultivation (73%). Most of the remaining uncertainty in our maps was due to low image availability during the mid-1990s, leading to abandonment in the 1990s sometimes only being detected in the 2000s. Our results suggest that of the ~4.7 million ha of cropland in our study area in 1985, roughly 40% had been abandoned by 2013. Knowing the timing of abandonment allowed for deeper insights into what drives these dynamics: recultivation after 2007 happened preferentially on those lands that had been abandoned most recently, suggesting that the most productive croplands were abandoned last and recultivated first. Likewise, knowing the timing of abandonment allowed for more precise estimates of the environmental impacts of abandonment (e.g., soil organic carbon sequestration estimated at 16.3 Mt. C compared to 24.0 Mt. C when assuming all abandonment happened right after the breakdown of the Soviet Union, with the uncertainty around emission estimates decreasing by 63%). Overall, our study emphasizes the value of the Landsat archive for understanding agricultural land-use dynamics, and the opportunities of trajectory-based approaches for mapping these dynamics.

## 1. Introduction

Grasslands cover about one fifth of the Earth's surface (Lieth, 1978), are rich in biodiversity (Suttie et al., 2005), and play an important role in global carbon storage (Scurlock and Hall, 1998; Anderson, 1991). At the same time, grasslands are often found on soils that are well-suited for agriculture (Millennium Ecosystem Assessment, 2005) and can be plowed at comparably low costs (Briggs et al., 2008). However, in some grassland regions croplands are abandoned, potentially leading to a restoration of native biodiversity (Benayas et al., 2007; Brinkert et al., 2016; Kamp et al., 2011) and carbon stocks (Kurganova et al., 2014; Sala et al., 1996). The degree of restoration, however, depends on the time since abandonment, and recovery often follows a non-linear trajectory. For example, carbon sequestration rates were estimated to be significantly lower for croplands abandoned at an earlier date than for more recently abandoned fields in Russia (the first 20 years vs. the next 30 years in Kurganova et al., 2014; the first 10 years vs. the next 20 years in Wertebach et al., 2017). Similarly, success in restoration of native grass species and a restitution of soil properties were highly dependent on the time since abandonment in China (Zhao et al., 2005). Given recent trends to recultivate some abandoned croplands (Meyfroidt et al., 2016; Schierhorn et al., 2014; Smaliychuk et al., 2016), better information on when croplands were abandoned is important.

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The Eurasian steppe belt is an example of a grassland region that has experienced widespread cropland abandonment, starting in the 1980s. Much of the Eurasian steppe belt is located in the former Soviet Union, and a major share of this region was plowed and converted into croplands during the Soviet Virgin Land Campaign (McCauley, 1976). While the region continues to be one of the world's major bread baskets (Swinnen et al., 2017), it experienced substantial cropland abandonment after the breakdown of the Soviet Union (Baydildina et al., 2000; Schierhorn et al., 2013). This may create an opportunity for mitigating environmental impacts of pre-abandonment land uses and restoring steppe ecosystems (Gerla et al., 2012), as biodiversity and soil carbon stocks can recover with adequate grazing levels and fire regimes (Benayas et al., 2007; Brinkert et al., 2016; Kamp et al., 2011; Kurganova et al., 2014; Sala et al., 1996). Yet, it takes time for soil and vegetation to fully recover, and while both depend on many factors, previous land use is a key factor (Wright et al., 2012). Identifying those areas that have recovered most, and that might be most valuable from a conservation perspective, depends on understanding land abandonment trajectories. However, reliable data of the exact timing of cropland abandonment in this vast region does not exist.

Remote sensing can play a key role in mapping the extent of cropland abandonment, for example in Eastern Europe (Alcantara et al., 2013; de Beurs and Ioffe, 2014; Estel et al., 2015; Prishchepov et al., 2012a), the African Sahel (Tong et al., 2017; Leroux et al., 2017), and in Central Asia (de Beurs et al., 2015; de Beurs and Henebry, 2004). Most studies that have focused on large areas have relied on coarser resolution data, mainly from the Moderate Resolution Imaging Spectroradiometer (MODIS, Alcantara et al., 2013; Estel et al., 2015; Yin et al., 2014). While MODIS data provide the high temporal resolution needed to monitor gradual processes such as post-abandonment recovery, MODIS and similar sensors (e.g., VIIRS) lack the temporal depth to assess agricultural abandonment trends in the post-Soviet era of the 1990s. Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) data has a higher spatial resolution and the long temporal record, reaching back into the 1980s, allowing to characterize land use since late Soviet times. However, existing Landsat-based work in the Eurasian steppe belt has relied on snapshots in time and generally lacked the temporal density to detect the exact timing of abandonment and recultivation (Kraemer et al., 2015; Baumann et al., 2011; Prishchepov et al., 2013). For example, cropland systems in Eurasia's steppes are often characterized by a few years of cultivation followed by one fallow year. Thus, studies relying on a few snapshots in time, as in Kraemer et al. (2015), may therefore confuse fallow periods with abandonment, or miss abandonment phases altogether if areas are put back into production after a few years. With the global availability of Landsat time series data (Wulder et al., 2016), there are now opportunities to overcome these issues by mapping cropland abandonment and recultivation at annual intervals.

Mapping cropland dynamics is challenging because of the high inter- and intra-annual spectral variabilities of cropland (Prishchepov et al., 2012b; Yin et al., 2014). Landsat-based time series approaches can help to overcome these challenges and several such approaches have recently been developed, albeit not with a focus on cropland dynamics. These approaches can be broadly categorized into two groups. The first involves time-series-based classifications of annual land cover (e.g. Vogelmann et al., 2009; Zhu, 2017) that captures transitions between land cover classes. The second category of time series approaches fits temporal trajectories to spectral indices for detecting vegetation changes (e.g. Forkel and Wutzler, 2015; Kennedy et al., 2010; Verbesselt et al., 2010), which can detect abrupt breakpoints and continuous trends, but cannot be used if the target class is spectrally highly variable, as is the case with croplands. A useful approach for overcoming these limitations, and making use of the advantages of both groups of time series approaches, is to first predict land-cover probabilities and then use time series of these probabilities as spectral metrics in trajectory-based change algorithms. Such an approach has so far only been applied to MODIS imagery (Yin et al., 2014, 2018) and it remains to be tested whether this approach can be transferred to Landsat time series to map cropland dynamics.

Another challenge for mapping gradual land-use trends with Landsat time series is variable data availability. While some areas, such as the conterminous Unites States or Australia, have a very high availability of Landsat imagery back to the 1980s (Wulder et al., 2016), imagery is scarce for many areas on the globe for at least some periods, often the 1990s (Kovalskyy and Roy, 2013). This is also one of the main challenges in utilizing Landsat imagery for mapping cropland abandonment and recultivation in post-Soviet countries, as data acquisition in the 1990s was often lower, while a majority of abandonment happened in this period. It is thus unclear whether it is possible to detect cropland abandonment and recultivation given such constraints in image availability (Kovalskyy and Roy, 2013; Loveland and Dwyer, 2012).

Our overarching goal therefore was to develop and test a trajectory-based mapping of cropland abandonment and recultivation in Eurasia‘s steppes. Focusing on northern Kazakhstan, we use all available Landsat imagery between 1984 and 2016 to create annual maps of cropland abandonment and recultivation, and to assess the impact of data sparseness on the reliability of our maps. Specifically, we addressed the following research questions:

1. How well do trajectory-based analyses of Landsat time series capture land abandonment and recultivation?
2. How do data-scarce periods affect the accuracy of time series analysis?
3. What is the potential value of more detailed information on abandonment for understanding agricultural dynamics and their environmental impacts?

## 2. Methods

### 2.1. Study area

Our study region covers ~79,000 $km^2$ in the Kostanay Oblast in northern Kazakhstan and considerably smaller border areas of Russia (Fig. 1). The area is interesting from the perspective of methods development for a number of reasons. First, Landsat data availability was scarce in the area during the 1990s. Such a situation is representative for post-Soviet countries and testing the robustness of methods towards data scarcity is therefore important. Secondly, the region is characterized by dynamic and regionally variable patterns of abandonment and recultivation, while at the same time allowing for comparisons with cropland areas that were farmed continuously. Third, the area experienced land-use change patterns typical for the whole region, i.e., cropland abandonment starting in the 1990s and recultivation after 2000 (Meyfroidt et al., 2016). Moreover, we have substantial knowledge of land-use processes in the region, including extensive land-use data useful for ground-truthing from several extensive field trips to the area.

The terrain in the study region is mostly flat, with elevation ranging between 150 and 300 m above sea level. Climate is continental, with cold and windy winters, followed by hot and dry summers. Annual precipitation varies depending on latitude from 250 to 400 mm. Average monthly temperatures range between −18 °C in February and +22 °C in July (Ilyakova et al., 2016). These climatic conditions result in a rather short growing season of about 150–180 days (Afonin et al., 2008), and snow cover for approximately 150 days per year (Kauazov et al., 2016). The most common soils are *Chernozems* in the more humid north and *Kastanozems* in the drier southern part of the study area (Beznosov and Uspanov, 1960). Both soil types are generally well-suited for agriculture.

The region has a long land-use history, characterized by nomadic pastoralism for millennia. Cropland cultivation started in the 19th