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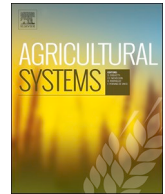
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# Quantifying the soil erosion legacy of the Soviet Union

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## ABSTRACT

We examine the historical legacy of the Soviet Union on the current rate of human-induced soil erosion in its successor countries. We use a spatial regression discontinuity design and high-resolution soil erosion data. Our results suggest strong discontinuities in current soil erosion rates along the former border of the Soviet Union. We find that soil erosion in countries that were part of the former Soviet Union is 26% lower than in neighboring countries (0.77 tons per hectare and year). In contrast, we do not find such discontinuity in potential soil erosion under natural vegetation, underlining that this effect is man-made. We show that the main mechanism is a sharp discontinuity in forest dynamics, whereas general economic and demographic differences are less important.

## 1. Introduction

Soil is essential for the production of food and many other ecosystem services and thus is also an essential input to the economy (Brausmann and Bretschger, 2018; Wall and Six, 2015). However, we currently degrade and lose our soil at unsustainably high rates, and erosion rates tend to increase in many regions (Borrelli et al., 2017; Nkonya et al., 2016; Blaikie and Brookfield, 2015). Soil erosion reduces agricultural and forestry productivity, and increases greenhouse gas emissions and water pollution (Borrelli et al., 2017; Sartori et al., 2019). A recent study estimates that soil erosion lowers the global GDP by 8 billion US dollars per year due to its negative effects on agricultural productivity (Sartori et al., 2019).

In this study, we attempt to make progress in understanding which socio-economic factors explain the current patterns of soil erosion. In particular, we consider the role of historical legacies with an empirical assessment of the persistent long-term effect of the Soviet Union. A wide range of socio-economic explanations for soil erosion has been examined, including poverty, market access, population pressure, land tenure, extension services, and culture (Nkonya et al., 2016; Mirzabaev, Nkonya et al., 2016; Nkonya and Anderson, 2015; Barbier and Hochard, 2016; Wuepper, 2020). We currently do not know much about historical legacies and soil erosion but there is a considerable literature on historical legacies and other environmental outcomes. Foster et al. (2003) and Perring et al. (2016) review early contributions. Empirically, Munteanu et al. (2015) and Munteanu et al. (2017) find that land-use legacies affect contemporary forests, agricultural areas, and

grasslands in Eastern Europe. Alix-Garcia et al. (2016) find that history and land privatization are among the most important cross-country explanations for forest dynamics in Eastern Europe and European Russia. Batáry et al. (2017) find that the historical inner-German division into East and West Germany after the second world war still shapes agro-biodiversity patterns and Wuepper et al. (2020a) find that it also still affects farming practices.

Also the effect of institutional and political change on soil erosion is not as well explored as it is for other environmental outcomes. Examples from this literature include Copeland and Scott Taylor (2004), who provide a comprehensive literature review on the link between economic growth and decline, trade, and the environment, and empirically, there are e.g. Barbier (2000) and Faria and Almeida (2016), who analyze the effect of economic liberalization and globalization on the environment, especially on forest conversion. Focusing on a historical case, Alix-Garcia et al. (2018) find that the creation of a customs union between Austria and Hungary in 1850 had a large, negative effect on its forests which were cleared for cropland. Also, the demise of the Soviet Union had large repercussions on the extent of cropland in all affected countries, albeit the rate of abandonment was highly heterogeneous (Prishchepov et al., 2012).

Using a spatial regression discontinuity design (Wuepper et al., 2020b) and a rich spatial dataset on soil erosion (Borrelli et al., 2017), we estimate whether the countries of the former Soviet Union (fSU) currently have a significantly lower rate of soil erosion now than they would with a different historical legacy. We find a surprisingly large effect: The countries of the fSU have 0.77 t/ha/ more soil erosion, an

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increase of 26%, than the countries outside but bordering the fSU.

We find that the main mechanism behind the historical legacy of the fSU are altered forest land dynamics caused by the collapse of the Soviet Union. In addition, also farmland abandonment plays a role. Importantly, not much of the fSU legacy effect is explainable by general differences in GDP, population density, GDP growth, or population growth.

In the next section, we describe the study background (2). This is followed by an outline of our empirical framework (3), our data (4), results (5), and a conclusion (6).

## 2. Background

After the collapse of the Soviet Union, land use intensity starkly diverged between the countries of the fSU and their neighbors (Gutman and Radeloff, 2017). Systematically different developments in the countries' primary sectors are the main reason why the countries of the fSU could have systematically lower soil erosion rates currently, compared to their neighbors in Eastern Europe and Central Asia.

Agricultural land extent in the Soviet Union reached two peaks, around 1963 and 1975–1980, with 218 and 217 Mha, respectively (USSR, 1958–1990). After the collapse of the Soviet Union, about 31% or 57 Mha of former cropland were left abandoned in Russia, Kazakhstan, and Ukraine alone (Meyfroidt et al., 2016). One key contributor to the decline in croplands was the collapse of livestock production and the accompanying cessation of fodder production (Schierhorn et al., 2016).

The paramount causes for the decline in agricultural production were the decline of state subsidies, which particularly affected the heavily subsidized livestock sector, where state support decreased by 95% (Prishchepov et al., 2020). The liberalization of output and input prices led to a deterioration of the terms of trade in agriculture, hence reducing farm profits (Rozelle and Swinnen, 2004). Moreover, many of the active trade networks of Soviet times disintegrated (Prishchepov et al., 2020), and the economic crisis during the 1990s contributed to lower domestic demand, particularly for higher value products (Schierhorn et al., 2016). While the production decline affected most areas used for agriculture, the rates of farmland abandonment were highest in less suitable areas with lower soil fertility and less infrastructure (Lerman and Shagaida, 2007; Prishchepov et al., 2013).

The rates of farmland contraction differed starkly between the territory of the fSU and Central and Eastern Europe, where much less farmland was abandoned (Alcantara et al., 2013). This suggests that socioeconomic as well as institutional changes after 1990 shaped subsequent land-use pathways. A pivotal cause for the pronounced differences in post-socialist farmland abandonment may have been the diverging post-socialist land reforms, with restitution to historical owners in most countries of Eastern Europe that had not been part of the Soviet Union while farmland was distributed in physical shares in most successor countries of the Soviet Union (Prishchepov et al., 2012; Lerman et al., 2004). Moreover, agricultural state support and subsequent policy developments, such as accession of many countries in Eastern Europe to the European Union, reduced abandonment rates compared outside of the fSU (Alcantara et al., 2013).

Not only agricultural land use but also forest management developed quite differently. Logging substantially decreased in the countries of the fSU while logging rates went up in Central and Eastern Europe (Potapov et al., 2015; Griffiths et al., 2014). The differences in post-socialist changes in forest management and thus in forest cover have arguably been due to the collapse of the timber industry in Russia and other countries of the former Soviet sphere, while in Eastern Europe the privatization of much of the forested areas contributed to increasing harvest rates (Griffiths et al., 2014).

Since around the late 1990s and early 2000s, modest recultivation of some of the abandoned croplands can be observed (Meyfroidt et al., 2016). However, recultivation in many areas is hampered by the

comparatively low productive potentials of many of the former croplands. Moreover, many areas that have been abandoned soon after the collapse of the Soviet Union revegetated into secondary woody vegetation and young forests. Reusing these areas is costly due to the necessary removal of the vegetation, including the plants' root systems (Larsson and Nilsson, 2005) and would cause large losses of the carbon stored in vegetation and soil (Schierhorn et al., 2013).

## 3. Empirical framework

We are interested in whether there is a legacy effect of the Soviet Union on current soil erosion.

First, we estimate whether there is a statistically significant border discontinuity in land-use related soil erosion at the fSU border, using a spatial regression discontinuity design (a). Second, we simulate the difference in overall soil erosion because of the legacy effect of the Soviet Union, using the Revised Universal Soil Loss Equation framework (b). And, third, we perform multiple robustness checks and test potential mechanisms (c).

### a. Identifying the legacy effect of the Soviet Union on current soil erosion

Our main empirical strategy is the spatial regression discontinuity design (Calonico et al., 2016; Keele and Titiunik, 2014; Bonilla-Mejía and Higuera-Mendieta, 2019; Wuepper, Borrelli et al., 2020b). As a first step towards having comparable observations from the different countries, we exclusively focus on observations close to the fSU border. We estimate what is the statistically optimal maximum distance to the border (the “bandwidth”) that minimizes omitted variable bias while still allowing for precise estimates (Cattaneo and Vazquez-Bare, 2016; Calonico et al., 2020). The main idea is to only compare observations close to each other (thus being more similar) and to control for all spatially continuously distributed confounders in the regression discontinuity design. Then we estimate whether there is a discontinuity right at the fSU border that can only be explained with the historical legacy of the fSU. This is based on three main assumptions that we test first and a few smaller assumptions that we test later. The three main assumptions are:

The border of the fSU haphazardly divided an area that would naturally have a continuous distribution of land cover and erosion, so that an estimated discontinuity in current soil cover and erosion must be caused by the political division (assumption 1). We test this assumption using the non-parametric local polynomial regression proposed by Calonico et al. (2014):

$$Nat_i = \beta_1 fSU_i + \beta_2 dist_i^{fSU} + \beta_3 dist_i^{-fSU} + \beta_4 location_i + \beta_5 \theta_i + \beta_6 \vartheta_j + \epsilon_i \quad (1)$$

where  $Nat_i$  is one of four indicators that the fSU border does not simply coincide with a natural erosion discontinuity. Our indicators are the modelled erosion effects of (i) the topography, (ii) the frequency and intensity of rainfall events, (iii) soil characteristics such as structure and soil types, and (iv) the modelled natural rate of soil erosion itself (i.e. the rate of soil erosion in absence of human influences on land use). Having all this data available for testing is a major advantage of our data, as we explain in the next section. Moreover,  $fSU_i$  is an indicator for whether an observation  $i$  (depending on the analysis, pixels of either  $1 \times 1$  km or  $30 \times 30$  m) is in a country of the fSU or not,  $dist_i^{fSU}$  and  $dist_i^{-fSU}$  control for all potential confounders that are a smooth function of border distance, separately on both sides of the fSU border,  $location_i$  is a polynomial of longitude and latitude that controls for all potential confounders that are generally continuously distributed spatially,  $\theta_i$  is a vector of natural erosion determinants, and  $\vartheta_j$  is a vector of fixed effects for each border  $j$ . Fig. 1 shows the location of the fSU border.

In order for an estimated fSU border discontinuity to have the

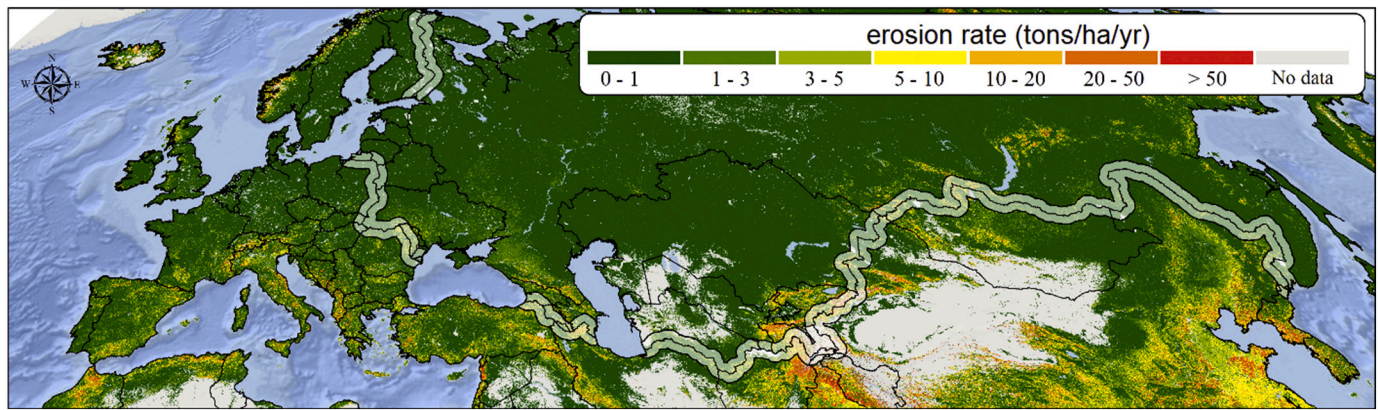


Fig. 1. Soil Erosion along the Border of the Former Soviet Union.

Notes: This map shows the rate of soil erosion at 1 km spatial resolution, computed with the Revised Universal Soil Loss Equation by Borrelli et al. (2017). Black lines identify country borders, the light band is a 80 km border distance to either side.

interpretation of a historical legacy effect of the fSU, we must be sure that soil cover and erosion are generally continuously distributed in the border area, so that we would not randomly find discontinuities in places other than the border (assumption 2), and since the fSU border aligns perfectly with the political borders of current countries, we must rule out that we pick up an effect of the contemporary country borders as the fSU legacy effect (assumption 3). To test assumptions 2 and 3, we estimate two placebo specifications:

$$E_i^{LU} = \beta_1 fSU_i^R + \beta_2 dist_i^{fSU^R} + \beta_3 dist_i^{-fSU^R} + \beta_4 location_i + \beta_5 \theta_i + \beta_6 \vartheta_j + \epsilon_i \quad (2)$$

and

$$E_i^{LU} = \beta_1 fSU_i^S + \beta_2 dist_i^{fSU^S} + \beta_3 dist_i^{-fSU^S} + \beta_4 location_i + \beta_5 \theta_i + \beta_6 \vartheta_j + \epsilon_i \quad (3)$$

where  $E_i^{LU}$  is soil erosion that is caused by the current land use, which is our main left-hand-side variable of interest in this study,  $fSU_i^R$  is a “randomized” fSU legacy, i.e. we randomly treat some countries as having been in the fSU and others not, irrespective of their actual history, and  $fSU_i^S$  is a “shifted” fSU legacy, i.e. we virtually move the fSU border 10 km away from its actual location to a place where currently no political border exists.

The idea of these two placebo tests is to rule out that (a) our estimated discontinuity at the border of the fSU is a discontinuity between the current countries and not a historical legacy of the fSU. We also control for the fact that (b) soil erosion is not continuously distributed, so that we are at risk of randomly finding discontinuities. If we would, e.g., find soil erosion discontinuities 10 km away from the actual border, this could indicate that our estimate of a border discontinuity could be due to random chance. If our main assumptions cannot be rejected, we can proceed to the estimation of the actual discontinuity in soil erosion at the fSU border. We continue with the Calonico et al. (2014) model and estimate:

$$E_i^{LU} = \beta_1 fSU_i + \beta_2 dist_i^{fSU} + \beta_3 dist_i^{-fSU} + \beta_4 location_i + \beta_5 \theta_i + \beta_6 \vartheta_j + \epsilon_i \quad (4)$$

All variables are defined as before. We test two kinds of standard errors: i) clustered at the borders and ii) clustered among the 100 nearest neighbors. We find no significant difference between the two and report standard errors clustered at the borders henceforward.

#### b. Simulating the Implied Effect on the Erosion Rate

In our main specifications we use the soil erosion that is a direct result of land use change and hence clearly caused by humans. A

drawback is that the erosion caused by land use is measured in percentage of the locally possible maximum soil erosion, which is heterogeneously distributed and thus the effect on the overall soil erosion is difficult to assess. To transform our estimates into easily understandable metrics, we use the Revised Universal Soil Loss Equation (RUSLE) to compute the change in soil erosion in t/ha/yr and overall percentage difference in soil erosion between a world with and a world without the fSU (see Borrelli et al. (2017) and our data section).

#### c. Robustness Checks and Identifying the Mechanism

We provide two robustness checks. First, we exclude Russia and China from our sample. The sheer size of these countries could mean that they dominate our results, in which case their general influence could create a bias. Second, we examine whether the fSU countries might have distinct soil erosion rates because of the general economic legacy of the fSU, i.e. differences in GDP and GDP growth, population density and population growth.

Next, we examine whether we can identify the mechanism for how the fSU legacy currently affects the soil erosion rate in its successor countries. Farmland abandonment and forest dynamics are the two most likely candidates (see Section 2). In principle, the effect of farmland abandonment is ambiguous. While farmland abandonment can increase the rate of soil erosion in the short-run, abandoned farmland tends to have a lower rate of soil erosion in the longer run, mainly because it is not tilled and has continuous soil cover. Established forest cover reduces the rate of soil erosion to almost zero (Borrelli et al., 2017; Borrelli et al., 2020b). It is well established that widespread farmland abandonment and reforestation occurred as a consequence of the fall of the Soviet Union (Mirzabaev et al., 2016a, b; Gutman and Radeloff, 2017).

The most popular approach to test for the role of such mechanisms is to include them in the regressions and see whether they control away the identified effect. However, as Acharya et al. (2016) show, directly conditioning on a post-treatment variable can lead to wrong inferences. The issue is *intermediate variable bias* – variables that are affected by the treatment and affect both mediator and outcome. This can be avoided with a two-stage approach called sequential g-estimation. First, the effect of the mediator is statistically removed from the outcome and then the treatment-effect is estimated on this “demediated” outcome. In our case, we first remove the effect of post-Soviet forest dynamics and post-Soviet farmland abandonment from the land use effect that we try to explain and then re-estimate our main specification. If the resulting “controlled direct effect” is considerably smaller after removing the effect of a mediator, this indicates how much of the estimated treatment effect is explained by this mediator. If the treatment effect is



statistically insignificant in the second stage, this suggests that the mediator is possibly even the only mechanism that explains how the treatment affects the outcome.

Another analysis that we perform is to restrict our main analysis to current cropland only. This helps us understand the relative importance of the general land-use mix versus farming practices and crop portfolios, by comparing the estimated effect on cropland to that on all land.

#### 4. Data

Our analysis requires high-resolution data for soil erosion and its determinants along the entire historical border of the fSU. Furthermore, measurement must follow the same methodology to avoid that we pick up methodological discontinuities and confound these with erosion discontinuities. On a large geographical scale, the density of homogeneously collected field measurements is far too low for our purpose. However, a global, gridded dataset on soil erosion provides methodologically unified, high resolution data for our entire study area in the year 2012 (Borrelli et al., 2017). The data is based on the Revised Universal Soil Loss Equation (RUSLE), which uses a combination of remote sensing and statistical data to compute individual factors that together provide a reliable soil erosion estimate for small pixels (1 km in our main data and  $30 \times 30$  meters for the dataset on cropland only). The soil erosion rate per pixel is computed as follows:

$$E_i = E_i^{Rain} * E_i^{Soil} * E_i^{Topo} * E_i^{LU} \quad (5)$$

where  $E_i$  is the annual average soil erosion ( $\text{Mg ha}^{-1} \text{ yr}^{-1}$ ),  $E_i^{Rain}$  is the rainfall erosivity effect ( $\text{MJ mm h}^{-1} \text{ ha}^{-1} \text{ yr}^{-1}$ ),  $E_i^{Soil}$  is the soil erodibility effect ( $\text{Mg h MJ}^{-1} \text{ mm}^{-1}$ ),  $E_i^{Topo}$  is the slope length and steepness effect (dimensionless), and  $E_i^{LU}$  is the land use effect (in percentage of the maximum erosion possible, which is the product of the first three effects). While the land use effect is our main dependent variable, we use the other effects for balance tests and as control variables. All parameters of Eq. (5) are the product of large amount of input data, which we summarize briefly below. For details see Borrelli et al. (2017).

The main input for the land use parameter are datasets from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) on land cover and vegetation. The data is available from the NASA EarthData facility ([reverb.echo.nasa.gov](https://reverb.echo.nasa.gov)). The first step is a pre-processing with the MODIS Reprojection Tool to obtain baseline land cover maps. To improve these maps, data on forests from Hansen et al. (2013), and data on croplands by Monfreda et al. (2008), Ramankutty et al. (2008), the FAOSTAT database (<http://www.fao.org/faostat/en/#data>) of the Food and Agriculture Organization, and the Land Processes Distributed Active Archive Center (2019) were used. A review and discussion of soil erosion effects of different land-covers is provided by Borrelli et al. (2017).

The topography parameter was computed using the approach of Desmet and Govers (1996) with data from the hole-filled digital elevation model and ASTER GDEM products (Robinson et al., 2014; Reuter et al., 2007). The computational operations were carried out with SAGA (Brenning et al., 2018).

The rainfall erosivity parameter was derived from pluviograph data of 3625 weather stations that are part of the global rainfall-runoff erosivity database (Panagos et al., 2017). For processing, a Gaussian process regression was trained on data of the WorldClim database ([www.worldclim.org](http://www.worldclim.org)), including average monthly precipitation, average minimum and maximum monthly precipitation, average monthly temperature, precipitation of the wettest month, precipitation of the driest month, and precipitation seasonality, to then predict the rainfall erosivity effect for each  $1 \text{ km}^2$  pixel.

These erosion estimates and their uncertainty have been extensively examined and cross-tested with field measurements and are the most reliable global soil erosion data that is currently available at this scale

(Borrelli et al., 2017).

Because we want to optimally test whether there are border discontinuities in the natural rate of soil erosion, we require one more variable: The natural soil cover. The RUSLE framework models soil erosion as maximum potential erosion, which is the product of topography, rainfall, and soil characteristics. RUSLE then quantifies how much of this maximum potential actually occurs because of less than 100% soil cover. The soil cover we currently observe is mostly a function of human land use. For the natural soil erosion rate, we need to understand what soil cover we would see without human land-use. This is provided by Bastin et al. (2019). They first trained a random forest machine learning algorithm in protected areas around the world, where one can observe the natural relationship between environmental characteristics and the natural vegetation. Then, based on these environmental characteristics, they predicted globally the distribution of the natural vegetation that we would observe without human land use (see Fig. S1 in the Appendix). We obtained their data in the same resolution as the rest of our data ( $1 \text{ km}^2$ ) and use it as input in the RUSLE, to predict the natural rate of soil erosion for each of our observations:

$$E_i^{Nat} = E_i^{Rain} * E_i^{Soil} * E_i^{Topo} * E_i^{Nat-Cov} \quad (6)$$

where most parameters are defined as before, except that  $E_i^{Nat}$  is the natural rate of soil erosion that we would observe without human land use and  $E_i^{Nat-Cov}$  is the soil erosion mitigation effect of the natural soil cover that we would observe without human land use.

For our examination of potential mechanisms, we use data on post-SU farmland abandonment, from Lesiv et al. (2018); and on post-SU forest dynamics, from Potapov et al. (2015).

Finally, for our covariates, we use data on population densities (SEDAC, 2019), socio-economic and political variables (World Bank, 2020; the Quality of Government Institute, 2020).

#### 5. Results

Before our formal econometric analysis, we begin with a visual inspection of the data (Fig. 2). For each plot, we set the sampling bandwidth to 60 km on each side of the border. This is a wider bandwidth than what is later statistically selected but it is helpful to see the “larger picture”. Observations are averaged in small, equally sized bins and plotted as a function of border distance. The general pattern is approximated with a flexible polynomial curve on each side of the border (Calónico et al., 2015).

Fig. 2a shows the natural rate of soil erosion in tons per hectare and year. The natural rate of soil erosion is small in magnitude (mostly between 0.2 and 0.3 t/ha/yr) and continuously distributed across the border, suggesting that we can treat the fSU border as exogenous. Fig. 2b shows the natural logarithm of the maximum erosion potential, which would occur without any soil cover, based on rainfall, topography, and soils.

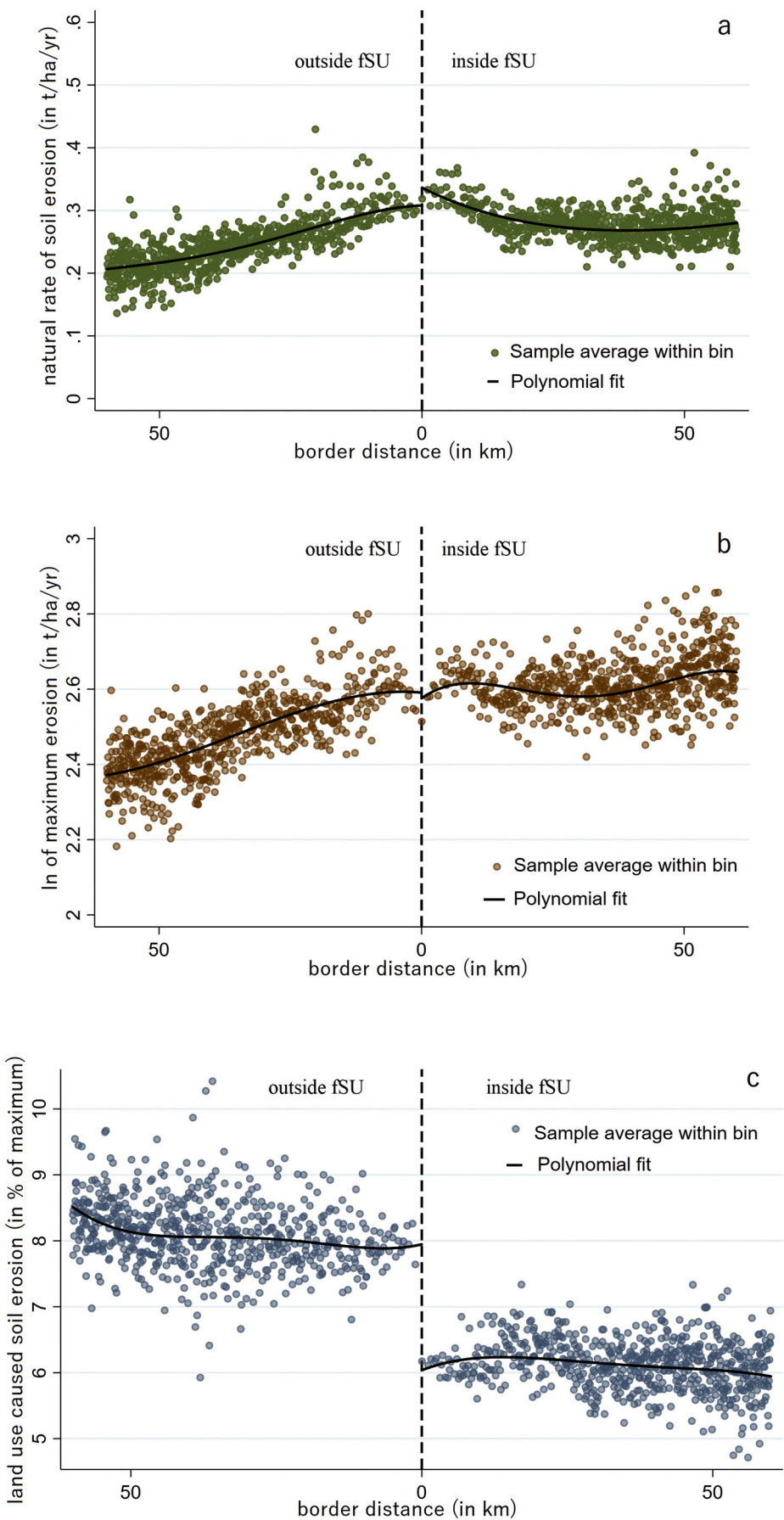
The maximum erosion potential is much higher than the natural rate of soil erosion, as the natural soil cover would mitigate most of it. Importantly, this too is distributed continuously, consistent with our first identifying assumption that the border is exogenous.

Fig. 2c shows what we are mainly interested in: There is a sharp border discontinuity in how much of the natural maximum soil erosion potential occurs because of land use. Outside the fSU, about 8% of the maximum soil erosion occurs, whereas inside the fSU, only 6% of the maximum soil erosion occurs, and this changes very abruptly at the political border.

In the following sub-sections, we use the framework of Calónico et al. (2014) to formally examine what is suggested by Fig. 2.

##### a. Baseline Tests and Estimates

We begin our formal econometric analysis with an examination of



(caption on next page)

**Fig. 2.** Natural Continuity and Man-Made Discontinuity.

Notes: Dots summarize the local average of each outcome (natural soil erosion (a), maximum erosion potential (b), and land use caused soil erosion (c), respectively) in small bins, as a function of border distance. The polynomial functions approximate the spatial distribution on each side. If the functions are connected, there is no border discontinuity; if they are disconnected, there is a border discontinuity.

**Table 1**

Covariate Continuity across the Border.

	(1)	(2)	(3)	(4)
	Topography	Soils	Rainfall	Natural Rate of Soil Erosion
fSU	−0.142 (−0.36/+0.077)	0.000 (−0.03/+0.15)	−5.749 (−33.93/+22.95)	0.002 (−0.08/+0.09)
Bandwidth	9753	9945	8489	13,447
N	255,805	255,805	221,528	331,057

Notes: all specifications include border fixed effects and a linear location polynomial. Standard errors are clustered at the border. No estimate is statistically significant any common level. Shown in brackets are the upper and the lower bound of the robust 95% confidence intervals of [Calonico et al. \(2014\)](#). The bandwidth is the maximum border distance (in km) beyond which we exclude observations from the analysis.

indications of natural discontinuities at the fSU border. [Table 1](#) shows four specifications, which suggest that there is no border discontinuity in topography (1), soils (2), rainfall (3), or the natural rate of soil erosion (4). As such, we find no evidence that the border of the fSU might naturally display a discontinuity in soil erosion. Instead, without the border, soil erosion would be distributed continuously, as shown in [Fig. 2a](#) above.

Shown in [Table 2](#) are the results of two placebo tests, to examine our two other critical assumptions. For Placebo A, we systematically shifted the fSU border 10 km away from its real location (shown in [Fig. 1](#)). It would be worrying if we were to find a random discontinuity in the rate of soil erosion in a place where no actual border exists. This could occur if the soil erosion data were not continuously distributed. However, we already saw in [Fig. 1](#) that it is and this is corroborated in [Table 2](#). For Placebo B, we randomized fSU membership, i.e. we use the real borders but we re-sort countries in and out of the fSU. Again, we do not find a statistically significant border discontinuity.

Together, [Table 1](#) and [Table 2](#) suggest that we can treat the fSU border as exogenous and if we find a soil erosion discontinuity, this is man-made and caused by the fSU border, not the borders of the individual countries and not by any random discontinuities. [Table 3](#) shows that indeed, there is a sharp, highly significant discontinuity in soil erosion caused by land use. Specification (1) is our baseline specification without additional covariates and specification (2) additionally includes the natural rate of soil erosion.

#### b. The Soil Erosion Legacy of the Soviet Union

In Section 5a, we estimated the fSU border discontinuity in the land-use caused soil erosion, which is defined as how much of the natural

**Table 2**

Placebo Tests: Shifting Borders and Randomizing fSU Membership.

	(1)	(2)
Dependent variable: Soil erosion caused by land use		
Placebo A	−0.000 (−0.002/+0.002)	
Placebo B		−0.001 (−0.008/+0.004)
Bandwidth	6437	9171
N	171,312	242,948

Notes: all specifications include border fixed effects and a linear location polynomial. Standard errors are clustered at the border. No estimate is statistically significant any common level. Shown in brackets are the upper and the lower bound of the robust 95% confidence intervals of [Calonico et al. \(2014\)](#). The bandwidth is the maximum border distance (in km) beyond which we exclude observations from the analysis.

**Table 3**

The Effect of the former Soviet Union.

	(1)	(2)
Dependent Variable: Land Use Caused Soil Erosion		
fSU	−0.017*** (−0.023/−0.010)	−0.017*** (−0.023/−0.011)
Added Controls	None	Natural Erosion
Bandwidth	10,577	10,406
N	274,006	268,351

Notes: all specifications include border fixed effects and a linear location polynomial. Standard errors are clustered at the border. Levels of statistical significance: 0.01 \*\*\*, 0.05 \*\*, 0.1 \*. Shown in brackets are the upper and the lower bound of the robust 95% confidence intervals of [Calonico et al. \(2014\)](#). The bandwidth is the maximum border distance (in km) beyond which we exclude observations from the analysis.

maximum potential soil erosion occurs because it is not mitigated by the current soil cover. This is the most precise estimate that we can get, because in contrast to the overall soil erosion, the land-use caused soil erosion is 100% man-made. The flip-side is that the maximum potential soil erosion is not the same throughout the border region, so it is not immediately understandable how large the estimated discontinuity is. To address this, we can use the RUSLE framework and remove the estimated effect of the fSU legacy. [Table 4](#) shows that soil erosion in the fSU countries would be 26% higher without the fSU legacy effect. The legacy effects amounts to 0.77 tons per hectare and year, which is economically quite meaningful.

#### c. Robustness Checks & Mechanisms

Already when we randomized the fSU legacy for Placebo B in [Table 2](#) we tested for the current influence of individual countries, in comparison to the joint fSU legacy. Another important test is to exclude Russia and China from our sample because these countries are

**Table 4**

The Effect of the former Soviet Union on Soil Erosion.

	(1)	(2)
	Percentage change	Absolute change
fSU	−26% (−24% / −29%)	−0.77 t/ha/year (−0.70 t/ha/year / −0.85 t/ha/year)
N	1,876,650	1,876,650

Notes: Estimates based on the Revised Universal Soil Loss Equation (RUSLE). The estimated fSU-legacy effect was subtracted from the actual land use effect and the difference is shown in percentage and absolute terms. Shown are point estimates and the 95% confidence interval in brackets.

**Table 5**  
Excluding China and Russia.

	(1)	(2)
Dependent Variable: Land Use Caused Soil Erosion		
fSU	−0.018*** (−0.025/−0.009)	−0.019*** (−0.02/−0.008)
Bandwidth	8418	10,169
Excluded	China	Russia
N	138,570	147,402

Notes: all specifications include border fixed effects. Standard errors are clustered at the border. Levels of statistical significance: 0.01 \*\*\*, 0.05 \*\*, 0.1 \*. Shown in brackets are the upper and the lower bound of the robust 95% confidence intervals of [Calonico et al. \(2014\)](#). The bandwidth is the maximum border distance (in km) beyond which we exclude observations from the analysis.

contributing a large share of observations, and thus these two countries may be responsible for much of the estimated effects. [Table 5](#) shows that excluding China from the sample changes the estimated discontinuity from −0.017 to −0.018 and excluding Russia changes it to −0.019. This suggests that our estimates do not depend on these two countries.

Notes: Dots summarize the local average of each shown outcome in small bins, as a function of border distance. The polynomial functions approximate the spatial distribution on each side of the border. If the functions are connected, there is no border discontinuity if they are disconnected, there is a border discontinuity.

Another robustness check is the examination of whether perhaps we are simply finding that countries with less economic activity have lower soil erosion rates. [Pinkovskiy \(2017\)](#) documents sharp border discontinuities in economic growth in the region. To examine this, we sort the countries in the sample according to (a) GDP, (b) GDP growth, (c) population density, and (d) population growth ([Fig. 3](#)).

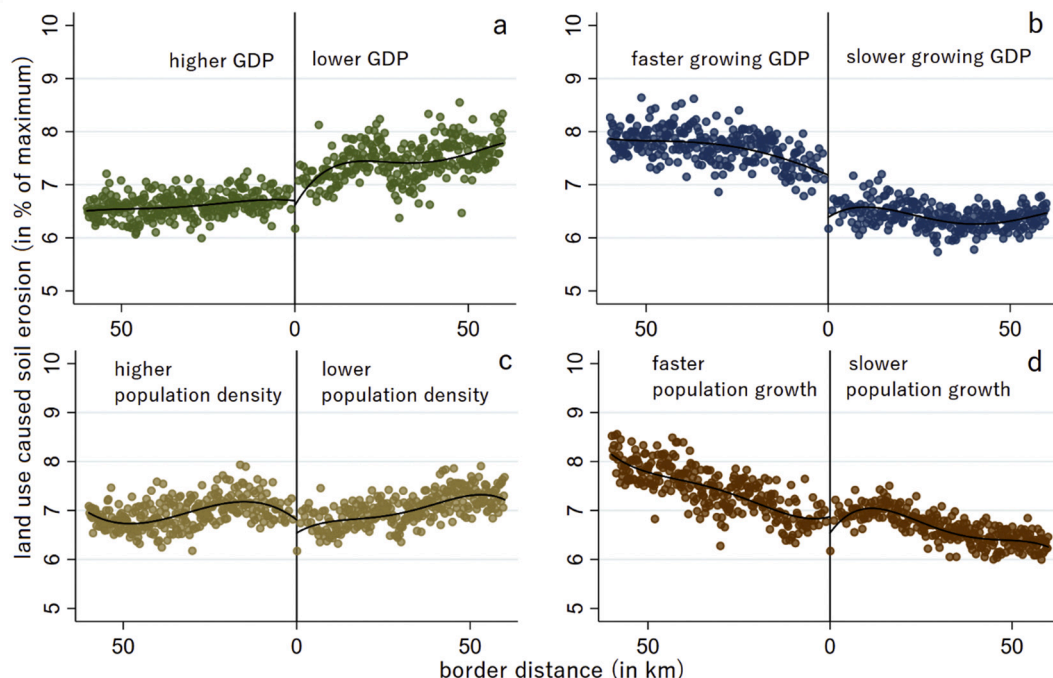
Out of the four ways of sorting the countries, none shows a clear discontinuity, but GDP growth (b) comes closest, with a possible discontinuity of half a percentage point. In [Table 6](#), we formally test this and we find a small, marginally significant discontinuity for countries of different GDPs (about 0.6 percentage points) but not for countries

that differ in GDP growth, population density, or population growth. Thus, economic activity alone does not seem to be the main explanation behind our estimated fSU legacy.

Our first step towards identifying the mechanism of the fSU legacy is to investigate whether we also find a spatial discontinuity in the rate of soil erosion right at the border of the fSU when we only analyze cropland. On cropland, soil erosion is affected by the types of crops grown and the farming practices used (e.g. degree of plowing, length of fallows, growing cover crops, keeping semi-natural vegetation between fields). As shown in [Table 7](#), we do not find the fSU legacy effect on cropland. This suggests that the mechanism of the fSU legacy is the land-use composition, i.e. the share and state of forests and grasslands, and not farming practices or grown crops.

We test two explanations for the fSU legacy, which are developments that were caused by the fall of the Soviet Union: differential forest dynamics and farmland abandonment rates. Due to data constraints, we can only investigate these mechanisms in Eastern Europe. We use the sequential g-estimation approach of [Acharya et al. \(2016\)](#) with which we examine whether the effect of the fSU legacy remains significant after we statistically removed (1) forest dynamics or (2) cropland abandonment. Again, due to data constraints, we are not able to examine pasture abandonment. Moreover, due to computational constraints, we can only use a linear parametric approach here, but as we estimate, the baseline estimate is the same as before. [Table 8](#) suggests that differential forest dynamics are the main explanation for the fSU legacy effect: Whereas the countries outside the fSU saw an increase in deforestation after the fall of the Soviet Union, the countries of the fSU saw a decrease in deforestation. This explains the entire fSU legacy effect. In contrast, removing farmland abandonment decreases the estimated “controlled direct effect” of the fSU legacy, suggesting that it plays a role too, but the effect remains statistically significant at any common level, indicating that farmland abandonment is not the main mechanism.

[Table 8](#) suggests that we should be able to see a discontinuity in forest dynamics at the fSU border. Indeed, using the same approach as before, this is clearly visible in [Fig. 4](#).



**Fig. 3.** Land Use and Soil Erosion Discontinuities and Economic Activity.



**Table 6**  
Estimating the Effect of Economic Activity.

	(1)	(2)	(3)	(4)
Dependent Variable: Land Use Caused Soil Erosion				
GDP	−0.006* (−0.13/+0.001)			
GDP growth		−0.006 (−0.16/+0.002)		
Pop density			−0.005 (−0.13/+0.002)	
Pop growth				−0.003 (−0.11/+0.004)
Bandwidth	11,649	9820	10,294	9294
N	301,465	255,805	267,102	245,795

Notes: all specifications include border fixed effects. Standard errors are clustered at the border. Levels of statistical significance: 0.01 \*\*\*, 0.05 \*\*, 0.1 \*. Shown in brackets are the upper and the lower bound of the robust 95% confidence intervals of [Calonico et al. \(2014\)](#). The bandwidth is the maximum border distance (in km) beyond which we exclude observations from the analysis.

**Table 7**  
The Effect on Cropland Only.

	(1)	(2)
Dependent Variable: Land Use Caused Soil Erosion		
fSU	0.020 (−0.003/+0.035)	0.020 (−0.003/+0.035)
Added Controls	None	Natural Erosion
Bandwidth	14,360	14,260
N	171,702	170,719

Notes: all specifications include border fixed effects and a linear location polynomial. Standard errors are clustered at the border. No estimate is statistically significant any common level. Shown in brackets are the upper and the lower bound of the robust 95% confidence intervals of [Calonico et al. \(2014\)](#). The bandwidth is the maximum border distance (in km) beyond which we exclude observations from the analysis.

**Table 8**  
The Role of Farmland Abandonment and Forest Dynamics.

	(1)	(2)
Controlled Direct Effect	−0.0003 (0.0005)	
Forest Dynamics		
Controlled Direct Effect		−0.0069*** (0.0005)
Cropland Abandonment		
N	330,951	330,951

Notes: Sequential g-estimation. Levels of statistical significance: 0.01 \*\*\*, 0.05 \*\*, 0.1 \*. Controls: Border distance separately on each side of the border, linear location polynomial, border fixed effects, natural erosion determinants.

## 6. Discussion and conclusion

Soil erosion reduces the primary productivity of the land and has important side effects, including greenhouse gas emissions and water pollution. We use a regression discontinuity design and geospatial data on soil erosion rates at 1 km spatial resolution as well as the the soil erosion rate without human activity as the counterfactual to identify the historical legacy of the former Soviet Union on the rate of soil erosion in 2012. We find that the border of the former Soviet Union would naturally not have a soil erosion discontinuity, but currently there is one, and the magnitude of the discontinuity is very large: The countries of the former Soviet Union experience 26% less soil erosion than their direct neighboring countries outside the former Soviet Union. This is not caused by general differences in economic activity, but by observed differences in land-use. Generally, we do not find that economic status, economic growth population density or population growth are decisive for the rate of soil erosion. Rather, our findings are consistent with a strong historic legacy effect on economic activities, such as forestry and agriculture.

The main mechanism is forest regrowth and former farmland that is now covered by grasses and shrubs with lower erosion rates. Overall, our analysis demonstrates the large and persistent effect that historical institutional change can have on land use and thus on environmental outcomes.

However, not all implications for overall sustainability are clear. The main reason is that the estimated reduction in soil erosion comes from a reduction in primary production, mainly a reduction in the production of forest commodities but also a reduction agricultural output. A comprehensive sustainability assessment would need to compare the relative magnitudes in the drop of production with ensuing environmental damages, to understand these trade-offs ([Kanter et al., 2018](#)). In addition, it must also be assessed how the global market responded to this. If other regions, have expanded and intensified their production in response to the production decline in the fSU, then the environmental impacts are displaced to other regions, and with unclear implications for global sustainability.

A sustainability implication emerges from two observations. First, the rate of soil erosion is rising globally ([Borrelli et al., 2017, 2020a](#)), with increasing economic damages ([Sartori et al., 2019; Nkonya et al., 2016](#)). Second, the examined regions of this study (Eastern Europe and Northern Asia) are highly important for global agricultural production and increasingly so ([Swinnen et al., 2017; Mueller et al., 2012](#)). The rising global demand for primary production (agriculture and forestry) provides incentives to expand and intensify production in the study region. We showed here that the erosion discontinuity is entirely man-made, caused by land-use. Thus, a shift in incentives and constraints for production may diminish the lower erosion rates inside the former Soviet Union. Thus, without effective land use policies that specifically aim at avoiding environmental damages, such as soil erosion, we might see a further acceleration in the regional rate of soil erosion.

It should be noted that our main estimate is an average for the entire length of the fSU border and it is estimated for only one point in time, nominally the year 2012. Clearly, it would be of great interest to further understand spatial and temporal heterogeneity. However, data on changes in erosion rates are currently not available. We also not cannot distinguish between the fSU legacy and contemporary differences between the individual countries (e.g. if we estimate a discontinuity between Russia and China, there are many differences between the two countries that are independent from the fact that Russia was part of the Soviet Union). Regarding temporal dynamics, panel data would allow to examine how soil erosion developed during and after the fall of the Soviet Union and would arguably reveal distinct spatial patterns in the causes for soil erosion over time. Space-time data on soil erosion at a sufficiently high resolution would also enable to examine these aspects of temporal dynamics and spatial heterogeneity, e.g. country-level legacies, and will thus be valuable for policy makers to account for legacy effects when designing sustainable land use policies.

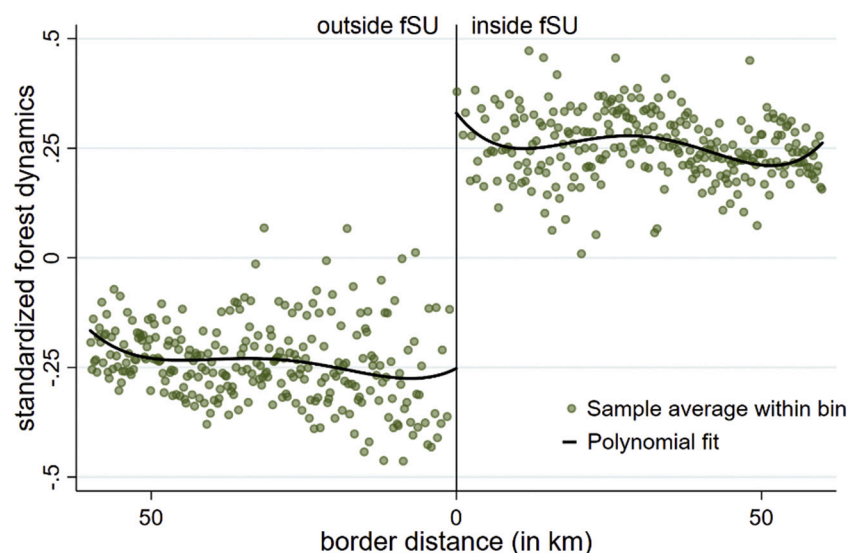


Fig. 4. The Discontinuity in Forest Dynamics.

Notes: Instead of soil erosion, forest dynamics are plotted here, which show a sharp border discontinuity.

### Declaration of Competing Interest

David Wuepper, Pasquale Borrelli, Daniel Mueller, and Robert Finger, declare that they have no relevant or material financial interests that relate to the research described in this paper.

### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agsy.2020.102940>.

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