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DETERMINANTS OF AGRICULTURAL LAND ABANDONMENT IN POST-SOVIET EUROPEAN RUSSIA

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Abstract

Socio-economic and institutional changes may accelerate land-use and land-cover change. Our goal was to explore the determinants of agricultural land abandonment within one agro-climatic and economic region of post-Soviet European Russia during the first decade of transition from a state-command to market-driven economy (between 1990 and 2000). We integrated maps of abandoned agricultural land derived from 30 m resolution Landsat TM/ETM+ images, environmental and socioeconomic variables and estimated logistic regressions. Results showed that post-Soviet agricultural land abandonment was significantly associated with lower average grain yields in the late 1980s, higher distance from the populated places, areas with low population densities, for isolated agricultural areas within the forest matrix and near the forest edges. Hierarchical partitioning showed that average grain yields in the late 1980s contributed the most in explaining the variability of agricultural land abandonment, followed by location characteristics of the land. While the spatial patterns correspond to the classic micro-economic theories of von Thünen and Ricardo, it was largely the macro-scale driving forces that fostered agricultural abandonment. In the light of continuum depopulation process in the studied region of European Russia, we expect continuing agricultural abandonment after the year 2000.

Keywords: agricultural land abandonment; institutional change, land use change; spatial analysis; logistic regression; remote sensing; Russia; Q15.

1. Introduction

Land use is a major cause of biodiversity declines, and diminishing ecosystem functioning and services (Vitousek, et al., 1997). Rapid socio-economic and institutional changes may accelerate land-use and land cover change (LULCC) or shift the land-use in the new mode. A major recent rapid socio-economic change was the collapse of socialism and the transition from state-command to market-driven economies (further transition) in Eastern Europe in the early 1990s. However, the impacts of this transition on LULCC are not well understood. The dismantling of state-governed economies, withdrawal of governmental support, and implementation of open markets changed the economy, human welfare, and health drastically (Kontorovich, 2001). For instance, during the first decade of the transition from state command to market driven economies from 1990 to 2000 (subsequently labeled "transition"), overall Russian life expectancy declined from 69 to 65 years and male life expectancy in rural area even slumped from 61 to 53 years in central European Russia (Rosstat, 2002). Profound changes were particularly common in rural regions of Russia where state-support of agriculture ceased, and rural development almost stopped (Rosstat, 2002).

These drastic socio-economic changes affected land use, but rates and patterns of LULCC varied dramatically both in Russia and among the post-communist countries in Eastern Europe (Kuemmerle, et al., 2008, Baumann, et al., 2011, Prishchepov, et al., *in review b*). During the transition period institutional changes heavily affected the agricultural sector in post-communist countries in Eastern Europe and agricultural land abandonment was widespread (Kuemmerle, et al., 2008, Baumann, et al., 2011, Prishchepov, et al., *in review a, b*). Agricultural land abandonment rates were higher in the post-Soviet countries in Eastern Europe, which had weak institutions during the transition (Prishchepov, et al., *in review b*). However, our knowledge about the drivers of LULCC in Eastern Europe and Russia, and of agricultural abandonment in particular, is limited.

The knowledge on the determinants of agricultural land abandonment were largely gained from the studies which took place in the European Union (EU) countries, where abandonment of agricultural land was long-term process over the 20th century and especially after Second World War (Baldock, et al., 1996). In European Union countries the abandoned agricultural lands were generally found in the unfavorable environmental conditions (e.g., higher elevation, steeper slopes, poorer soils, and poorly meliorated agricultural fields), in physical remoteness, and isolated agricultural areas (Baldock, et al., 1996, MacDonald, et al. 2000). Agricultural land abandonment was also strongly associated with landowner characteristics (Grinfelde & Mathijs, 2004, Kristensen, et al., 2004). Part-time farmers and older landowners were more likely to reforest agricultural land than any other types of landowners in EU (Kristensen, et al., 2004). Last but not least, smaller farms throughout Europe were more likely to abandon farmland than larger enterprises (Baldock, et al., 1996, Kristensen, et al., 2004).

Yet to date, only few quantitative studies have examined the determinants of post-socialist agricultural abandonment in Eastern Europe in general (Müller, et al., 2008, Baumann, et al., 2011) and for such vast agricultural lands as in Russia in particular. However, it is not clear if the same set of factors which determined agricultural land abandonment in European Union were important in the former Soviet Bloc countries, including Russia where agricultural production was dominated by large-scale farming.

The recent fine-scale detailed mapping of agricultural land abandonment with remote sensing data in European Russia allowed receiving spatially explicit results on agricultural land abandonment rates and patterns for the first decade of transition (1989-1991 to 1991-2001) for the large territory (Prishchepov et al., *in review b*). Using produced agricultural land abandonment maps, socio-economic and biophysical statistics our major goal was to explore determinants of agricultural land abandonment during the first decade of transition (1990-2000) in one large agro-climatic and economic region of post-Soviet Russia. We do this with spatially explicit-logistic regression analysis of the determinants of land-use change at the pixel level. To identify the relative contribution of the covariates to agricultural abandonment we used hierarchical partitioning.

2 Methods

2.1 Study area

Available to us maps of abandoned agricultural represent temperate zone of European Russia. The area covered by five 184x184 km 30 meter resolution Landsat TM/ETM+ satellite footprints comprised 150,550 km^2 and allowed covering 67 districts (rajons, roughly equivalent to counties in the United States or the NUTS 3 level in the EU) with average size of district equaling to 1,520 km^2 in Smolensk, Kaluga, Tula, Rjazan and Vladimir provinces of Russia (Figure 1).

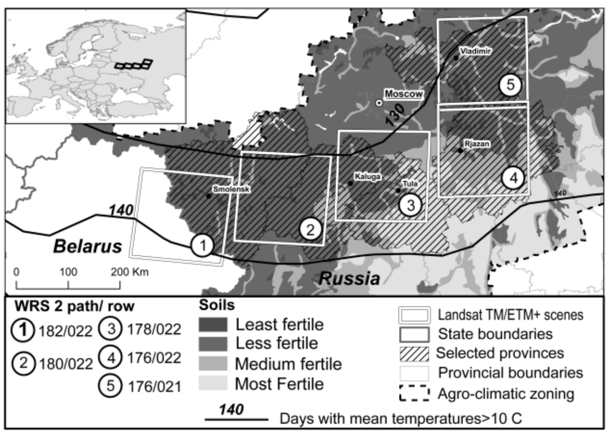


Figure 1: Study area and Landsat footprints

Climate in the outlined study region is temperate-continental. Days with temperatures >10 °C are from 125 to 142 days and annual precipitation is from 428 mm to 713 mm (Afonin, et al., 2010). The topography ranges only between 0 and 300 m. On average, 30% of the region is forested, with higher proportions of forest in the northern part of the study area. Soils mainly consist of podzols, luvisols and gleysols and fluvisols along rivers (Batijes, 2001). In the south-eastern corner of the region phaeozem and chernozem soils occur.

The study region is well-suited for agriculture, especially after melioration, liming and fertilization of podzolic soils. During the last decades of the Soviet era, the region became one of primary agricultural areas, especially after the failed attempts of the Soviet government to expand wheat growing in Kazakhstan (Ioffe & Nefedova, 2004). Main summer crops are barley, rye, oats, sugar beets, fodder maize, potatoes, peas, summer rapeseed, and flax, and main winter crops are winter wheat, winter barley, and winter rapeseed (Gataulina, 1992, Afonin, et al., 2010). Grain yields per hectare were comparable among the Russian oblasts in the study area (Table 1), but were lower than in the neighboring countries (e.g., Belarus, Lithuania, Poland, Ioffe & Nefedova, 2006, Prishchepov, et al., *in review b*). Cattle breeding, dairy farming, and poultry production is also common. State and collective farms were controlling for more than 98% of agricultural land and produced more than 90% of agricultural output during the Soviet time.

Table 1: Socio-economic and environmental conditions of the selected provinces (oblasts) in Russia in 1989, i.e., the pre-transition time from state-state command to market driven economies.

Provinces	Rural population density (people/km^2)[1]	Road density (km/km^2)[1]	Annual Milk production (kg/cow)[1]	Grain yields (tons/hectare)[1]	Average annual precipitation[2] (mm)	Average number of days with mean temperatures over 10 °C[2]	Soil pH	% agricultural land before 1990[4]
Smolensk	7.4	11.0	2478.0	1.13	649.0	132.0	6.6	31
Kaluga	11.0	14.0	2527.0	1.38	680.0	134.7	6.6	35
Tula	13.5	18.0	2645.0	1.92	638.0	135.3	6.7	55
Rjazan	11.8	12.0	2881.0	1.68	566.0	138.2	6.4	49
Vladimir	11.8	15.0	2880.0	1.62	605.0	131.6	6.7	23

[1] Statistical data from Goskomstat (2000); [2] climatic data from IIASA (2000); [3] soil data are taken from Batijes (2001);[4] -percentage of agricultural land are calculated from classified multi-date Landsat TM/ ETM+ images.

The study area experienced rural depopulation, especially during the last three decades before the collapse of the USSR (Ioffe, et al., 2004a, Ioffe, et al., 2004b). Prior to the dissolution of the Soviet Union rural population density was as low as 5 people/ km^2 in some districts (e.g., in Smolensk province).

Russia transitioned from a state-controlled to a market-driven economy after the dissolution of the Soviet Union in 1990 (Lerman, et al., 2004). Governmental regulation of agriculture and subsidies were largely withdrawn. The land and assets of collective and state farms were redistributed among former farms workers in the form of paper shares. However, a moratorium on agricultural land transactions was imposed to prevent potential land speculation and kept in place until 2002 (Lerman & Shagaida, 2007). National official statistics mirror the accompanying decline of agricultural production during the first decade of postsocialism with a decrease in sown area of up to 44% in Smolensk province since 1990 and of livestock numbers by up to 68%, again in Smolensk (Rosstat, 2002).

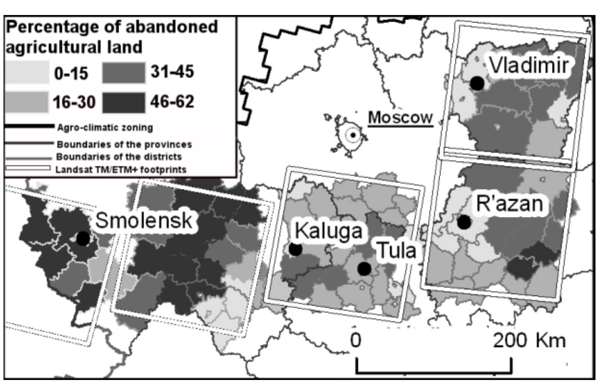


Figure 2: Rates of agricultural abandonment from 1989-1991 to 1999-2001 at the district level.

2.2 Maps of abandoned agricultural land

Detailed data on agricultural land abandonment derived from remote sensing classifications and covered Kaluga, Vladimir, Rjazan province, Smolensk province, and Tula provinces (Prishchepov, et al., *in review b*) (Figure 1). The authors used multi-date images and support vector machines classifier to derive land cover maps. The classifications yielded “Stable managed agricultural land” and “Abandoned agricultural land”. “Stable managed agricultural land" consisted of tilled agricultural land and grasslands intensively used for grazing and hay-cutting. Authors defined abandoned agricultural land from a remote-sensing perspective as agricultural land used before 1990 for grains, hay cutting, and livestock grazing, but no longer used in 1999-2001, and thus covered by non-managed grasslands often with succession shrubs at different stages. Average conditional Kappa among five Landsat TM/ETM+ footprints for "Stable managed agricultural land" equaled to 0.89 and "for Abandoned agricultural land" equaled to 0.84. The classifications indicated that from 1989-1991 to 1999-2001 31% of the agricultural land in 1989 was abandoned in the study area, comprising 1.7 million hectares. 46% of total 1989 agricultural land was abandoned in Smolensk province, 30% in Kaluga, 26% in Tula, 28% in Rjazan, and 27% in Vladimir province and abandonment rates were much higher at the district level (Prishchepov, et al., *in review b*) (Figure 2).

2.3 Explanatory variables

We assumed that agricultural land abandonment was mainly driven by economic decisions of maximizing net stream of income (Irwin & Geoghegan, 2001). Based on these assumptions we selected variables that impact on the productivity of agricultural production, that capture the proximity of locations to roads and markets centers, demographic changes, the availability of infrastructural facilities, and variables that capture agricultural productivity. We also assumed that the natural suitability of a plot of land crucially affects the profits that can be derived from agricultural production and included spatially explicit biophysical variables (Table 2). Since time variant socio-economic variables can be partially representing endogeneity to LULCC (Chomitz & Gray, 1996, Müller, et al., 2009) we used only time-invariant variables (e.g., elevation, slope) and variables which represent socio-economic conditions prior the dissolution of the Soviet Union (e.g., average grain yields and population densities, road densities in the late 1980s) (Table 2).

Table 2: Explanatory variables

Variables *(units)*	**Source**	**Spatial resolution**
Biophysical		
Soil pH *(units)*	SOVEUR/ SOTER 1:2,0000,000 digital maps	Rasterized vector dataset
Elevation *(meters),* slope *(degrees)*	Shuttle Radar Terrain Mission (SRTM)	Resampled raster 90 m dataset
Average annual evapotranspiration *(millimeters)*, number of days with temperature over10 °C *(degrees)*	AgroAtlas, 2010	Resampled raster 10 km dataset
Distance from the nearest forest edge *(100 meters)*	30 m Landsat TM/ETM+ classifications	Pixel level calculations
Isolated agricultural areas within forest matrix in 1990	30 m Landsat TM/ETM+ classifications	Pixel level calculations
Agricultural productivity		

Average grain yields in the late 1980s *(centners/ hectare)*, milk production per cow in the late 1980s *(kilograms/ hectare)*	Rosstat, 2002	Rasterized district level statistics
Population		
Interpolated population from the settlements in the late 1980s *(people/ 30 meters^2)*	1:100,000 declassified Soviet topographic maps	Pixel level calculations
Proximate		
Distance from provincial capital *(kilometers)*, distance from the nearest district center *(kilometers)*, distance to the nearest municipality center *(kilometers)*, distance to the nearest settlement with over 500 people *(kilometers)*, distance the nearest village *(kilometers)*	1:100,000 declassified Soviet topographic maps	Pixel level calculations
Distance from the nearest road with hard coverage *(100 meters)*	1:500,000 declassified Soviet topographic maps	Pixel level calculations
Infrastructure		
Road density in the late 1980s *(kilometers/ kilometer^2)*	1:500,000 digital dataset	Rasterized district level statistics
density of settlements in the late 1980s *(settlements/100 kilometer^2)*	1:100,000 digital dataset	Rasterized district level statistics

Average annual reference evapotranspiration, the number of days with temperature larger than 10 degrees Celsius, and the soil pH were derived climatic variables using GIS Agroatlas for Russia at 10-km resolution (Afonin, et al., 2010). Elevation and slope were derived from the 90 meter digital elevation model (USGS, 2004). We also assumed that higher forest percentage in the districts indicate that land surfaces in the respective area are of minor quality and less suited for agricultural production. Forest percentage was derived from 30-m resolution forest-cover maps for pre-abandonment (circa 1989) from the same classifications that yielded agricultural land abandonment (Prishchepov, et al, *in review b*). We also assumed that abandoned agricultural fields would be closer to the forest edges and we included the Euclidean distances to forest edges in the regression. We also observed that many abandoned agricultural areas were individual patches surrounded by a forest matrix. We thus digitized isolated agricultural areas within the forest matrix and created a binary variable that captures these areas.

To measure the effects of agricultural productivity we obtained agricultural statistics about average grain and milk yields in the late 1980s from official sources at the district level (Ioffe, et al., 2004). To calculate continuous population densities from the settlements we used 1:100,000 Soviet topographic maps from the end of the 1980s (VTU Gsh, 1989a). We digitized provincial, district, municipality centers and villages and we assigned the population for each settlement as printed in these maps. We calculated a continuous measure for population density from digitized settlements by interpolating the population using second-order inverse distance weights (Müller, et al., 2008). By late 1980s, 38% of 11,972 digitized settlements for our study area represented settlements with a population of less than 20 people.

To estimate the proximities effects we calculated the Euclidean distances to provincial, district and municipal centers indicating travel costs to the potential markets and distances to villages. Based on the field observations and summary of the digitized settlements by population, we assumed many villages were not playing the forming stable population and services provision network in the Central Russia. Additionally we calculated the proximities to the settlements with over 500 people as we assumed that such large settlements were important in provision of the goods and socio-economic services in the countryside.

As a measure of the infrastructure we also calculated settlements densities on district level. We thus incorporated the importance of larger population settlements for the provision of social infrastructures (e.g., stores, schools and hospitals), because we anticipated the availability of public service as an important factor for curbing outmigration and thus agricultural land abandonment. To calculate road densities and distances to roads we used a GIS dataset for Russia that was derived from 1:500,000 declassified Soviet topographic maps from the late 1980s (VTU Gsh, 1989b). Descriptive statistics for the selected variables are summarized in Table 3.

Table 3: Descriptive statistics of explanatory variables.

Variables	**Level**	**Unit**	**Mean**	**Median**	**Standard Deviation**	**Minimum**	**Maximum**
Abandoned agricultural land	Pixel	Dummy (1/0)	0.293	0	0.455	0	1
Soil pH	Pixel	Units	662.3	690	6.432	422.00	738.00
Number of days with mean temperatures over 10 **°C**	Pixel	Degree days	134.9	135	3.467	125.00	142.00
Elevation	Pixel	M	167.6	170	4.533	66.00	309.00
Slope	Pixel	Degrees	1.253	1	1.653	0.00	29.00
Average annual evapotranspiration	Pixel	Mm	700.9	689	5.871	554.00	882.00
Distance from the nearest forest edge	Pixel	100 m	7.169	4.37	7.864	0.00	70.59
Isolated agricultural areas within forest matrix in 1990	Pixel	Dummy (1/0)				0	1
Average grain yields in the late	District	Centners/Ha	15.9	16	4.568	8.00	27.00

1980s							
Average milk yields in the lat 1980s	District	Kg/Year	2648	2658	3.566	1743.00	3442.00
Interpolated population from settlements in the late 1980s	Pixel	Number of people/ 900 m^2	267.81	115.77	8.041	0.16	85337.80
Distance from provincial capitals	Pixel	Km	71.6	68.05	3.797	0.40	210.61
Distance from nearest district center	Pixel	Km	15.62	14.7	7.898	0.11	52.30
Distance from nearest municipality center	Pixel	Km	4.105	3.74	2.34	0.00	23.55
Distance from nearest settlement over 500 people	Pixel	Km	6.784	5.7	5.9	0.00	39.47
Settlements density	District	Number of villages / 100 km^2	10.6	10.0	3.30	4.00	18.00
Road density	District	Km/ 100 Km^2	344.4	351	40.8	257.00	449.00
Distance from the nearest road with hard coverage	Pixel	100 m	8.79	7	7.327	0.30	79.59

2.4 Logistic regression and hierarchical partitioning

Based on the assumptions that the cumulative distribution function for the residual error of the explanatory variables follows the logistic distribution it is possible to construct spatially explicit logistic regression model. For the logistic regressions we defined “1” to represent abandoned agricultural land and “0” for stable agricultural land.

For our global model we randomly sampled 132,015 pixels from the available 52 million pixels for agricultural areas, which represent 0.25% of the total population of the total number of pixels. In the sampling process we ensured a gap of at least 500-m distance between sampled observations to reduce the spatial autocorrelation which was measured previously for our study area (Prishchepov, et al., *in review b*). For each of 67 districts we had on average 2,000 sampled pixels. The final sample is fairly balanced with 30% of the sampled pixels labeled as abandoned.

For the statistical analysis we used R statistical package (R Team, 2009). We checked for collinearity (Maddala & Lahiri, 2009). When R >0.5 for two explanatory variable, we retained the variable that was more strongly related to abandonment in our regression models. However, we did explore the predictive power of correlated explanatory variables using descriptive statistics and univariate models.

Since the observations within districts may not be completely independent from each other we introduced a group structure and conducted a statistical adjustment of the clustered data structure in our logistic model (Gellrich, et al., 2007, Müller, et al., 2008).We thus applied the Huber-White sandwich estimator that controls for such clustering at the district level (administrative units where the main land use decisions and governance actions are taking place that systematically affect the decision making of local producers about the use of the agricultural land) without affecting the estimated coefficients in the model (Huber, 1967, White, 1982).

To assess the goodness-of-fit of the regression we calculated the log-likelihood for the logistic model, the Akaike Information Criterion (AIC), the deviance for the residuals of the null and fitted models and the area under the receiver operating characteristics curve (AUC) (Pontius & Schneider, 2001, R Team, 2009). Finally, we used hierarchical partitioning (Walsh & Mac Nally, 2009) that allows assessing the contribution of the independent variables for explaining the variability of the dependent variable individually or in the conjunction with other variables (Millington, et al, 2007, Baumann, et al., 2011). Hence we were able to explore the relative importance of each statistically significant variable for the total explained variance. We followed this procedure for the entire sample and for each province separately to explore provincial-level bearings for agricultural land abandonment.

3. Results

3.1 Selection of the variables for the logistic regression

We found that average grain yields in the late 1980s variable was positively correlated with milk yields in 1990 (R=0.54). We hence retained only average grain yields in late 1980s for the multivariate logistic regression modeling. Forest percentage and distance from the nearest forest edge variables represented medium correlation (R=0.51) above the self-imposed threshold of R=0.5 and negatively correlates with the density of municipal centers (R=-0.57). For the model we retained only distance from the nearest forest edge as it had higher correlation with abandoned and non-abandoned agricultural land (R=0.16) comparable to forest percentage (R=0.1) and density of municipal centers (R=-0.1).

Average annual evapotranspiration was also positively correlated with settlements density in the late 1980s (R=0.59) and elevation (R=0.67). We retained average annual evapotranspiration as it had higher correlation with agricultural land abandonment compared to settlements density in the late 1980s and elevation. We also decided to exclude the number of days with mean temperature over 10 °C as it negatively correlated with the retained average annual evapotranspiration variable (R=-0.52). The final dataset consists of 14 independent variables (Figure 3).

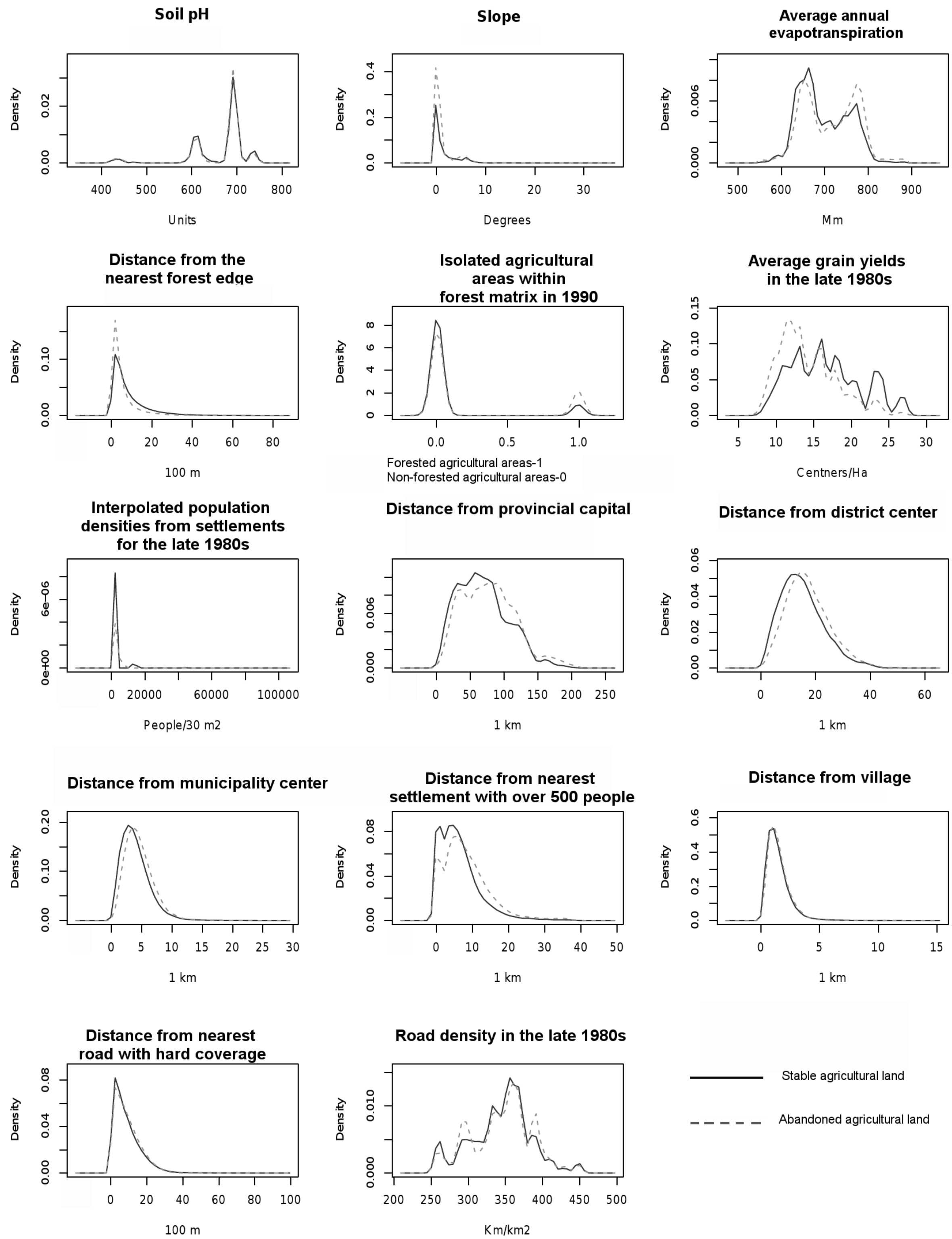


Figure 3: Distribution of explanatory variables for abandoned pixels and stable managed agricultural land for all five provinces combined.

3.2 Logistic regression

The explanatory power of the models for the studied area was relatively low (adjusted R^2 = 0.151) (Table 4). However it is the common case to have low adjusted R^2 for spatially-explicit pixel-based logistic regression models and this measure has to be interpreted with caution (Gellrich, et al., 2007, Müller, et al., 2008). The model goodness-of-fit (area under the curve, AUC) for our logistic regression model was 0.708 (Table 4). This means that with a probability of 71% model can distinguish correctly between two classes (stable managed agricultural land and abandoned agricultural land) which is substantially better than probability of the separability of these two classes by chance (AUC=0.5) (DeLeo 1993, Gellrich, et al., 2007).

Table 4: Regression results for the global model (all five provinces combined)

Variable	Odds ratio	Standard Error	P
Soil pH	0.960	0.084947	0.6288
Slope	0.992	0.008328	0.3656
Average annual evapotranspiration	0.788	0.123117	0.0531
Distance from the nearest forest edge	**0.961**	**0.005604**	**0.0001*****
Isolated agricultural areas within forest matrix in 1990	**1.484**	**0.125129**	**0.0016****
Average grain yields in the late 1980s	**0.890**	**0.018938**	**0.0001*****
Interpolated population from the settlements in late 1980s	**0.965**	**0.014576**	**0.017***
Distance from provincial capital	0.998	0.001864	0.2935
Distance from nearest district center	1.006	0.005517	0.2723
Distance from nearest municipality center	**1.063**	**0.015025**	**0.0001*****
Distance from nearest settlement over 500 people	**1.032**	**0.008324**	**0.0002*****
Distance from nearest villages	**1.086**	**0.037934**	**0.0293***
Road density	1.001	0.001399	0.29
Distance from the nearest road with hard coverage	1.004	0.006313	0.5702
AIC= 145,704	*AUC= 70.3*	*Adj.* R^2*= 0.144*	
Model log likelihood ratio= 14095.75	*Residual deviance= 145,674*	*Null Deviance= 159,770*	

Significance is indicated with ***, **, * and for p<0.001, p<0.01 and p<0.05, respectively. Coefficients in boldface indicate significance at p<0.05 or higher.

Seven variables were statistically significant at the 5% level ($p<0.05$) with the expected sign (Table 4). Results show that probability of abandonment decreases by 4% for every 100m away from the forest edge and increases by 48% for the agricultural areas within the forest matrix (Table 4). A decrease of crop yields by one centner (0.1 ton) per hectare raises the likelihood of agricultural land abandonment by 11%. The likelihood to observe abandoned agricultural land increases by 3.5% if population drops by 100 people. The highest bearing of on abandonment among the proximity variables was for the distance to the nearest village. For every kilometer away from villages the probability of agricultural land abandonment increases by 8%.

The province-level results demonstrate the high impact of the distance from the nearest forest edge for Kaluga province, where the likelihood of agricultural land abandonment would decrease by 11% for every 100 meters away from the forest edge (Table 5). In Vladimir province the likelihood to observe the abandonment in isolated agricultural patches within the forest matrix was the highest among all five provinces and with a 2.4 times higher likelihood for isolated agricultural areas within the forest matrix to be abandoned. The likelihood to observe abandoned agricultural land on low productive agricultural lands (districts with low crop yields) is highest in Rjazan province, where abandonment was 15% more likely for every 0.1 tons per hectare of grain yield deccrease. The influence of distances from roads, market and populated places yielded mixed results across the five provinces. However, there is a tendency that abandonment increases with the distance measures. Population density was only significant in Smolensk province and higher density increases the chance to observe abandoned agricultural land. Slope negatively affects abandonment in Kaluga and Smolensk provinces, but is insignificant in the other three provinces while a higher soil pH fosters abandonment in Tula and Vladimir and discourages abandonment in Rjazan. Finally, higher evaporation has positive effects in Kaluga, but negative effects in Rjazan (Table 5).

Table 5: Odds ratios, AUC and adjusted R^2 estimates reported for each province individually

Variables	Smolensk	Kaluga	Tula	Rjazan	Vladimir
Soil pH	0.980	1.167	**1.448**	**0.759**	1.26
Slope	**0.957**	**0.966**	0.990	0.999	0.985
Average annual evapotranspiration	1.850	**2.059**	0.741	**0.411**	0.777
Distance from the nearest forest edge	**0.905**	**0.887**	**0.952**	**0.962**	**0.892**
Isolated agricultural areas within forest matrix in 1990	1.202	**2.339**	0.982	0.891	**2.48**
Average grain yields in the late 1980s	0.933	**0.898**	**0.875**	**0.851**	**0.943**
Interpolated population from the settlements in late 1980s	**0.949**	0.931	0.996	0.952	0.973
Distance from provincial capital	1.001	0.997	**0.985**	**1.006**	1.003
Distance from nearest district center	1.007	0.996	1.025	0.998	**1.019**
Distance from nearest municipality center	**1.105**	1.043	1.028	**1.093**	1.019
Distance from nearest settlement over 500 people	**1.017**	1.014	**1.068**	**1.059**	1.041
Distance from nearest villages	**1.256**	**1.390**	1.074	0.971	0.964

Road density	**1.008**	1.000	1.002	1.001	0.997
Distance from the nearest road with hard coverage	**1.015**	**1.017**	**1.020**	0.989	1.009
AUC	*0.68*	*0.752*	*0.653*	*0.745*	*0.748*
Adjusted R^2	*0.131*	*0.213*	*0.085*	*0.203*	*0.199*

Odds ratios in boldface indicate significance at p<0.05 or higher.

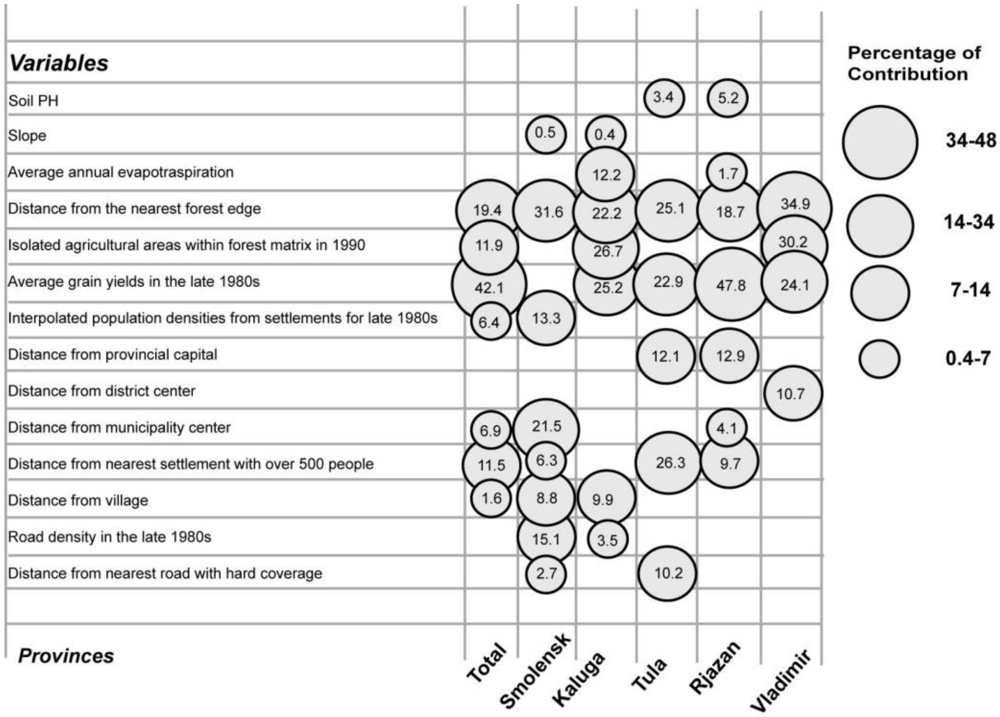
3.3 Hierarchical partitioning

Of seven statistically significant variables in the global model, average grain yields in the late 1980s contributed most to explaining agricultural land abandonment (42.1%, of the total variability) (Figure 4). This was followed by the distance from the nearest forest edge (19.5%), distance from the nearest settlement over 500 people (11.5%), and isolated agricultural areas within the forest matrix (11.9%). Less important in explaining total variance was the distance from the nearest municipality center (6.9%), the interpolated population from the settlements (6.4%), and distance from the nearest village (1.6%).

The analysis of the determinants of agricultural land abandonment at the provincial level showed that agricultural land abandonment was largely determined by a mix of environmental and socio-economic factors. However, such factor as soil pH was statistically significant variable ($p<0.05$) in provinces where better soils occurred (e.g., increase of the percentage of chernozem soils in Tula, Rjazan and Vladimir provinces). In the same time, socio-economic factors, such as different distances and interpolated population from the settlements in the late 1980s determined agricultural land abandonment in Smolensk province, where rural population density was the lowest among selected provinces (Table 1).

The importance of the explanatory variables for the province-level models demonstrated considerable differences (Figure 4). While average grain yields in the late 1980s significantly contributed more than one fifth of total variation in Kaluga, Tula, Rjazan, and Vladimir provinces, it is insignificant in Smolensk. The only variable that makes a significant and consistent contribution (above 19% in all provinces) is the distance from the nearest forest edge while distance from the nearest settlement over 500 inhabitants is contributing in all provinces except of Kaluga province. In Smolensk, the province with the highest rates of agricultural abandonment (see also figure 2), lower population density and variables related to physical accessibility shaped abandonment patterns to a much larger degree than in other provinces. Many environmental variables (e.g. soil pH, slope, average annual evapotranspiration) had modest contributions for explaining agricultural land abandonment.

Figure 4. Results of hierarchical partitioning analysis for statistically significant variables.



4. Discussion

Agricultural land abandonment is an important land use change in developed countries, and arguably the dominant land change across Europe (MacDonald, et al. 2000, Gellrich, et al., 2007, Prishchepov et al., *in review a*). However the extent of agricultural abandonment is more pronounced and happened more recent in post-socialist Eastern Europe and the former Soviet Union than in its Western European counterparts. The transition from state-command to a market-driven economy also resulted in widespread agricultural land abandonment in European Russia.

Our results suggest that agricultural land abandonment was found in the districts that already had low agricultural productivity levels during the Soviet period, in proximity to forest edges, for the agricultural areas within the forest matrix and distant from the populated places. One of the main lessons from the regression results is the increasing penetration of market principles for shaping agricultural land use. The high likelihood of abandonment closer to forested areas and of isolated agricultural areas suggests the rising importance of profit maximization for land use, because both closeness to forests and isolated cultivated areas likely increase production costs. Commonly, isolated agricultural areas are further constrained in their suitability for agricultural production by the low quality of rural roads in the Russian countryside, which complicates access to agricultural input and output markets. Therefore, these areas typically also support lower population densities. Abandonment in forested areas and nearby forest edges provides a promising opportunity to defragment the forests, because forest regrowth may increase species habitat.

The modeling results also showed that areas that had higher agricultural productivities in the Soviet period continue to be in cultivation until today, which again underscores the structural change in Russian agriculture towards more market-oriented production (Ioffe & Nefedova, 2004, Lyuri, et al., 2010). In other words, agricultural land use patterns moved away from the subsidized Soviet-style agricultural patterns where the State fostered agricultural land expansion into marginal areas, towards landscapes that are predominantly shaped by economic forces without much State intervention. The statistical results therefore corroborate that the 90% of the subsidies withdrawal for agricultural production between 1990 and 2000 was likely the dominant underlying cause of agricultural land abandonment in remote regions with lower production potentials. Abandonment of low productive agricultural lands coincided with the drastic decline of crops yield for the same study area of European Russia, when the removal of producer (e.g., fertilizer supply) and consumer subsidies during the transition widen the gap of crop productivity (yields) larger in reform era than 30 years before between Russia and globe yield leaders (Trueblood & Arnade, 2001). Change of the institutions, inadequate investment likely created additional pressure on the remaining productive agricultural land, causing the depletion of the soil and thus consequent abandonment.

The importance of the accessibility of agricultural fields emerges as an important predictor in most models. Plots are more likely to be abandoned, if they are located further from populated places and market centers. Thus, land use patterns are increasingly shaped by von Thünen-type patterns, where transportation costs to and from plots become increasingly important. Villages, municipalities and settlements over 500 people represent important infrastructural networks that support was crucial agricultural production, possibly of the access to input and output markets.

Considerable variation exists in the patterns and determinants of agricultural land abandonment and we find marked differences at the provincial level. For example, in Smolensk province - where 46% of 1989 managed agricultural land were abandoned by 2000 and rural population density and crop yields during Soviet times were the lowest among five provinces, the initial population density and accessibility variables had a larger bearing on land use than elsewhere. Availability of abundant agricultural land with lower population density likely fostered massive agricultural land abandonment in socio-economically unfavorable areas of Smolensk province, while in other provinces distant areas with low productivity were the first to be abandoned. In general we observed that socioeconomic determinants tend to be more important towards the west of the study area in Smolensk and Kaluga provinces while a mix of environmental and socioeconomic factors determined abandonment in the eastern and northern provinces of Tula, Rjazan and Vladimir. The differences in the rates and determinants of agricultural land abandonment at the provincial level also likely reflected the effects in the regional policies among the selected provinces on self-supply of agricultural production as a response to the uncertain institutional settings within the country during the transition (Trueblood & Arnade, 2001).

Our modeling approach was limited to an exploration of the determinants of agricultural land abandonment and we did not investigate the causal factors that lead to changes in land use decision making. Yet, we believe that such modeling approaches yield valuable insights into the spatial patterns and determinants of land change and pave the way for a detailed, fine-scale analysis of causal changes at the level of land use decision makers. Moreover, our analysis generated statistically representative insights for a large territory (>150,000 km^2). However, the large size of the study area unsurprisingly masked considerable variations within smaller subregions by generating mean coefficients across the entire study area. We partly accounted for this with the disaggregated provincial-level models that allow inferences for smaller administrative regions.

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