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Determinants of agricultural land abandonment in post-Soviet European Russia

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ABSTRACT

The breakdown of socialism caused massive socio-economic and institutional changes that led to substantial agricultural land abandonment. The goal of our study was to identify the determinants of agricultural land abandonment in post-Soviet Russia during the first decade of transition from a state-controlled economy to a market-driven economy (1990–2000). We analyzed the determinants of agricultural land abandonment for approximately 150,550 km^2 of land area in the provinces (oblasts) of Kaluga, Rjazan, Smolensk, Tula and Vladimir in European Russia. Based on the economic assumptions of profit maximization, we integrated maps of abandoned agricultural land from five ~185 km × 185 km Landsat TM/ETM+ footprints with socio-economic, environmental and geographic variables, and we estimated logistic regressions at the pixel level to identify the determinants of agricultural land abandonment. Our results showed that a higher likelihood of agricultural land abandonment was significantly associated with lower average grain yields in the late 1980s and with higher distances from the nearest settlements, municipality centers, and settlements with more than 500 citizens. Hierarchical partitioning showed that the average grain yields in the late 1980s had the greatest power to explain agricultural land abandonment in our models, followed by the locational attributes of the agricultural land. We hypothesize that the termination of 90% of state subsidies for agriculture from 1990 to 2000 was an important underlying cause for the decrease of cultivation in economically and environmentally marginal agriculture areas. Thus, whereas the spatial patterns corresponded to the land rent theory of von Thünen, it was primarily the macro-scale driving forces that fostered agricultural abandonment. Our study highlighted the value of spatially explicit statistical models for studying the determinants of land-use and land-cover change in large areas.

Introduction

Widespread agricultural expansion is a major driver of habitat loss and changes in ecosystem functions (Vitousek et al., 1997; Tilman, 1999). Concurrently, many developed and emerging economies are experiencing a decline of agricultural areas (Baldock et al., 1996; Benjamin et al., 2007; Bergen et al., 2008; Grau et al., 2003; Meyfroidt and Lambin, 2008; Prishchepov et al., 2012). Rapid socio-economic and institutional changes may accelerate land-use and land-cover change (LULCC) or shift land use to a new mode. A major recent and rapid socio-economic change was the collapse of socialism and communism and the accompanying transition from state-controlled to market-driven economies in Eastern Europe and the former Soviet Union in the early 1990s. However, the impacts of this transition on LULCC are not well understood. The dismantling of state-controlled economies, the withdrawal of governmental support, and the implementation of open markets has drastically changed economies, human welfare, and health in post-Soviet countries (Kontorovich, 2001; Shkolnikov et al., 2001). For instance, from 1990 to 2000 in Russia, the average life expectancy declined from 69 to 65 years, and the male life expectancy in rural areas of central European Russia declined even more rapidly – from 61 to 53 years (Rosstat, 2002). During the same period, Russia's GDP declined by 67% (World Bank, 2008). Profound changes were particularly common in rural regions of Russia, where state support of agriculture ended and rural development ceased almost entirely (Rosstat, 2002). Between 1990 and 2000, investments in the Russian agricultural sector declined from $39 billion to $2 billion (Goskomstat, 2000). The removal of fertilizer subsidies caused crop yields to decline (Frühauf and Keller, 2010; Trueblood and Arnade, 2001) and depleted soil fertility (Sedik et al., 1999; Trueblood and Arnade, 2001).

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These drastic socio-economic changes affected agricultural land use and led to widespread agricultural land abandonment in Eastern Europe. However, the rates and patterns of LULCC varied considerably, both within Russia and among the post-socialist and post-communist countries of Eastern Europe (Baumann et al., 2011; Bergen et al., 2008; Hostert et al., 2011; Kuemmerle et al., 2008; Milanova et al., 1999; Peterson and Aunap, 1998; Prishchepov et al., 2012; Prishchepov et al., in review; Vanwambeke et al., 2012). Agricultural land abandonment rates were especially high in the post-Soviet countries, including Russia, where institutions that regulated land use changed during the transition and time was required to establish new institutions (Baumann et al., 2011; Hostert et al., 2011; Prishchepov et al., 2012; Vanwambeke et al., 2012). However, existing evidence from the literature is patchy, and our knowledge about the drivers and determinants of LULCC in Eastern Europe and Russia is limited. In particular, we have little information about the factors producing agricultural abandonment.

Agricultural land abandonment substantially affects both environmental and socio-economic processes. For instance, reforestation on abandoned agricultural lands can defragment forests, sequester carbon (Vuichard et al., 2009), and improve hydrological regimes (Sileika et al., 2006). However, early successional vegetation that grows on abandoned fields provides fuel for wildfires (Dubinin et al., 2010) and increases the propagule pressure of weeds, pests and pathogens on the remaining agricultural fields (Smelansky, 2003). Abandonment may also cause spillover effects that lead to the economic marginalization of historic agricultural landscapes (Elbakidze and Angelstam, 2007). In the globalized world, widespread agricultural land abandonment in one area may shift agricultural production and land use elsewhere, potentially threatening vulnerable ecological systems (Lambin and Meyfroidt, 2011). For example, drastic declines in domestic meat production in post-Soviet Russia after 1990 resulted in a steep increase in meat imports from Brazil (Novozhenina et al., 2009), which contributed to deforestation in Amazonia (Kaimowitz et al., 2004). Conversely, a reduction of agricultural land abandonment and recultivation of abandoned areas may result in increased agricultural production and reduce the pressure on world food markets (FAO, 2010). In sum, changes in agricultural land use have multiple repercussions on ecosystem services, biodiversity, and the economy. Therefore, better monitoring and understanding of the determinants and drivers of agricultural land abandonment is important and can provide valuable guidance for land-use policies.

Ample knowledge exists about the determinants of agricultural land abandonment in European Union (EU) countries, where agricultural land abandonment has been widespread during the 20th century, especially after the Second World War (Baldock et al., 1996). There, abandoned agricultural land is generally found in unfavorable environmental conditions (e.g., higher elevations, steeper slopes, poorer soils, and poorly ameliorated agricultural fields) as well as in remote and isolated agricultural areas (Baldock et al., 1996; MacDonald et al., 2000). Agricultural land abandonment is also strongly associated with landowner characteristics. Part-time farmers and older landowners have a greater likelihood of abandoning agricultural land than any other type of landowner (Grinfelde and Mathijs, 2004; Kristensen et al., 2004; Van Doorn and Bakker, 2007). Farm structures also shape abandonment patterns: smaller farms throughout Europe have a greater likelihood of abandoning farmland than larger enterprises (Baldock et al., 1996; Kristensen et al., 2004). Market access and availability of better-paid jobs in neighboring urbanized areas also influences agricultural abandonment. For example, this process occurs in southern France (Van Eetvelde and Antrop, 2004) and in Switzerland (Gellrich et al., 2007), where agricultural land abandonment is more common closer to administrative centers and in areas with rapid population growth.

Similarly, the few studies that examined agricultural abandonment in post-socialist Eastern Europe identified factors such as unfavorable environmental conditions (e.g., higher elevations and steeper slopes) and adverse market access as determinants of abandonment (Milanova et al., 1999; Müller and Sikor, 2006; Müller et al., 2009). Agricultural land abandonment also typically occurs far from administrative centers and roads in post-socialist Albania (Müller and Munroe, 2008) and Romania (Müller et al., 2009). In addition, the socio-economic adaptation of farm households to the changing conditions of an external framework increasingly influences the spatial patterns of abandonment. For example, high part-time agricultural employment and rural population emigration are the key determinants of agricultural land abandonment in post-socialist Albania (Müller and Sikor, 2006) and Romania (Müller et al., 2009). Differences in farm structures also determine agricultural land abandonment in post-Soviet Latvia (Grinfelde and Mathijs, 2004) and Ukraine (Baumann et al., 2011).

To date, however, only a few quantitative studies have examined the determinants of post-socialist agricultural abandonment in Eastern Europe in general and for the Former Soviet Union countries including Russia in particular. Therefore, it is not clear if the same set of factors that determined agricultural land abandonment in the European Union were also important in the former Soviet Bloc countries, including Russia. In contrast to other Eastern European countries, agricultural production in the Soviet Union was dominated by large-scale farming (Ioffe et al., 2006; Lerman et al., 2004). In response to socio-economic changes, the agricultural land abandonment process in the EU was slower than abandonment in post-socialist Eastern Europe (Baldock et al., 1996; Baumann et al., 2011; Gellrich et al., 2007; Lyuri et al., 2010). Moreover, prior studies that analyzed the determinants of agricultural land abandonment in Western and Eastern Europe with spatially explicit methods focused on regions that are marginal for agriculture (e.g., mountainous regions). Thus, for large parts of post-Soviet Eastern Europe, including Russia, the patterns and determinants of agricultural land abandonment remain unclear. This situation is unfortunate because agricultural land abandonment also affected productive areas, for instance in Belarus, Russia and the Baltic States (Alcantara et al., 2012; Hostert et al., 2011; Ioffe et al., 2006; Prishchepov et al., 2012; Prishchepov et al., in review).

The major goal of our research was to explore the spatial determinants of post-Soviet agricultural land abandonment in European Russia during the first decade of transition (1990–2000). We analyzed maps of agricultural land abandonment that had been derived from multi-seasonal 30-m resolution Landsat TM/ETM+ satellite images for five provinces (oblasts) in post-Soviet European Russia and available images spanning dates from 1985 to 1991 (circa 1990) and from 1999 to 2002 (circa 2000) (Prishchepov et al., 2012). We employed spatially explicit logistic regression analysis at the pixel level to obtain statistically representative results for our study area ($\sim$150,550 km^2). We developed a global logistic regression model for the entire study area and estimated logistic regression models for each province separately. Finally, we measured the relative contribution of the covariates of agricultural abandonment.

Methods

Study area

We focus on temperate European Russia, where agricultural land abandonment is widespread (Fig. 1). In our previous study, a large uniform agro-ecological zone was defined based on climate and agro-ecological data (Prishchepov et al., 2012).

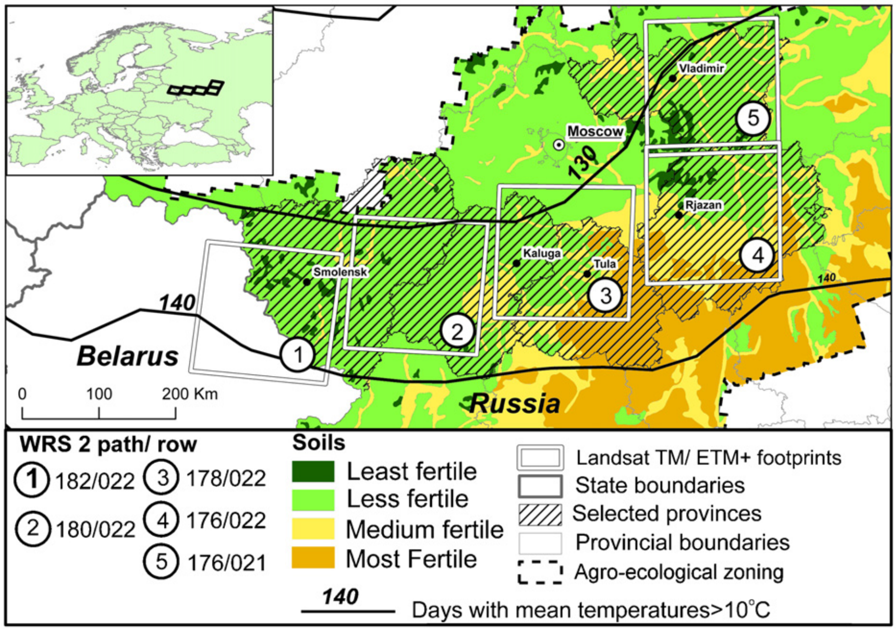

Fig. 1. Study area and the five selected Landsat footprints. Soils fertility is based on reclassification of soils taken from Batjes (2001). Climatic constraints are taken from IIASA (2000) and based on the agro-ecological stratification (Prishchepov et al., 2012). Countries boundaries are bold gray and province boundaries are hatched. (For interpretation of the references to color in this figure, the reader is referred to the web version of the article.)

Five ∼ 185 km × 185 km Landsat TM/ETM+ footprints were selected in temperate European Russia, and satellite images for these footprints were classified (see Prishchepov et al., 2012, for details). The area covered by that study comprised ∼150,550 km^2 (approximately the size of the American State of Georgia, or half the size of Poland) and included portions of five Russian provinces (oblasts), namely, Smolensk, Kaluga, Tula, Rjazan, and Vladimir (Fig. 1), covering 67 districts (rajons).

The climate in the study area is temperate-continental, with average maximum temperatures in the warmest month (July) ranging from 30 °C to 34 °C. The average minimum temperatures in the coldest month (January) range from −37 °C to −28 °C (Afonin et al., 2008). The number of days with mean temperatures greater than 10 °C ranges between 125 and 142 days, and the average annual evapotranspiration is 428–713 mm (Afonin et al., 2008). The study area is part of the Russian Plain, and the topography ranges only from 0 to 300 m. The region itself is part of the temperate mixed forest and the Sarmatic mixed forests zones (Olson et al., 2001). The northernmost part of the study area represents the southern taiga-mixed forest boundary, and the southern portion of the study area borders the forest-steppe zone (Tula and Rjazan provinces of Russia) (Alexandrova and Yurkovskaja, 1989; Kashtanov, 1983). One-third of the study area is forested, with higher proportions of forest in its northern portion. The dominant tree species include Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), Silver birch (*Betula pendula*), and Pedunculate oak (*Quercus robur*) (Folch, 2000). The soils consist primarily of podzols and luvisols, and gleysols and fluvisols are found along rivers (Batjes, 2001). In the southeastern corner of the study area, phaeozem and chernozem soils are also found (Fig. 1). The overall study area is a part of the central macroeconomic area of Russia (Lavrishchev, 1969), which coincides with the Russian non-chernozem agricultural zone (Jasny, 1949).

The study area is well suited for agriculture, especially after the amelioration, liming, and fertilizing of the podzolic soils. During the last decades of the Soviet era, the region became one of the primary agricultural areas, especially after the failed attempts of the Soviet government to expand wheat growing in Kazakhstan (Ioffe and Nefedova, 2004). In the two decades prior to the collapse of the Soviet Union, the government substantially invested in rural infrastructure (e.g., road construction), agricultural production (e.g., amelioration campaigns and mechanization), and capital construction (e.g., housing) in study area (Ioffe and Nefedova, 2004; Ioffe et al., 2004). The primary summer crops are barley, rye, oats, sugar beets, fodder maize, potatoes, peas, summer rapeseed, and flax; the primary winter crops are winter wheat, winter barley, and winter rapeseed (Afonin et al., 2008; Gataulina, 1992). Grain yields per hectare were similar among the Russian oblasts in the study area (Table 1) but lower than in neighboring countries (e.g., Ioffe et al., 2006; Prishchepov et al., 2012). Cattle breeding, dairy farming, and poultry production were also common. State and collective farms controlled more than 98% of the agricultural land and produced more than 90% of the agricultural output during the Soviet era (Goskomstat RSFSR, 1990). The study area experienced rural depopulation beginning in the 1960s (Ioffe et al., 2004). Prior to the collapse of the Soviet Union, rural population density was as low as 5 people/km^2 in certain districts in Smolensk province (Rosstat, 2002).

Russia transitioned from a state-controlled to a market-driven economy after the collapse of the Soviet Union in 1991 (Lerman et al., 2004). As a result, both governmental regulation of agriculture and subsidies were largely withdrawn. The land and assets of collective and state farms were redistributed among former farm workers as paper shares. However, a moratorium on agricultural land transactions was imposed to prevent potential land speculation, and this moratorium continued until 2002 (Lerman and Shagaida, 2007). National statistics highlight the accompanying substantial decline of agricultural production in the study area during the 1990s, with a decrease in sown area of up to 44% and of livestock numbers by up to 68% in Smolensk province (Rosstat, 2002).

Maps of abandoned agricultural land

Detailed maps showing agricultural land abandonment in the study area were derived from 30-m resolution Landsat images (Prishchepov et al., 2012) for circa 1990 and 2000. The selection of satellite imagery was based primarily on multi-seasonal image dates availability. Therefore, the images for the pre-transition

Table 1
Socio-economic and environmental conditions of the selected provinces (oblasts) in pre-transition Russia, 1989.

Provinces	Rural population density (people/km^2)[a]	Density of paved roads (km/100 km^2)[a]	Milk yields (kg/cow)[a]	Grain yields (tons/hectare)[a]	Tractors (Tractors/1000 ha arable land)[a]	Average annual precipitation[b] (mm)	Average number of days with a mean temperature greater than 10 °C[b]	Soil pH[c]	% agricultural land before 1990[d]
Smolensk	7.4	11.0	2478.0	1.13	82.0	649.0	132.0	6.6	31
Kaluga	11.0	14.0	2527.0	1.38	54.0	680.0	134.7	6.6	35
Tula	13.5	18.0	2645.0	1.92	[e]	638.0	135.3	6.7	55
Rjazan	11.8	12.0	2881.0	1.68	70.0	566.0	138.2	6.4	49
Vladimir	11.8	15.0	2880.0	1.62	74.0	605.0	131.6	6.7	23

[a] Statistical data from Goskomstat (2000) and Rosstat (2002)
[b] Climatic data from IIASA (2000).
[c] Soil data from Batjes (2001).
[d] Percentage of agricultural land calculated from classified multi-date Landsat TM/ETM+ images.
[e] Not available.

period range from 1985 to 1991 (hereinafter, 1990) and for the post-transition from 1999 to 2002 (hereinafter, 2000). Multi-seasonal satellite images were classified for five Landsat footprints that covered 77% of Kaluga province, 72% of Vladimir province, 72% of Rjazan province, 55% of Smolensk province, and 51% of Tula province (Fig. 1)."Stable agricultural land" was defined as agricultural land used for crops planting, hay, and livestock grazing for time I (circa 1990) and time II (circa 2000). "Abandoned agricultural land" was defined as agricultural land used for crops planting, hay, and livestock grazing for time I but no longer used for time II and, thus, often covered during the latter period by non-managed grasslands with early successional shrubs and trees (Baumann et al., 2011; Hostert et al., 2011; Kuemmerle et al., 2008; Prishchepov et al., 2012). Shrub encroachment in the study area usually occurs within three to five years after abandonment, with faster shrub advancement on well-drained and formerly plowed fields (Karlsson et al., 1998; Lyuri et al., 2010; Utkin et al., 2005; Prishchepov et al., in review). Fields invaded by shrubs tend to remain abandoned, leading to subsequent forest succession due to the high costs of converting such fields back to agriculture (Larsson and Nilsson, 2005). And we hypothesize that the limited economic incentive for the recultivation of abandoned agricultural lands in our study area represents an additional factor contributing to the long-term abandonment of these lands. The classification of multi-seasonal composites of Landsat images was performed with a support vector machine algorithm (SVM) (Prishchepov et al., 2012). The classified maps were assessed for accuracy with validation data independent of the training sets. The validation data were collected as a component of the 2007 and 2008 field work (Prishchepov et al., 2012). The classified maps were of good accuracy. The accuracy for the classified footprints ranged from 83 to 92% of the overall accuracy. The conditional kappa values varied from 79 to 93% for "stable agricultural land" and from 76 to 91% for "abandoned agricultural land".

The classifications for the study area indicated that 31% (1.7 million ha) of the agricultural land used in 1990 was abandoned by 2000. In all, 46% of the total 1990 agricultural land was abandoned in Smolensk province, 30% in Kaluga, 26% in Tula, 28% in Rjazan, and 27% in Vladimir province. The abandonment rates were even higher at the district level, reaching 62% for certain districts in Smolensk province (Fig. 2).

Explanatory variables

From 1990 to 2000, the most detailed agricultural statistics for Russia were available at the district (rajon) level, roughly equivalent to counties in the United States or the Nomenclature of Territorial Units for Statistics (NUTS) level 3 in the EU. The average size of rural districts is 1520 km^2, and our remote sensing classifications covered 67 districts (14 of 25 in Smolensk, 15 of 24 in Kaluga, 10

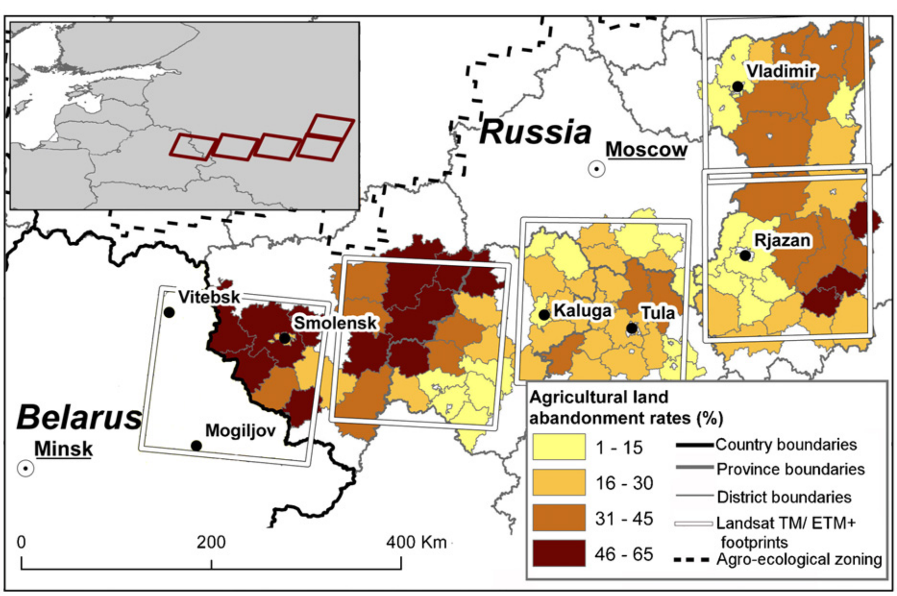

Fig. 2. Rates of agricultural land abandonment from 1990 to 2000. Countries boundaries are bold black, province boundaries are bold gray, district boundaries are fine gray, and agro-ecological zoning is depicted with the black dotted line. (For interpretation of the references to color in this figure, the reader is referred to the web version of the article.)

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 (m), slope (°)	Shuttle Radar Terrain Mission (SRTM)	Resampled raster 90 m dataset
Average annual evapotranspiration (mm), number of days with a mean temperature greater than 10 °C (°)	AgroAtlas, 2010	Resampled raster 10 km dataset
Distance from nearest forest edge (100 m)	30 m Landsat TM/ETM+ classifications	Pixel level calculations
Isolated agricultural areas within forest matrix in 1990 (dummy)	30 m Landsat TM/ETM+ classifications	Pixel level calculations
Agricultural productivity		
Average grain yields in the late 1980s (centners/ha), milk yields in 1990 (kg/cow)	Rosstat (2002)	Rasterized district level statistics
Population		
Interpolated population counts from settlements in the late 1980s (the proxy for population density) (number of people)	1:100,000 declassified Soviet topographic maps	Pixel level calculations
Distance variables		
Distance from provincial capital (km)	1:100,000 declassified Soviet topographic maps	Pixel level calculations
Distance from nearest district center (km)	1:100,000 declassified Soviet topographic maps	Pixel level calculations
Distance from nearest municipality center (km)	1:100,000 declassified Soviet topographic maps	Pixel level calculations
Distance from nearest settlement with more than 500 people (km)	1:100,000 declassified Soviet topographic maps	Pixel level calculations
Distance from nearest settlement (km)	1:100,000 declassified Soviet topographic maps	Pixel level calculations
Distance from nearest hard-surfaced road (100 m)	1:500,000 declassified Soviet topographic maps	Pixel level calculations
Infrastructure		
Road density in the late 1980s (km/100 km^2)	1:500,000 digital dataset	Rasterized district level statistics
Density of settlements in the late 1980s (settlements/100 km^2)	1:100,000 digital dataset	Rasterized district level statistics

of 22 in Tula, 17 of 25 in Rjazan, and 11 of 16 in Vladimir province, Fig. 2).

Economic theory generally assumes that agricultural producers choose the land use that maximizes the net stream of income (Gellrich et al., 2007; Maddala and Lahiri, 2006). We assumed that agricultural land abandonment was driven primarily by economic decisions (Irwin and Geoghegan, 2001). Specifically, agricultural producers discontinue farming if the returns from agricultural production are outweighed by production costs. Based on this assumption, we selected explanatory variables that may affect the decision of agricultural producers to abandon agricultural land, such as agricultural productivity levels, proximity to market centers, and demography that may affect the supply of labor and infrastructure (Table 2). We also assumed that the natural suitability of a plot of land crucially affects the profits that can be derived from agricultural production. To control for natural suitability, we included biophysical determinants representing climatic conditions, quality of soils, terrain, and variables representing the long-term environmental marginality of agricultural land.

To measure the effects of agricultural productivity, we obtained district-level agricultural statistics on average grain yields in the late 1980s and milk yields in 1990 prior to the collapse of the USSR (Ioffe et al., 2004). Population densities were calculated from the settlements found on 1:100,000 Soviet topographic maps dating from the middle to the end of the 1980s (VTU GSh, 1989a). We digitized provincial, district, and municipality centers and settlements, and we used the information shown on these maps to obtain the population for each settlement. To obtain a proxy for population density, we interpolated population counts from the settlements in the late 1980s using second-order inverse distance weights (Müller and Munroe, 2005; Müller and Zeller, 2002). By the late 1980s, 38% of the 11,972 digitized settlements for our study area represented settlements whose population was less than 20 inhabitants.

To estimate market access, we calculated the Euclidean distances from the provincial, district, and municipal centers. We also calculated the distance from the nearest settlement with more than 500 people because we assumed that only these larger settlements are provided with goods and socio-economic services by the government.

As a measure of infrastructure, we calculated settlement densities at the district level, the density of settlements with more than 500 people, and the density of municipal centers because we anticipated that the availability of public services might curb outmigration and thus agricultural land abandonment. To calculate the road densities and distances from the nearest road, we used a road network dataset for hard-surfaced roads in Russia derived from 1:500,000 declassified Soviet topographic maps from the late 1980s (VTU GSh, 1989b).

The climatic variables that we used were the average annual evapotranspiration (Penman-Monteith) and the number of days with a mean temperature greater than 10 °C at 10 km resolution (Afonin et al., 2008). As the soil variable, we used the soil pH based on a 1:2,500,000 scale soil map (Batjes, 2001). Elevation and slope were derived from the 90-m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (USGS, 2006). We also assumed that a higher forest percentage in a given district indicated a lower suitability for agricultural production. The forest percentage was derived from 30-m resolution forest-cover maps for pre-abandonment (circa 1990) from the same classifications that yielded the data on agricultural land abandonment (Prishchepov et al., 2012). During our field visits, we observed that many agricultural areas near forest edges were abandoned. We assumed that environmentally marginal and distant agricultural fields are most likely closer to forest edges (Gellrich et al., 2007), and we included the Euclidean distances from the nearest forest edge in the regressions. We also observed that many abandoned agricultural areas were individual patches within a forest matrix. Thus, we

Table 3
Descriptive statistics for 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	6.62	6.9	0.066	4.22	7.38
Number of days with a mean temperature greater than 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/100	7.0	6.9	0.58	5.54	8.82
Distance from 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 1980s	District	Centners/ha	15.9	16	4.568	8.00	27.00
Milk yields in 1990	District	kg/cow	2648	2658	3.566	1743.00	3442.00
Interpolated population counts from settlements in the late 1980s (the proxy for the population density)	Pixel	Number of people	267.81	115.77	8.041	0.16	85337.80
Distance from provincial capital	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 with more than 500 people	Pixel	km	6.784	5.7	5.9	0.00	39.47
Distance from nearest settlement	Pixel	km	1.45	1.26	0.944	0.03	12.18
Density of settlements in the late 1980s	District	Number of settlements/100 km^2	10.6	10.0	3.30	4.00	18.00
Road density in the late 1980s	District	km/100 km^2	34.4	35.1	4.8	25.7	44.9
Distance from nearest hard-surfaced road	Pixel	100 m	8.79	7	7.327	0.30	79.59

digitized isolated agricultural areas within the forest matrix (i.e., agricultural areas surrounded by forests) for the late 1980s and created a binary variable to represent these areas.

Time-varying socio-economic variables can be endogenous to LULCC (Chomitz and Gray, 1996; Müller and Zeller, 2002). For example, changes in rural population density may cause agricultural land abandonment, whereas agricultural land abandonment may also be a precursor for an exodus of the population from marginal agricultural areas. Thus, the actual relationship between endogenous variables over the same period is unclear. Hence, we used only time-invariant socio-economic variables that represent the socio-economic conditions prior to the collapse of the Soviet Union in the regressions (e.g., average grain yields, population densities, road densities in the late 1980s).

All variables were calculated or resampled at 30-m resolution to match the agricultural land-use maps derived from the Landsat TM/ETM+ satellite images. The descriptive statistics for the selected variables are summarized in Table 3.

Logistic regression and hierarchical partitioning

To estimate the determinants of agricultural land abandonment, we constructed logistic regression models. These models assumed that the cumulative distribution function for the residual error of the explanatory variables follows a logistic distribution. For the logistic regressions, we defined “1” as representing “abandoned agricultural land” and “0” as “stable agricultural land”. Areas not covered by agricultural land uses were excluded from the analysis and coded as missing.

We measured spatial autocorrelation in our land-use change maps with isotropic variograms using the GS+^{TM} statistical package for twelve 30-m resolution 10 km × 10 km blocks (www.gammadesign.com). We maintained a gap of at least 500 m between samples, which reduced Moran’s I by 0.15–0.25 for the classified Landsat footprints (Prishchepov et al., 2012).

We used *R* for the statistical analyses (R Development Core Team, 2011) and checked all covariates for collinearity. If Pearson’s correlation coefficient *R* was greater than 0.5 for any pair of variables, we retained only the variable that was more strongly related to abandonment in our regression models.

Multiple samples within the same administrative unit (i.e., the same district) are not truly independent (Gellrich et al., 2007; Müller and Munroe, 2008). To control for this lack of independence, we introduced a group structure and performed a statistical adjustment of the clustered data structure in our logistic model, which also accounts for spatial autocorrelation (Gellrich et al., 2007; Müller and Munroe, 2008). We assumed that cluster adjustment was necessary for observations belonging to the same district (rajon) because districts are the administrative units where the primary land-use decisions and governance actions occur that systematically affect the decision-making by the local producers regarding agricultural land use. For this reason, we applied the Huber–White sandwich estimator that controls for such clustering by estimating robust standard errors without affecting the estimated coefficients in the model (Huber, 1967; Müller et al., 2009; White, 1982). This approach has the added advantage of controlling for potential spatial autocorrelation in the model’s residuals by incorporating correlations between observations within clusters (Gellrich et al., 2007). We assessed the goodness-of-fit of the regressions using the log-likelihood for the logistic model, the deviance for the residuals of the null and fitted models, and the area under the receiver operating characteristics curve (AUC) (Pontius and Schneider, 2001; R Development Core Team, 2011). Finally, we used hierarchical partitioning to assess the contribution of each independent variable to the full model by calculating the percentage of the total variance explained by each individual, statistically significant variable ($p < 0.05$) (Baumann et al., 2011; Chevan and Sutherland, 1991; Mac Nally, 1996; Millington et al., 2007). We followed this procedure for the entire sample and for each province separately to explore provincial-level differences in the determinants of agricultural land abandonment.

Results

Selection of the variables for the logistic regression

We found that “average grain yields in the late 1980s” was positively correlated with “milk yields in 1990” ($R = 0.54$). For this reason, we retained only “average grain yields in late 1980s” for

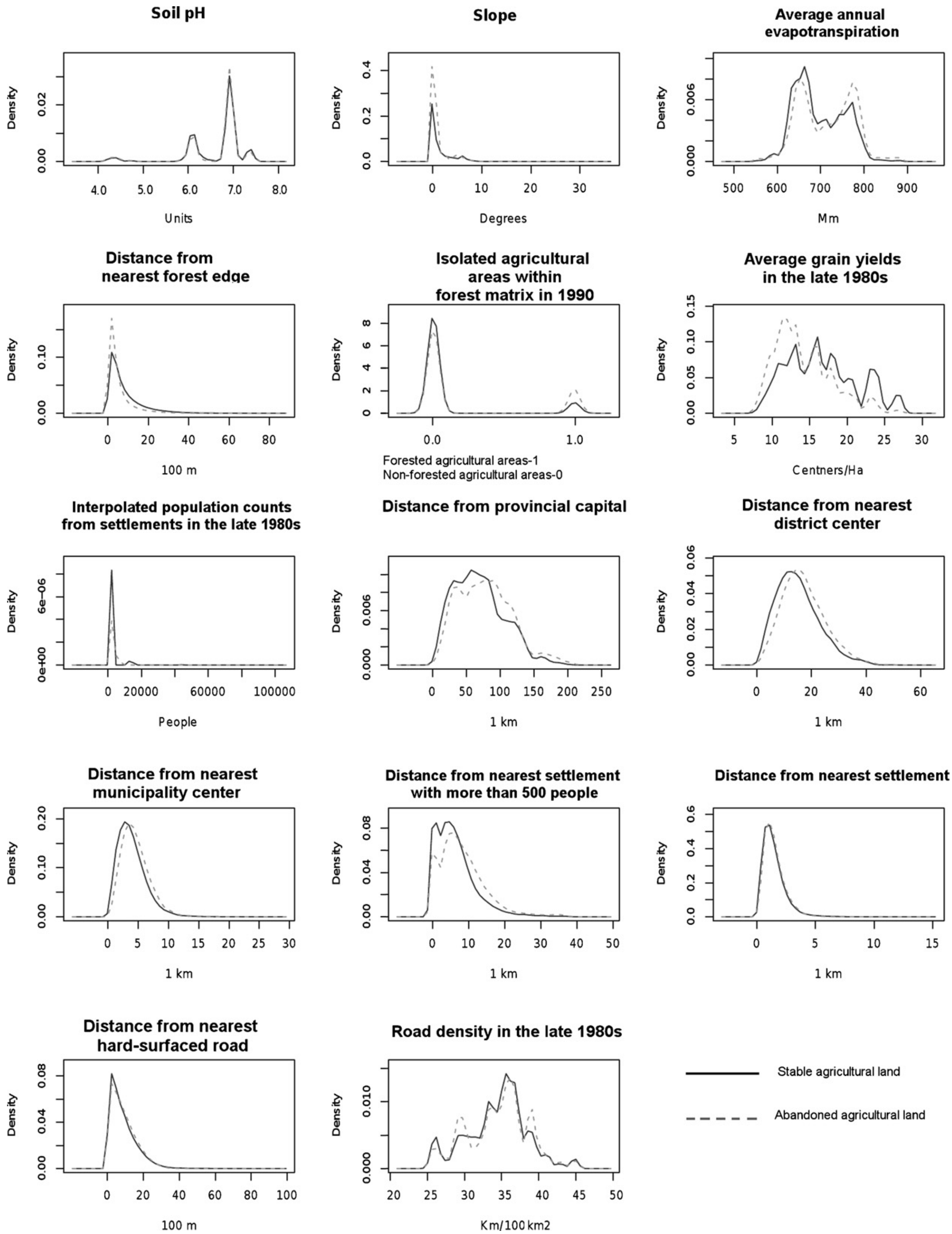

Fig. 3. Frequency distributions of explanatory variables for abandoned pixels and stable agricultural land for all five provinces.

the multivariate logistic regression modeling. "Forest percentage" and "distance from nearest forest edge" were also positively correlated ($R = 0.51$) and were negatively correlated with "density of municipal centers" ($R = -0.57$). For the model, we retained only "distance from nearest forest edge" because it had a higher correlation with abandoned and non-abandoned agricultural land ($R = 0.16$) than "forest percentage" ($R = 0.1$) or "density of municipal centers" ($R = -0.1$).

"Average annual evapotranspiration" was positively correlated with "density of settlements in the late 1980s" ($R = 0.59$), as was "elevation" ($R = 0.67$). We retained only "average annual evapotranspiration" because it had the highest univariate

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

Variable	Odds ratio	Standard error	*p*
Soil pH	0.960	0.085	0.6288
Slope	0.992	0.008	0.3656
Average annual evapotranspiration	0.788	0.123	0.0531
Distance from nearest forest edge	**0.961**	**0.006**	**0.0001***
Isolated agricultural areas within forest matrix in 1990	**1.484**	**0.125**	**0.0016**
Average grain yields in the late 1980s	**0.890**	**0.019**	**0.0001***
Interpolated population counts from settlements in the late 1980s (proxy for population density)	**0.965**	**0.015**	**0.017***
Distance from provincial capital	0.998	0.002	0.2935
Distance from nearest district center	1.006	0.006	0.2723
Distance from nearest municipality center	**1.063**	**0.015**	**0.0001***
Distance from nearest settlement with more than 500 people	**1.032**	**0.008**	**0.0002***
Distance from nearest settlement	**1.086**	**0.038**	**0.0293***
Road density in the late 1980s	1.001	0.001	0.29
Distance from nearest hard-surfaced road	1.004	0.006	0.5702

Model log likelihood ratio = 14095.75; AUC = 70.3; Adj. R^2 = 0.144; residual deviance = 145,674; null deviance = 159,770.
Coefficients in bold indicate significance at $p < 0.05$.
* Significance at $p < 0.05$.
** Significance at $p < 0.01$.
*** Significance at $p < 0.001$.

correlation with agricultural land abandonment. We also excluded "number of days with a mean temperature greater than 10 °C" because this variable was negatively correlated with "average annual evapotranspiration" ($R = -0.52$). The final dataset consisted of 14 independent variables, of which two were district-level variables ("average grain yields in the late 1980s" and "road density in the late 1980s") and the remainder were pixel-level variables (Fig. 3).

Logistic regression

The explanatory power of the models for the study area was relatively low (adjusted R^2 = 0.144) (Table 4). However, it is common to have a low adjusted R^2 for spatially explicit pixel-based logistic regression models, and this measure is to be interpreted with caution (Gellrich et al., 2007; Müller and Munroe, 2008). The model goodness-of-fit (area under the curve, AUC) for our logistic regression model was 0.703 (Table 4). This value means that the model can distinguish correctly between two classes (stable managed agricultural land and abandoned agricultural land) with a probability of 70%. This result is substantially better than the probability of separating these two classes solely by chance (AUC = 0.5) (DeLeo, 1993; Gellrich et al., 2007).

Seven variables were statistically significant at $p < 0.05$, and all of them had a relationship with abandoned agriculture with the expected sign (±) (Table 4). The probability of abandonment decreased by 4% for every 100 m of separation from the forest edge (odds ratio = 0.961, Table 4) and increased by 48% for the agricultural areas within the forest matrix (odds ratio = 1.484, Table 4). A decrease of crop yields by 0.1 tons/ha between the districts in the late 1980s raised the probability of agricultural land abandonment between 1990 and 2000 by 11% (odds ratio = 0.890, Table 4). Agricultural land abandonment was also statistically significantly associated with a decrease of values of "interpolated population counts from settlements in the late 1980s". Among the proximity variables, the most important was "distance from nearest settlement". For every kilometer away from settlements, the probability of agricultural land abandonment from 1990 to 2000 increased by 8% (odds ratio = 1.086, Table 4).

Overall, the province-level results were relatively similar to the model for the entire study area, but interesting differences were also evident. In Kaluga province, the probability of agricultural land abandonment decreased by 11% for every 100 m of separation from the forest edge (Table 5). In Vladimir province, the probability that isolated agricultural areas in the late 1980s would be abandoned was 2.4 times higher within the forest matrix than outside of the matrix. This rate was the highest found for the five provinces. The probability of abandoned agricultural land appearing on less productive agricultural lands (districts with low crop yields in the late 1980s) was the highest in Rjazan province, where abandonment was 15% more probable for a decrease of 0.1 tons/ha of grain yield in the late 1980s. The influence of distances from roads, markets, and populated areas yielded mixed results among the five provinces. However, there was a general tendency for abandonment to increase at larger distances. "Interpolated population counts from settlements in the late 1980s" was only significant in Smolensk province, and a smaller population increased the likelihood of abandoned agricultural land. An increased slope decreased the likelihood of agricultural land abandonment in the Kaluga and Smolensk provinces but was insignificant in the other three provinces, whereas a higher soil pH fostered abandonment in Tula and Vladimir provinces and discouraged abandonment in Rjazan province. Finally, higher evapotransporation had positive effects in Kaluga province but negative effects in Rjazan province (Table 5).

Hierarchical partitioning

Of the seven statistically significant variables in the global model, "average grain yields in the late 1980s" had the highest explanatory power for agricultural land abandonment (42.1% of the total variability) (Fig. 4). "Average grain yields in the late 1980s" was followed by "distance from nearest forest edge" (19.4%), "distance from nearest settlement with more than 500 people" (11.5%), and "isolated agricultural areas within the forest matrix" (11.9%). Variables that were less important for explaining the total variance were the "distance from the nearest municipality center" (6.9%), "interpolated population counts from settlements in the late 1980s" (6.4%), and "distance from nearest settlement" (1.6%).

The importance of the explanatory variables differed considerably among the provinces (Fig. 4). For instance, the "soil pH" variable was only statistically significant ($p < 0.05$) in provinces where better soils occurred (e.g., in the Tula, Rjazan and Vladimir provinces). Although "average grain yields in the late 1980s" was a significant predictor in the Kaluga, Tula, Rjazan, and Vladimir provinces, where it explained between 21% and 48% of the variation,

Table 5
Odds ratios, AUC, and adjusted R^2 for each province.

	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 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 counts from settlements in the late 1980s (the proxy for the population density)	**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 with more than 500 people	**1.017**	1.014	**1.068**	**1.059**	**1.041**
Distance from nearest settlement	**1.256**	**1.390**	1.074	0.971	0.964
Road density in the late 1980s	**1.082**	**1.010**	1.020	1.010	0.997
Distance from nearest hard-surfaced road	**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.

it was insignificant in Smolensk province. The only variable that made a large contribution (above 19%) in all provinces was “distance from nearest forest edge”, and “distance from nearest settlement with more than 500 people” was an important contributor in all provinces except Kaluga province. In Smolensk, the province with the highest rates of agricultural abandonment (see also Fig. 2), lower rural population densities in the late 1980s and variables related to physical accessibility shaped abandonment patterns to a much greater degree than in other provinces. Among all provinces, many environmental variables (e.g., “soil pH”, “slope”, “average annual evapotranspiration”) had low explanatory power.

Discussion

Agricultural land abandonment in post-Soviet Russia was widespread across the studied Russian provinces (Prishchepov et al., 2012). Our results suggest that within Russia, the highest likelihood of agricultural land abandonment was in districts that already had low agricultural productivity during the Soviet period, in areas close to forest edges, in isolated agricultural areas embedded in a forest matrix, and in areas far from populated places. One of the main lessons from the regression results is that market principles shaped agricultural land use. In the absence of governmental support, less profitable agricultural areas were rapidly abandoned.

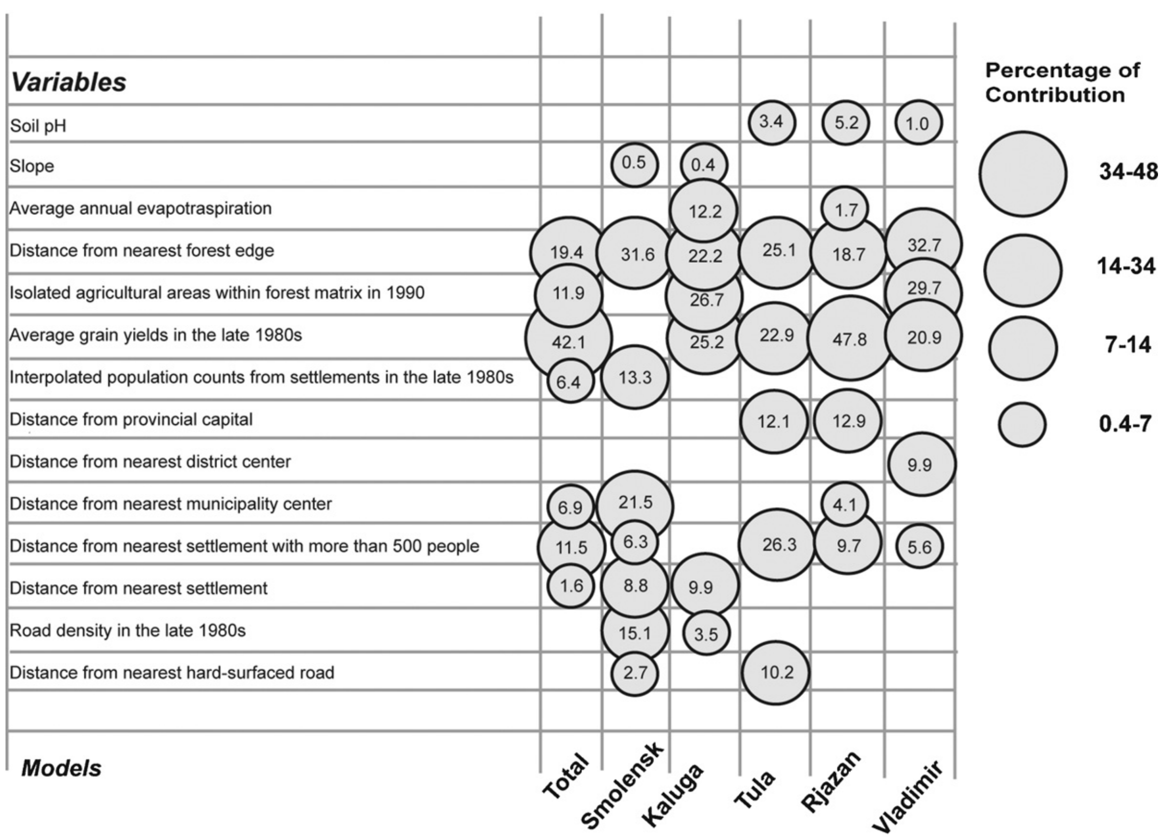

Fig. 4. Results of hierarchical partitioning analysis for statistically significant variables.

The high likelihood of abandonment closer to forested areas and of isolated agricultural areas also suggests the increasing importance of profit maximization for land use because closeness to forests and isolated cultivated areas most likely increase production costs (Gellrich et al., 2007). Isolated agricultural areas are constrained in their suitability for agricultural production due to the low quality of roads in the Russian countryside, which complicates access to agricultural input and output markets.

The modeling results also showed that areas that had higher agricultural productivity during the Soviet period continued to be cultivated. This finding again underscores the structural change in Russian agriculture toward more market-oriented production (Ioffe and Nefedova, 2004; Lyuri et al., 2010). Agricultural land-use patterns moved away from the subsidized Soviet-style agricultural pattern, where the government fostered agricultural cultivation in marginal areas, and toward landscapes shaped predominantly by economic forces with much less governmental intervention. The drastic socio-economic changes that occurred, such as the abrupt termination of 90% of the subsidies for agricultural production after 1990, were most likely a dominant cause of agricultural land abandonment in remote regions with lower agricultural potential. The abandonment of low-productivity agricultural lands coincided with the drastic decline of crop yields for the same study area of European Russia, when the removal of producer (e.g., fertilizer supply) and consumer subsidies (e.g., retail price subsidies for staple food products such as bread and milk) during the transition widened the yield gap between Russia and other global yield leaders (Trueblood and Arnade, 2001). The change of institutions that regulated land use, delay in their establishment, and inadequate investment most likely created additional pressure on the remaining productive agricultural land, causing the depletion of the soil and thus abandonment (Prishchepov et al., 2012).

The accessibility of agricultural fields was an important predictor in most models. Fields had a higher likelihood of being abandoned if they were located farther from populated places and market centers. Thus, land-use patterns appear to be shaped increasingly by von Thünen-type patterns involving the increasing importance of transportation costs (Ioffe et al., 2004). Settlements (villages), municipalities, and particularly settlements with more than 500 people represent important infrastructural networks, the support of which was crucial to agricultural production. It is possible that the support of these networks was also crucial for access to input and output markets and to provide vital social functions for rural population involved in agriculture. Biophysical factors (e.g., “soil pH”, “slope”, “average annual evapotranspiration”) explained relatively little about the agricultural land abandonment patterns in our models. However, this result may be due, in part, to the selection of a uniform agro-ecological region and the low level of variation of the region’s topography.

We found considerable variation in the patterns and the determinants of agricultural land abandonment among the provinces. In Smolensk province, for example, 46% of the managed agricultural land from 1990 was abandoned by 2000, and the rural population density and crop yields during Soviet times were the lowest among the five provinces. The combination of abundant agricultural land with low population density most likely fostered massive agricultural land abandonment in socio-economically unfavorable areas throughout Smolensk province. In contrast, distant areas with low productivity were the first to be abandoned in other provinces. In general, we observed that socio-economic determinants tended to be more important toward the west of the study area (i.e., in Smolensk and Kaluga provinces), whereas a combination of environmental and socio-economic factors determined the abandonment rates in the eastern and northern provinces (i.e., Tula, Rjazan and Vladimir). The differences in the rates and determinants of agricultural land abandonment at the provincial level also most likely reflected the effects of regional policies among the selected provinces in terms of self-supply with agricultural products as a response to the uncertain institutional settings during the transition (Trueblood and Arnade, 2001).

Our modeling approach was limited to an exploration of the determinants of agricultural land abandonment, and the available data sources did not allow us to identify the causal factors that produced changes in decision-making regarding land use. Nevertheless, our modeling approach yields valuable insights into the spatial patterns and determinants of land-use change and paves the way for a detailed, fine-scale analysis of causal changes at the level of land-use decision-making. Moreover, our analysis generated statistically representative insights for a large territory ($\sim$150,500 km^2). However, the large size of the study area also masked variation within our study area and provided only mean values of the coefficients. In part, we recognized this problem by defining disaggregated provincial-level models that provided inferences for smaller administrative regions. Nevertheless, the driving forces underlying agricultural land abandonment warrant increasing attention in the future. These potential underlying drivers of agricultural LULCC in Russia may include incomplete land reform, limited economic incentives in agriculture, Soviet legacies (whether agricultural enterprises were subsidized and were de facto bankrupt prior to the transition), labor skills, and the individual characteristics of the agricultural producers.

Agricultural land abandonment has strong environmental and socio-economic implications, providing both opportunities and constraints. We expect a further concentration of cultivated agricultural areas in response to favorable agro-climatic and favorable socio-economic conditions (e.g., available workforce) and in areas proximate to market centers. To reduce future abandonment, we suggest maintaining soil fertility on the remaining managed agricultural fields and improving the accessibility of the settlements that provide vital socio-economic functions. The high likelihood of agricultural land abandonment in isolated agricultural areas within the forest matrix and nearby forest edges provides a promising opportunity to defragment the forests because forest regrowth may increase species habitat and sequester carbon. Additionally, such remote areas are not of interest to large-scale corporate farms and agroholdings, and large-scale recultivation is therefore unlikely. However, areas with low population pressure are usually of high natural value and can be promoted for extensive agriculture, e.g., to maintain agro-biodiversity, to stimulate ecotourism, or for the production of organic food products.

The concurrence of idle agricultural potential, the possibility for carbon sequestration, and the effects of biodiversity when forests regrow in abandoned areas suggest important future avenues for research in analyzing the trade-offs on abandoned agricultural land in European Russia. This opportunity for research is particularly relevant in the face of the continuing decline of agricultural lands in the studied region of European Russia after 2000, with a slow but steady encroachment of forests on former agricultural lands.

Conclusions

We identified the main factors associated with agricultural land abandonment in temperate European Russia. The results suggested that agricultural decision-making in Russia shifted toward market-based principles, with the profitability of agricultural production increasingly shaping the allocation of production factors. The growing market orientation in post-Soviet agricultural production was also reflected in the high importance of access to agricultural areas. Areas that enjoyed high land productivity during Soviet times continued to be cultivated, reflecting their higher suitability for profitable agricultural production. Agricultural land abandonment in European Russia was hence driven primarily by macro-scale socio-economic and political legacies, such as the withdrawal of agricultural subsidies that supported agricultural production on socially and environmentally marginal land prior to the transition. The drastic reduction of agricultural subsidies in Russia after the collapse of socialism, as well as the absence of liberalized markets and clear government policies, also contributed to the unprecedented abandonment of agricultural land. Given the environmental and socio-economic implications of massive agricultural land abandonment, this process has to be addressed in future government policies because agricultural land abandonment may produce spillover effects on the economy and the environment. Overexploitation of the remaining agricultural lands without proper investment in soil fertility will most likely cause further agricultural land abandonment, particularly in areas with low agricultural productivity, distant from populated places, and isolated from large productive agricultural areas.

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