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Correlates of forest-cover change in European Russia, 1989–2012[★]

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ABSTRACT

European Russia rapidly transitioned after the collapse of the Soviet Union from state socialism to a market economy. How did this political and economic transformation interact with ecological conditions to determine forest loss and gain? We explore this question with a study of European Russia in the two decades following the collapse of the Soviet Union. We identify three sets of potential determinants of forest-cover change—supply-side (environmental), demand-side (economic), and political/administrative factors. Using new satellite data for three distinct types of forest-cover change—logging, forest fires, and forest gain—we quantify the relative importance of these variables in province-level regression models during periods of a) state collapse (1990s), and b) state growth (2000s). The three sets of covariates jointly explain considerable variation in the outcomes we examine, with size of forest bureaucracy, autonomous status of the region, and prevalence of evergreen forests emerging as robust predictors of forest-cover change. Overall, economic and administrative variables are significantly associated with rates of logging and reforestation, while environmental variables have high explanatory power for patterns of forest fire loss.

1. Introduction

The collapse of the Soviet Union in 1991 and accompanying transition to a market economy in fifteen successor republics resulted in major changes in political institutions and economic policy, with potentially major consequences for forest cover and land use (Baumann et al., 2012, 2015; Levers et al., 2018). In Russia, there were substantial reforms of federal and regional forestry administrations, and the previously state-controlled timber market was exposed to global markets (Wendland et al., 2011). Illegal logging expanded as other economic opportunities disappeared for many actors, rural areas became net recipients of domestic migrants, and opportunities emerged for marketing timber outside of state channels. Concomitantly, large areas of marginal agricultural land were abandoned (Alcantara et al., 2013; Meyfroidt et al., 2016; Smaliychuk et al., 2016).

We ask here: a) what are the effects on forest-cover change of the transition from state socialism to a market economy, and b) how do political and economic changes interact with ecological characteristics to determine forest loss and gain? Prior work on these issues addresses these questions with remotely sensed data of limited spatial or temporal coverage, and typically explores only certain types of forest-cover change. For example, Wendland, Lewis and Alix-Garcia (2014) examine the impact of decentralized governance on deforestation, one of several possible types of forest change, and only for a sample of study areas across in European Russia. (For related work from outside of the post-Soviet region, see Burgess et al. (2012).) Other work on post-socialist outcomes takes a more inclusive approach to forest-cover change, but focuses on differences among countries (Alix-Garcia et al., 2016), samples a relatively small number of regions within Russia (Kuemmerle et al., 2007; Griffiths et al., 2012; Baumann et al., 2012), or analyzes data with a limited time span (Kuemmerle et al., 2009). Nonetheless, these prior studies highlight that there was considerable change in rates

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of forest logging and in forest area after the collapse of the Soviet Union, but also substantial variation among countries and regions in Eastern Europe in terms of how forests changed. A related literature in political science shows that one specific category of forest-cover change—forest fires—are a determinant of various political outcomes, including voting patterns (unpublished work of Szakonyi D), political support for a non-democratic regime (Lazarev et al., 2014), and performance of regional governors (Schultz and Libman, 2015).

We build on this previous work using new, and much more comprehensive, remote-sensing data from Potapov et al. (2015) to examine the process of forest-cover change across European Russia, summarized by region, from 1989 to 2012. Our empirical setting allows us to compare regions with varying economic and environmental profiles during periods of state collapse (the 1990s) and state growth (the 2000s). By exploiting both cross-sectional and intertemporal variation, we address three related goals: 1) to assess the relative importance of various potential correlates of a) forest gain, b) logging, and c) forest fires; 2) to reexamine, based on much better data, the role of determinants identified in previous studies; and 3) to examine change over time in correlates of forest-cover change.

Our focus on within-country variation allows us to avoid some of the inference problems that have plagued other work on the post-socialist transition (for a review, see Gehlbach and Malesky, 2014). There are numerous legacies of the pre-socialist and socialist periods (de Melo et al., 2001; Pop-Eleches, 2007) and a large set of policy and institutional changes in the 1990s (Svejnar, 2002), both with potential importance for outcomes. By examining variation across regions within European Russia, we hold constant many of these factors, allowing us to better identify the effect of a smaller set of variables.

Nonetheless, there are substantial empirical challenges to identifying causes of forest-cover change, even in a partially controlled study such as this one. Forest loss and gain are measured with error, and the magnitude of these errors changes over time due to differences in the availability of satellite imagery (Potapov et al., 2015). Similarly, some potential determinants of forest-cover change (e.g., governance) are measured imperfectly and infrequently. Furthermore, feedback in political and economic processes implies that causes of forest gain and loss may themselves be affected by forest-cover change.

Various elements of our empirical strategy are intended to minimize these concerns. Our basic research design is a comparison of cross-sectional regressions from two periods: 1989–2000 and 2001–2012, corresponding to periods of state collapse and growth, respectively, as well as periods of greater and lesser measurement error in forest-cover change. Further, we generally restrict attention to plausibly exogenous determinants of forest gain and loss, reserving for future work the role of potentially endogenous mediators.

Nonetheless, we emphasize that the overarching goal of our study is to identify correlates, not necessarily determinants, of forest-cover change. Identification of causal effects is arguably best accomplished through a focus on one or a few variables that exhibit (as-if) random variation or discontinuities (e.g., Dunning, 2012). We focus instead on a slightly larger set of potential determinants of theoretical importance, asking for each variable what its association is with forest gain or loss, while holding constant other political, economic, and ecological variables.

The remainder of this paper is organized as follows. In Section 2, we discuss our study area, data, and empirical strategy. We present our results visually and statistically in Section 3. Finally, we summarize our findings and discuss implications for future work in Section 4.

2. Methods

2.1. Study area and period

Our study area includes 49 regions in western Russia, with an approximate total area of 3.69 million km^2, spanning a vast expanse from 43 to 70 degrees northern latitude and from 28 to 55 degrees eastern longitude. In 2000, approximately half of this territory was forested, with the majority of the forests located in the regions of Arkhangel'sk, Kirov, Perm', Vologda, and Komi and Karelia Republics (Potapov et al., 2011). Boreal forests dominate the northern part of the study region, while temperate forests are common in the south. Following the collapse of the Soviet Union, Russia experienced large forest losses due to logging and fire (Potapov et al., 2011), but also widespread agricultural abandonment (Alcantara et al., 2012) which led to forest cover recovery (Prishchepov et al., 2013).

We analyze forest-cover change at the level of regions (“oblasts” and equivalent administrative units). For each of these regions, we quantify *forest loss due to logging*, *forest loss due to fire*, and *forest gain* for two time intervals: 1989–2000, and 2001–2012. For the former period, we observe total forest gain from 1985 to 2000. We assume a linear rate of forest gain over this period to impute gain from 1989 to 2000. We extract these regional variables from Potapov et al.’s (2015) consistent multi-decadal forest dynamics dataset for Eastern Europe, described in detail in that paper. To map forest-cover change, Potapov et al. (2015) analyzed the entire image archive collected by the Landsat satellite series from the 1980s to 2012. Images were automatically processed and composited into spatially and temporally consistent time-series and classified based on a set of supervised classification tree models to map forest extent and forest change. Consistent with Potapov et al. (2015), we define forest as woody vegetation above five meters tall with a canopy cover of ≤ 48 %. We map forest dynamic classes (loss and gain) using independent classification models to ensure map consistency and quality. We further separate forest loss into “loss due to logging” and “loss due to wildfires” by applying a separate classification tree model. For annual forest-cover loss, 90 % of change area has a disturbance detection date within one year of the actual reference (Potapov et al., 2015).

The overall accuracy of forest-cover change products is ≥ 97 %, which means that error rates are considerably lower than the total forest loss rate of about 11 % for the entire time period (Potapov et al., 2015). Furthermore, the accuracies of the change classes are even higher, i.e., 99.6 % ± 0.3 %, 99.6 % ± 0.4 % for forest loss in 1985–2000 and 2000–2012, respectively, and 97.2 % ± 1.5 % and 98.0 % ± 1.4 % for forest gain after forest loss and forest gain on 1985 non-forest, respectively. Last but not least, user’s and producer’s accuracies for the change classes are similar (Potapov et al., 2015), so that there is no inherent bias in area estimates that are derived from the map. This last point is important, as bias-adjusted area estimates are only feasible for the entire study area, not for each of the administrative regions that constitute the sampling units for our analysis. To bias-adjust the area estimates that we obtain from the analysis by Potapov et al. (2015) for each region would require an accuracy assessment for each region, which is not feasible in our case, nor done in other remote sensing studies, given the exorbitant quantity of validation data that would be necessary to do so. Unfortunately, there are no existing data on spatial differences in change detection accuracy. Although collecting such data is beyond the scope of our study, we do report robustness to controlling for spatial correlation in unobservables, including errors in change detection.

Our empirical strategy, discussed below, focuses on cross-sectional correlates of forest-cover change for 1989–2000 and 2001–2012. We opted against a panel design, even though the forest loss data is available annually, because many potential determinants of forest loss and gain are measured infrequently or change slowly over time. By defining two periods of equal length, we derive dependent variables with similar measurement error. For each interval, we normalize forest loss as the percentage of forest area in 1985 and 2000, respectively. Forest gain, in turn, is normalized over non-forest land to capture forest regrowth on abandoned agricultural land. All areas that reach our forest definition by 2000 and 2012, respectively, are classified as “forest gain.” For the period 1989–2000, we construct the forest gain variable

Table 1
Summary statistics.

Variable[a,b] (Measurement unit)	Sources	Mean	Std. Dev.	Min	Max
Crop suitability (% of total land area)	FAO and IIASA (2012)	76.601	28.126	0.000	100.000
Remoteness (hours)	Nelson (2008)	3.149	2.084	1.400	11.835
Percent evergreen forest (% total forest area)	Bartalev et al. (2014)	16.751	17.479	0.838	77.185
Distance to Moscow or St.P. (1000 km)	Rosstat (2002)	0.783	0.570	0.000	2.166
Autonomous status (binary)	Bradshaw and Hanson (2002)	0.265	0.446	0.000	1.000
Early Period					
Forest loss (logging), 1989–2000 (% total forest, 1985)	Computed by authors	3.417	1.821	0.328	7.286
Forest loss (fire), 1989–2000 (% total forest, 1985)	Computed by authors	0.125	0.199	0.000	0.818
Forest gain, 1989–2000 (% non-forest land, 1985)	Computed by authors	1.027	1.142	0.007	4.054
Percent urban population, 1991 (% total population)	Rosstat (1991)	68.333	9.788	43.600	92.000
Income per capita (log), 1990 (rubles)[c]	Rosstat (1991)	−1.621	0.136	−2.048	−1.207
Forest bureaucrats per hectare (log), 1988 (count)[d]	Roslesinforg (2002)	−6.391	1.277	−10.054	−4.181
Total forest area (log), 1985 (hectares)	Computed by authors	14.034	1.359	11.829	17.166
Governance score, 1991 (count)	Petrov and Titkov (2013)	27.745	5.234	17.000	41.000
Late period					
Forest loss (logging), 2001–2012 (% total forest, 2000)	Computed by authors	3.568	2.063	0.603	9.300
Forest loss (fire), 2001–2012 (% total forest, 2000)	Computed by authors	1.136	2.038	0.000	10.129
Forest gain, 2001–2012 (% non-forest land, 2000)	Computed by authors	1.950	2.247	0.002	7.625
Percent urban population, 2001 (% total population)	Rosstat (2001)	68.139	9.925	39.900	91.700
Income per capita (log), 2001 (rubles)	Rosstat (2001)	7.632	0.288	7.040	8.489
Forest bureaucrats per hectare (log), 2001 (count)	Roslesinforg (2012)	−6.441	1.070	−9.486	−4.790
Total forest area (log), 2000 (hectares)	Computed by authors	14.070	1.296	12.117	17.131
Governance score, 2001 (count)	Petrov (2004)	28.878	5.622	17.000	42.000

[a] Data for Arkhangelsk and Perm' include their administrative subordinates, Nenets and Komi-Permyak respectively.

[b] Variable definitions are in Electronic Supplementary Material, Table A1.

[c] For Adygeya and Karachaevo Cherkessia regions, we use income per capita in 1991, as the values for 1990 are missing.

[d] For Adygeya, we use forest bureaucrats in 1992, as the value for 1988 is missing.

based on gain between 1985 and 2000, assuming that forest gain has a linear trend within the observed interval.

Our definitions of the particular periods are dictated both by historical events and by data availability. With respect to the former, the earlier period generally corresponds to the collapse of the Soviet state and "transition depression" of the 1990s, whereas the latter represents a period of state building and economic growth. With respect to the latter, the availability of remote-sensing images improved markedly with the launch of the new Landsat 7 satellite in April 1999. Summary statistics show substantially greater forest-cover change and greater variance across regions in 2001–2012 than in 1989–2000, which may be partly due to the increased availability of satellite data (Table 1).

2.2. Covariates

Our analysis includes three sets of potential determinants of forest-cover change: "supply-side," "demand-side," and "governance" factors. While this terminology is most apt in referring to forest loss due to logging, we retain it for the other types of forest change for consistency. The first set—supply-side factors—includes *crop suitability* as a measure of comparative advantage of agricultural production. Deforestation may be higher on land more suitable for certain crops, because forests are more likely to be converted to agricultural use (Etter et al., 2006; Müller et al., 2012). Such land is also less likely to experience reforestation, which is primarily caused by land abandonment in post-Soviet countries (Taff et al., 2009). The relationship between agricultural land abandonment and forest fire is ambiguous: on the one hand, homogenization and increase in fuel biomass (shrubland) can increase fire frequency and intensity (Benayas et al., 2007); on the other hand, the decrease in human activity resulting from abandonment may reduce fire incidence given that one of the primary causes of forest fire in Russia is carelessness (World Wildlife Fund, 2017). We define crop suitability as the percentage of the region's area that is able to support production of the main type of crop for the wider region. For European Russia, this is operationalized as the percentage of land with a crop suitability index ≥ 41 (i.e., medium or better) for low input levels of rain-fed cereal, as specified in FAO and IIASA (2012).

To capture that rough terrain and poor roads increase timber production costs (Holopainen et al., 2006), and that inaccessible forest fires are harder to monitor (Henry and Douhovnikoff, 2008) and fight, we include *remoteness*, defined in Nelson (2008) as average (surface-based) time to reach a town with population of at least 50,000. This variable also measures a region's propensity for reforestation due to absence of human activities. Finally, we include *percent evergreen forest,* because the relative scarcity of such forests (Torniainen, 2010) and their match with Soviet-era wood-processing technology (Wendland et al., 2014) make them comparatively more valuable and thus more attractive for logging (Levers et al., 2014). Conifer-dominated forests are also more prone to fire and support more rapid fire spread than deciduous forests (Loboda et al., 2017). In some cases, evergreen forests may grow more slowly than deciduous forests (Way and Oren, 2010).

With respect to demand-side factors, we include both market accessibility and living standards. We proxy for the former with *distance to Moscow or St. Petersburg* (whichever is closer), which are important domestic markets. Better access to major product markets can improve the profitability of the forestry industry (Holopainen et al., 2006) and consequently increase the logging rate of a region. For demand from local markets, we include *percent urban population*, which may also affect the supply side of logging, given the impact of urbanization on local labor costs. Previous work has shown that distance from populated areas is positively correlated with agricultural land abandonment (Prishchepov et al., 2013), which in turn may result in reforestation. In addition, as mentioned earlier, human activities may increase ignitions of forest fires. Therefore, we expect regions closer to Moscow and St. Petersburg to have a higher rate of logging and fire, but a lower rate of reforestation; we have similar expectations for more urban regions.

The potential effect of living standards, our second demand-side factor, which we measure as *regional income per capita*, is also unclear. On the one hand, higher income may result in more demand for forest products, either directly (e.g., construction) or indirectly (e.g., packing materials) (Holopainen et al., 2006), both of which imply higher logging loss. On the other hand, as with urbanization, wealthier regions may have more economic activities other than logging and thus logging loss may be lower in these regions. Higher regional income level may

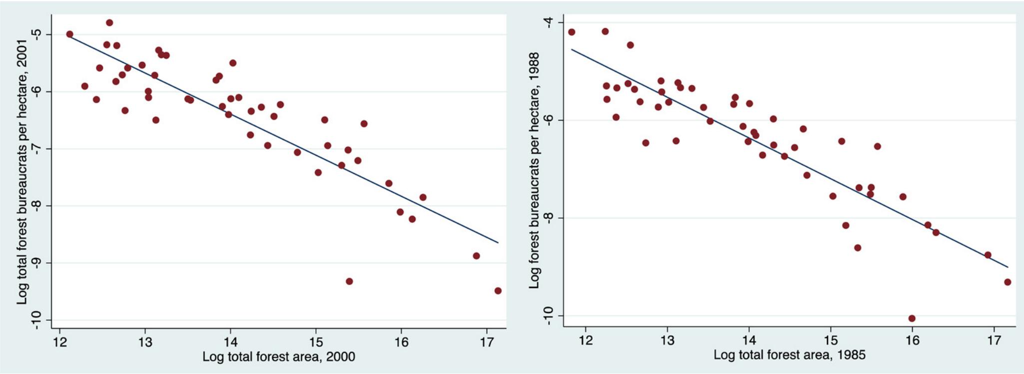

Fig. 1. Economies of scale in Russian forest administration: regions with larger forests needed fewer forest officials per hectare at the beginning of the two periods we studied—in 1988 (a) and 2001 (b).

also correspond to greater capacity to prevent and combat natural disasters, including forest fires (Petrova, 2004). Finally, we expect wealthier regions to experience less forest gain, as in these regions the demand for local agricultural products is likely to be higher, thereby reducing land abandonment and subsequent reforestation.

The third set of variables captures administrative and political features of regions. Because the state owns and manages Russia's forests, the relative number of forestry officials may influence the administrative cost of logging (Wendland et al., 2014). Further, more forestry officials may imply greater capacity to combat fire and to implement reforestation policy more effectively. We therefore include the (log of) number of *forest bureaucrats per hectare of forest land*. We define forest bureaucrats as forest-sector employees and staffers at all bureaucratic levels. As with Russian public-administration more generally (Brown et al., 2009), the intertemporal correlation of this variable is very high, suggesting that forest-cover change does not exert a causal effect on bureaucracy size, at least short-term. As normalized, this variable captures that more bureaucrats are needed for more forests.

That said, economies of scale in forest administration imply that regions with larger forests need fewer bureaucrats *per hectare* (see Fig. 1). To capture this relationship, we include (log) *total forest area* at the beginning of each period as an additional control. Substantial prior work (e.g., Alesina and Spolaore, 2003; Gehlbach, 2008) demonstrates the existence of economies of scale in public administration: fewer bureaucrats are needed to produce the same level of public goods in larger (more populous) units than in smaller (less populous) units. In our setting, this relationship exists with respect to physical area, given that forest bureaucrats are responsible for administering area rather than population. Observe that we could equivalently control for log forest bureaucrats (not normalized) and total forest area, as $\alpha\cdot\log(\text{bureaucrats/area}) + \beta\cdot\log(\text{area}) = \alpha\cdot\log(\text{bureaucrats}) + (\beta - \alpha)\cdot\log(\text{area})$.

In addition, we consider a *governance score* widely used in the political science literature, which prior work showed to be correlated with forest-cover change (Wendland, Lewis and Alix- Garcia, 2014). This variable reflects the overall rating of the level of democracy in the region and is based on expert scores of ten political spheres, including political openness, fairness in federal, regional, and local elections, degree of media independence, and corruption (Petrov, 2004). Regions with more political competition and transparency may have better governance and hence capacity to manage publicly-owned resources, such as forests. In addition, perceptions of governance quality may affect investment risk and thus the intensity of economic activity, including commercial and illegal logging.

Finally, we include an indicator variable equal to 1 if the region has *autonomous status*. Russia's federal government structure is "asymmetrical" in that the federal-regional relationship varies among regions. Especially in the 1990s, regions with autonomous status often implicitly threatened secession to extract more resources, benefits, and autonomy from the federal government (Treisman, 2001). As a consequence, these regions typically resisted market-oriented reforms in the early years of transition (Desai et al., 2003), with potential implications for commercial logging activities and reforestation.

2.3. *Empirical strategy*

As stated above, we focus on three sets of potential determinants of forest-cover change: "supply-side," "demand-side," and "political/administrative" factors. For each of the two periods described above, our estimating equation is

$$Y_i = \beta_0 + \beta_1\theta_i + \beta_2\gamma_i + \beta_3\psi_i + \varepsilon_i, \tag{1}$$

where i indexes regions. Depending on the regression, Y_i is forest loss due either to logging or to fire, as a percent of forest land at the beginning of the period, or forest gain, as a percent of non-forest land at the beginning of the period. The latter normalization captures in particular forest gain on abandoned agricultural land. As discussed above, we observe forest area in 1985, not 1989. We therefore define the "baseline" forest area for the 1989–2000 time interval as forest area in 1985, on the assumption that total forest area is unlikely to have changed substantially over the subsequent four years. For the 2001–2012 interval, we use forest area in 2000 as the baseline.

With respect to the right-hand side of Eq. 1, θ_i is a vector of our covariates measuring supply-side factors, γ_i a vector of our covariates measuring demand-side factors, and ψ_i is a vector of our covariates capturing various administrative and political characteristics of the region. The β terms are (vectors of) parameters to be estimated. Finally, ε_i is an error term that captures measurement error in the dependent variable as well as unobserved determinants of forest-cover change. The tables below report heteroskedasticity-robust standard errors, which correct for the greater measurement error, and thus larger variance of ε_i, in regions with less forest land.

3. Results and discussion

3.1. *Forest loss due to logging*

Visual comparison of forest loss due to logging for the 49 regions in our sample reveals substantial variation across time and space (Fig. 2a and b). In the early years following the collapse of the Soviet Union, logging rates were highest in the central part of European Russia—especially in the autonomous ethnic republics of Chuvashia and Tatarstan. Forest area change in these regions naturally exhibits higher variance, as the total forest area is relatively small. During the 2000s, there was a visible shift of forest-loss intensity toward western Russia. Logging increased substantially in regions close to major markets, including Moscow and St. Petersburg, reflecting the increasing

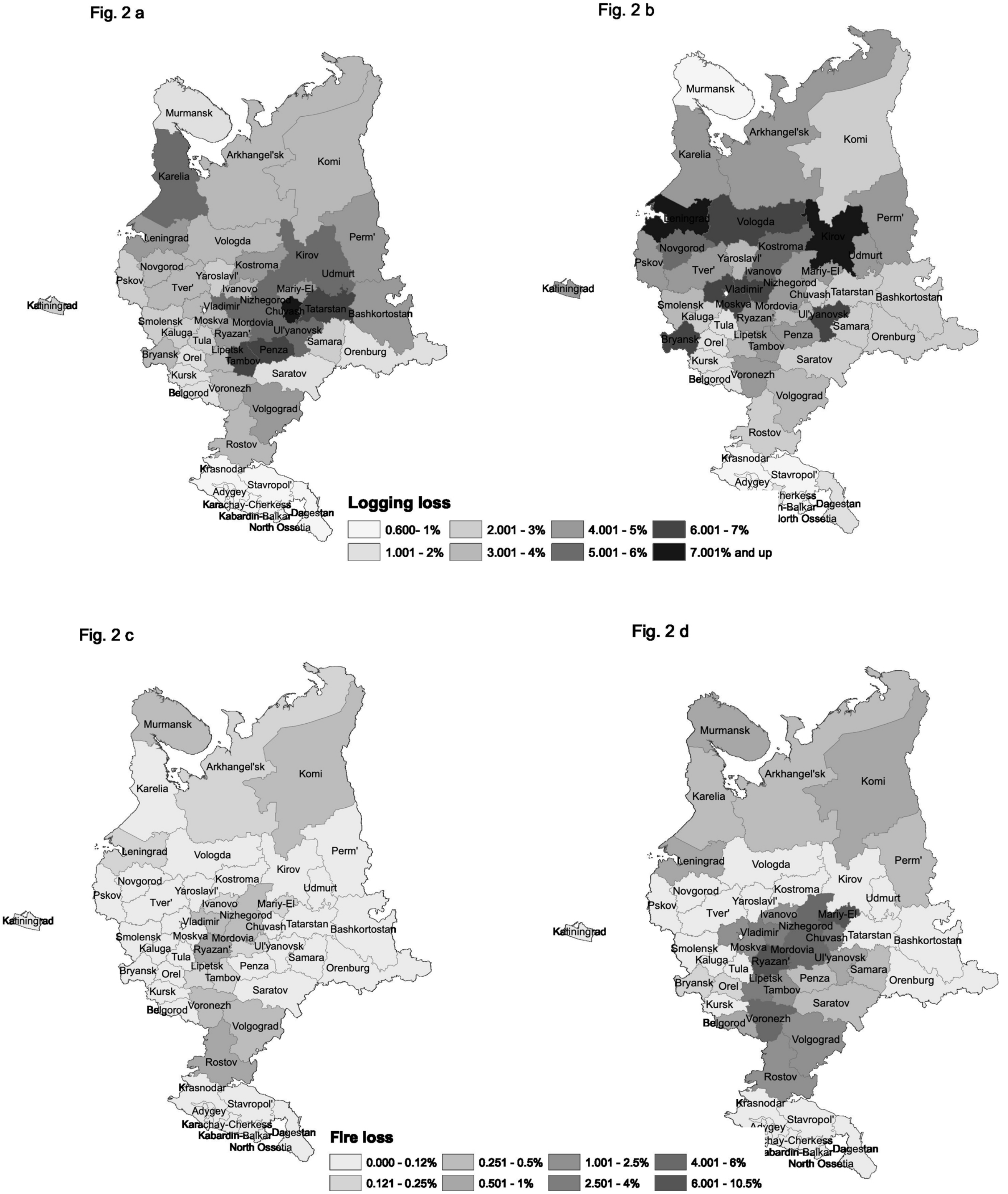

Fig. 2. Forest loss patterns in 1989–2000 vs. 2001–2012.

a) Logging loss, 1989–2000 (as % of total forest in 1985): Logging rates were highest in the central part of European Russia; b) Logging loss, 2001–2012 (as % of total forest in 2000): There was a visible shift of forest-loss intensity toward regions close to major markets. Logging in the agriculturally fertile Black Earth region remained relatively stable; c) Fire loss, 1989–2000 (as % of total forest in 1985); d) Fire loss, 2001–2012 (as % of total forest in 2000): The 2000s saw a substantial increase in forest loss due to fire, especially in regions located in central and southern European Russia.

Table 2
Correlates of forest loss, 1989–2000 vs. 2001–2012.

	(1) OLS	(2) SAR	(3) OLS	(4) SAR	(5) OLS	(6) SAR	(7) OLS	(8) SAR
Supply-side variables								
Crop suitability	0.026	0.022	−0.030**	−0.025**	0.001	0.001	0.063**	0.064**
	(0.016)	(0.015)	(0.015)	(0.011)	(0.001)	(0.002)	(0.018)	(0.020)
Remoteness	0.054	0.033	−0.187	−0.089	0.001	0.001	0.198	0.210
	(0.153)	(0.161)	(0.194)	(0.165)	(0.017)	(0.022)	(0.177)	(0.271)
Percent evergreen forest	0.048**	0.043**	0.010	0.012	0.011***	0.012***	0.112***	0.113***
	(0.021)	(0.018)	(0.023)	(0.019)	(0.002)	(0.002)	(0.029)	(0.030)
Demand-side variables								
Distance to Moscow or St. Petersburg	−1.644**	−1.702***	−1.425**	−1.245**	−0.057	−0.059	−0.821	−0.820
	(0.645)	(0.489)	(0.529)	(0.385)	(0.070)	(0.064)	(0.714)	(0.674)
Percent urban population	−0.010	−0.008	0.019	0.027	−0.001	−0.002	−0.035	−0.035
	(0.025)	(0.022)	(0.028)	(0.021)	(0.003)	(0.003)	(0.026)	(0.035)
Income per capita (log)	−1.510	−1.458	−2.799**	−3.165***	0.182	0.175	−1.445	−1.514
	(1.453)	(1.412)	(0.914)	(0.746)	(0.124)	(0.194)	(1.009)	(1.303)
Administrative/political variables								
Forest bureaucrats per hectare (log)	1.126**	1.046**	1.611***	1.870***	0.129**	0.130**	0.170	0.164
	(0.442)	(0.407)	(0.444)	(0.417)	(0.063)	(0.057)	(0.450)	(0.671)
Total forest area (log)	1.051**	1.005**	1.758***	1.966***	0.032	0.030	−0.399	−0.412
	(0.313)	(0.314)	(0.349)	(0.275)	(0.039)	(0.044)	(0.289)	(0.445)
Governance score	0.063	0.056	0.031	0.039	−0.000	0.000	−0.001	0.001
	(0.044)	(0.038)	(0.048)	(0.043)	(0.005)	(0.005)	(0.062)	(0.064)
Autonomous status	1.920**	1.803***	−0.771	−0.723*	−0.008	−0.015	0.699	0.716
	(0.577)	(0.476)	(0.640)	(0.433)	(0.049)	(0.064)	(0.645)	(0.699)
Constant	−9.872**	−9.086**	12.432**	12.310**	0.635	0.681	14.411**	14.884*
	(3.803)	(3.483)	(5.664)	(4.975)	(0.388)	(0.438)	(6.274)	(8.565)
N	49	49	49	49	49	49	49	49
R^2	0.654		0.744		0.450		0.382	
Spatial-disturbance parameter (ρ)		0.425		−2.318**		−0.647		−0.133
		(0.375)		(0.977)		(0.790)		(0.631)

Notes: The dependent variables in Columns 1 and 2 are logging loss in the 1990s, Columns 3 and 4 are logging loss in the 2000s, Columns 5 and 6 are fire loss in the 1990s, and Columns 7 and 8 are fire loss in the 2000s. Columns 1, 3, 5, and 7 show the results of the baseline OLS models, while Columns 2, 4, 6, and 8 are models with spatial autoregressive disturbances. Heteroskedasticity-robust standard errors for all specifications (including SAR models) in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

importance of market forces after the initial transition period. In contrast, logging in the agriculturally fertile Black Earth region (roughly bordered by Bryansk, Volgograd, and Penza) appears relatively stable across the two periods, most likely because time-invariant geographical features, such as soil quality and long growing seasons, imply a steady predominance of agricultural activities.

Our statistical analyses explore the variation in logging more systematically (Columns 1 and 3 in Table 2), revealing several interesting relationships. First, the effects of some of the *supply-side variables*, especially those directly related to the environment, are inconsistent over time when we condition on other covariates. Land fertility, for instance, has different effects on logging loss in the 1990s (positive) versus the 2000s (negative), though the estimated effect is statistically significant for the second period only. This result is in contrast to previous studies, situated mostly in tropical regions, that suggest a strong positive correlation between deforestation and soil quality (Veldkamp et al., 1992; Etter et al., 2006), but this may be because deforestation in the tropical regions is often due to the expansion of agriculture, whereas logging in Russia was not. Similarly, regions with more evergreen forest experienced greater logging loss in the 1990s, but this association disappears in the 2000s, perhaps because of investment in harvesting and production technology that increased the relative attractiveness of logging in deciduous forests.

Second, market mechanisms reflected in *demand-side variables* play an important role in explaining geographic variation in forest loss due to logging. Market access, measured by distance to Moscow or St. Petersburg, is significantly negatively correlated with logging loss in both periods—regions further away from these major markets experienced less logging loss. Because distance to St. Petersburg is highly correlated with distance to major timber ports in Arkhangel'sk and Leningrad regions, this variable also implicitly captures demand from international markets. Interestingly, urbanization does not have a statistically significant effect on logging in either of the two decades. The last of the demand-side variables, income per capita, is negatively correlated with logging in the 2000s, which may be due to greater availability of alternative economic activities in wealthier regions during the second decade of transition.

Among *administrative and political variables*, we find a large, positive, and statistically significant relationship between size of forest bureaucracy, when holding constant economies of scale in public administration, and logging loss in both periods—possibly the consequence of decreased queuing for permits when bureaucrats are numerous (Shleifer and Vishny, 1993; Brown et al., 2009). The effect of forest bureaucracy on logging is larger and more precisely estimated in the 2000s, a period that included passage of the Russian Forest Code of 2006, which aimed to liberalize the forest industry. Regions with larger forest administrations may have been better at adopting market-oriented measures (e.g., establishing checkpoints to determine origin of timber harvested in the region or holding open auctions for forest leases) under the new Forest Code, which may have magnified the importance of bureaucracy size in the 2000s.

The estimated relationship between logging loss and autonomous status is statistically significant and *positive* for the 1990s, not negative as we expected, given the general resistance to liberalizing reforms in autonomous regions during this period. In the 2000s, there is no significant relationship between the two variables.

Finally, the relationship between logging and regional governance, which previous work showed to be an important predictor of forest-cover change (Wendland et al., 2014), is not significantly correlated with forest loss in either period after conditioning on other political, economic, and ecological variables.

The results reported above are based on models that assume no

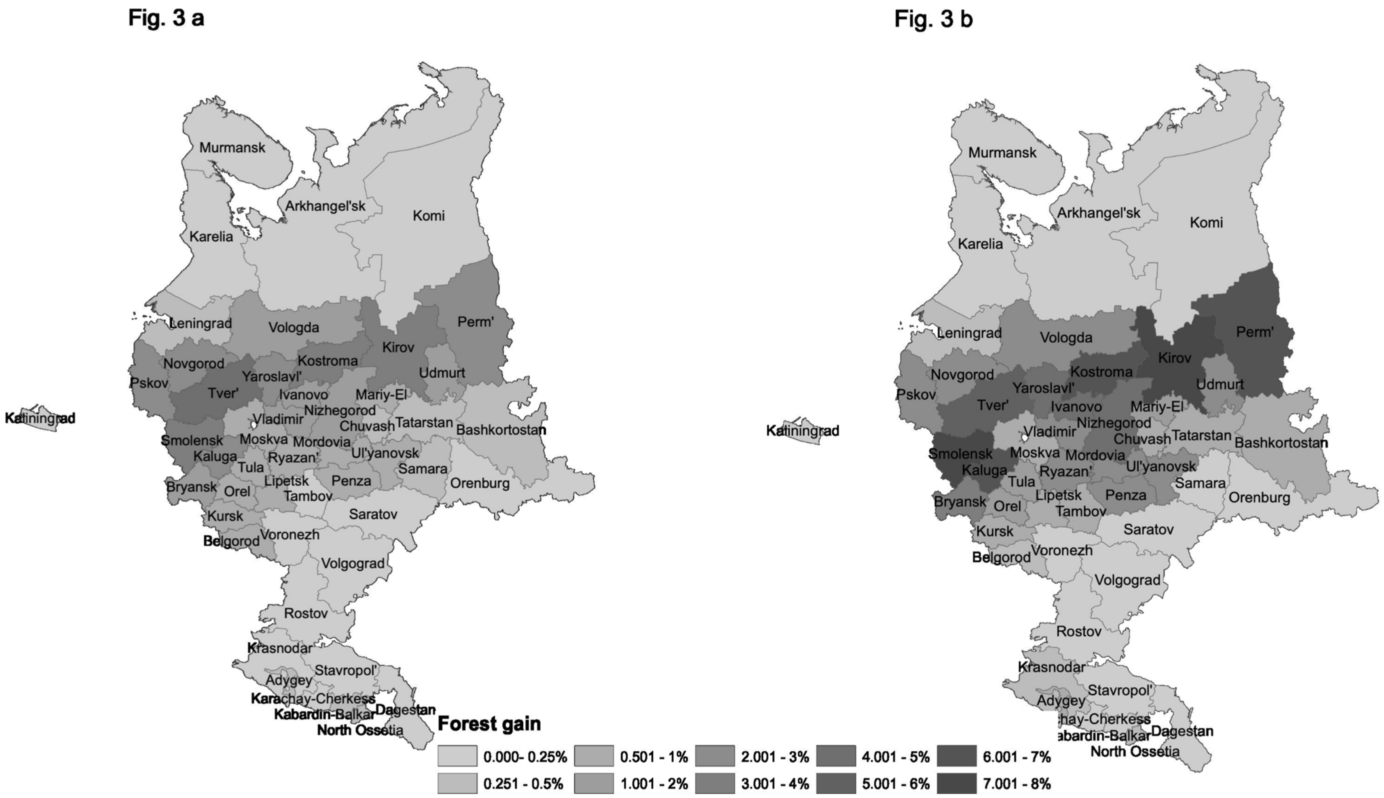
Fig. 3 a

Fig. 3 b

Fig. 3. Forest gain patterns in 1989–2000 vs. 2001–2012, a) Forest gain, 1989–2000 (as % of non-forest area, 1985): The regions with the greatest forest gain were located in the temperate belt running roughly from Vologda in the north to Penza in the south; b) Forest gain, 2001–2012 (as % of non-forest area, 2000): Regions that experienced the highest forest gain remained broadly the same in the 2000s, but forest growth accelerated in these regions.

unobserved spatial dependence among regions. Indeed, much of the spatial pattern documented in Figs. 2 and 3—regions that are closer to each other experienced similar levels of forest-cover changes in the two decades following the fall of the Soviet Union—reflects spatial correlation in *observables*. Nonetheless, spatial dependence in unobservables is also possible—for example, because vegetative reproduction and seed dispersal transcend regional borders, or because of spatial correlation in change-detection accuracy. To correct for this, we re-estimate the baseline model with spatial autoregressive disturbances using an inverse-distance spatial weighting matrix. The estimated effects of all variables, reported in Columns 2 and 4 of Table 2, are similar in magnitude and statistical significance, except for autonomous status in the 2000s. The estimated coefficient on autonomous status is imprecisely estimated in the baseline model, but it becomes significant in the models with spatial autoregressive disturbances. As shown in the Supplementary Material (Columns 1 and 2 in Table A14), we obtain almost identical results if we instead employ a contiguity matrix that assigns a value of one to immediately neighboring regions. Our findings regarding the relationship between logging loss and supply-side, demand-side, and administrative/political factors are robust to accounting for similarities among nearby or neighboring regions.

We additionally checked for robustness to changes in measurement of both dependent and independent variables as well as in modeling strategy, as shown in the Supplementary Material. We re-run the regressions in Table 2, in turn 1) dropping the politically volatile years of 1989 and 1990 from the earlier period and dropping 2011 and 2012 from the latter period for balanced comparison; 2) altering the method for calculating total forest cover in 2000; 3) considering alternative definitions of crop suitability, and forest bureaucracy; 4) allowing for non-monotonic effects of governance, as suggested by Wendland, Lewis and Alix-Garcia (2014); 5) adjusting income per capita according to a regional consumer price index; and 6) adopting hierarchical linear models to reflect Russia's nested governance structure. Across all these checks, the magnitude and significance of our estimates are largely unchanged. There are three exceptions. When we define crop suitability more broadly, the estimated coefficient on crop suitability gains significance in the 1990s (Column 1 in Table A6) and loses significance in the 2000s (Column 2 in Table A6). The estimated coefficient on crop suitability for the period between 1989 and 2000 also becomes significant in the hierarchical linear model (Column 1 in Table A16). Finally, when we use CPI-adjusted regional income in the regressions for the 2000s, the estimated effect of regional income per capita loses significance (Column 1 in Table A11).

3.2. *Forest loss due to fire*

As with logging loss, the 2000s saw a substantial increase in forest loss due to fire (Fig. 2c and d), especially in regions located in central and southern European Russia. The main reason for this difference was the widespread forest fires of 2010, to which hot weather, abnormally low precipitation, and apparent mismanagement all contributed (Schultz and Libman, 2015).

Our regression results (Columns 5 and 7 in Table 2) show that few of our covariates are correlated with forest loss due to fires in the past two decades. We suspect that this may be because fire loss is more random and also less dependent on market and political forces. Among the few factors that are correlated with fire loss, environmental variables have the most explanatory power. Percent evergreen forest is robustly correlated with fire loss in both periods, confirming our expectation that coniferous forests are more likely to experience forest fires than deciduous forests. Further, regions with more agriculturally suitable land saw more loss of forests due to fires in the 2000s. This likely reflects a multitude of factors. First of all, regions with more agriculturally suitable land on average have higher annual temperatures. Secondly, human activity may be distributed more evenly across regions with substantial agricultural activity. Finally, agricultural burning is widespread in Russia (McCarty et al., 2012), providing a source of ignitions for forest fires. In contrast, variables related to the fire-fighting capacity of the region, such as income per capita, are not significantly correlated with forest fire loss.

Among the political and economic factors that we consider, only forest bureaucrats per hectare of forest is significantly correlated with forest fire loss, and that only for the 1990s: regions with more forest bureaucrats lost more forest to fire. Taken at face value, this result supports a theory of bureaucracy that associates size of public administration with inefficiency in providing public goods (Shleifer and Vishny, 1993; Brown et al., 2009)—in this case, combating forest fires. That said, any such inefficiencies appear to become less important over time, as there is no significant relationship between bureaucracy size and fire loss for the 2000s.

These results are fully robust to estimating a model with spatial autoregressive disturbances, whether we use an inverse-distance (Columns 6 and 8 in Table 2) or contiguity (Columns 3 and 4 in Electronic Supplementary Material Table A14) weighting matrix. We additionally check if our results are affected by excluding forest loss due to fire from the period 2009–2011, which includes the major fire year of 2010: they are not. Finally, we run the same robustness checks described above and find that the results are mostly not sensitive to changes in variable definitions and modeling strategy. We note two changes from our baseline results. First, the estimated effect of income per capita for the period between 1989 and 2000 is qualitatively affected by the definition of crop suitability—regional wealth is associated with more fire loss in the 1990s when fertile area is defined broadly (Column 3 in Table A6). Second, when nominal regional income is adjusted to CPI in the regressions for the 2000s, the estimated coefficient on urban population gains significance, though it is still negative (Column 2 in Table A11).

3.3. Forest gain

Finally, we observe a consistent pattern of forest gain over time (Fig. 3a and b). In both the 1990s and 2000s, the regions with the greatest forest gain were located in the temperate belt running roughly from Vologda in the north to Penza in the south. These regions saw substantial agricultural activity on marginal lands during the Soviet period and thus experienced considerable land abandonment following the collapse of socialism (Alcantara et al., 2013). Forest growth soon followed, accelerating in the latter part of our study period, which may partly reflect the time it takes tree seedlings to reach the necessary size to be mapped as forests (Potapov et al., 2015). In contrast, regions in the north and south experienced little reforestation—in the former case, because less land was farmed to begin with and because forests were slow to grow where land was abandoned (Ioffe et al., 2012); in the latter, because these regions are located outside of forested ecoregions and because residents continued to rely on agricultural activities (Ioffe et al., 2014). Consistent with these general patterns, percent evergreen forest (greater in the north) is negatively correlated with forest gain in both periods (Columns 1 and 3 in Table 3).

Other results from the multivariate analysis shed light on the relative importance of the two types of processes causing forest gain, i.e., forest regrowth naturally occurring on abandoned land and regrowth resulting from planned reforestation efforts. Since previous studies show agricultural land abandonment is the main driver of reforestation in post-Soviet countries (Potapov et al., 2015), we expected to observe less forest gain in regions with more fertile soil. However, the conditional effect of soil fertility runs counter to expectations, with a positive and significant relationship between fertility and forest gain in both the 1990s and 2000s. One potential explanation for this result may be that trees grow faster on more fertile soils. Further, we find that regions with larger urban population experienced more forest gain in the 2000s, which also surprised us, but may be due to greater rural land abandonment, and is similar to what occurred in western Ukraine (Baumann et al., 2011). Population increase implies development of, and higher wages in, service and industrial sectors and often concomitant shrinkage of the agricultural sector. Previous scholarship finds similar relationship in Romania and Latvia (Taff et al., 2009). Finally, forest gain is significantly lower in wealthier regions in the 2000s. Regions with higher income per capita may offer viable economic and energy alternatives to logging and timber use, respectively, potentially allowing natural forest regrowth. However, demand for local agricultural products is also higher in these regions, and this means that land abandonment and reforestation may be lower unless these higher demands are met by imports from other regions or countries.

Table 3
Correlates of forest gain, 1989–2000 vs. 2001–2012.

Dependent variable:	(1) OLS	(2) SAR	(3) OLS	(4) SAR
Supply-side variables				
Crop suitability	0.017**	0.018**	0.040**	0.042***
	(0.007)	(0.008)	(0.015)	(0.013)
Remoteness	−0.025	−0.020	−0.132	−0.148
	(0.108)	(0.090)	(0.263)	(0.183)
Percent evergreen forest	−0.038**	−0.037***	−0.048**	−0.045**
	(0.011)	(0.010)	(0.023)	(0.020)
Demand-side variables				
Distance to Moscow or St. Petersburg	0.082	0.080	0.449	0.486
	(0.269)	(0.269)	(0.645)	(0.432)
Percent urban population	0.004	0.003	0.060**	0.060**
	(0.012)	(0.012)	(0.023)	(0.023)
Income per capita (log)	−0.724	−0.685	−4.160***	−4.259***
	(0.684)	(0.789)	(0.988)	(0.848)
Administrative/political variables				
Forest bureaucrats per hectare (log)	−1.052***	−1.048***	−2.058**	−2.112***
	(0.235)	(0.228)	(0.590)	(0.458)
Total forest area (log)	−0.027	−0.032	0.373	0.346
	(0.213)	(0.176)	(0.389)	(0.302)
Governance score	−0.002	−0.001	0.045	0.044
	(0.025)	(0.022)	(0.056)	(0.046)
Autonomous status	−0.702**	−0.699**	−0.837*	−0.793*
	(0.240)	(0.265)	(0.475)	(0.477)
Constant	−7.154***	−7.062***	7.870	8.452
	(1.790)	(1.907)	(8.023)	(5.632)
N	49	49	49	49
R^2	0.728		0.751	
Spatial-disturbance parameter (ρ)		0.217		−1.523
		(0.483)		(0.937)

Notes: The dependent variables in Column 1 and 2 are forest gain in the 1990s, Columns 3 and 4 are forest gain in the 2000s. Columns 1 and 3 show the results of the baseline OLS models, while Columns 2 and 4 are models with spatial autoregressive disturbances. Heteroskedasticity-robust standard errors for all specifications (including SAR models) in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Political factors emerge as equally important for forest gain, possibly reflecting the significance of the second type of process behind forest growth—replantation efforts. Size of forest bureaucracy is negatively correlated with forest gain in both periods, and so is autonomous status. Both covariates may be associated with less effectual reforestation efforts by the state. Because state reforestation policy was the exclusive domain of the federal government for the majority of the study period (until 2007), funding for reforestation came directly from the federal budget. A greater number of bureaucrats, who may be more interested in cutting than planting to begin with, might imply more claimants to a “piece of the pie,” leaving less to invest on policy implementation. Similarly, autonomous regions may have more discretion in implementing reforestation plans, which facilitates rent-seeking behavior and less effective forestry policy compared to other regions.

As with the determinants of forest loss, the correlates of forest gain are robust to modeling spatial autoregressive errors (see Columns 2 and 4 in Table 3 and Supplementary Material Table A15). We additionally check robustness to the changes in measurement and specification discussed above. In general, the statistical significance and magnitude of our estimates in the forest-gain regressions are more sensitive than are those in the other two sets of regressions. In particular, when we define crop suitability more broadly, the estimated coefficients on crop suitability in the 1990s (Column 1 in Table A7), percent evergreen forest in the 2000s (Column 2 in Table A7), and autonomous status in the 2000s (Column 2 in Table A7) become insignificant. Further, the effect of crop suitability is imprecisely estimated in both periods when that variable is more narrowly defined (Columns 1 and 2 in Table A9). Finally, when we adjust regional income in the 2000s to CPI, the estimated effects of three covariates—crop suitability, urban population, and autonomous status—lose significance (Column 3 in Table A11).

4. Conclusion

Major socio-political events can greatly alter land use patterns, and sometimes irreversibly so (Baumann et al., 2015). Understanding the dynamics and correlates of one type of land use change—forest-cover change—has important implications for vexing issues facing the world, such as climate change and carbon stocks (Nogueira et al., 2018).

Here, we examine how political and economic changes during the post-socialist transition interact with environmental factors to determine forest-cover change in European Russian regions from 1989 to 2012. Our statistical analyses suggest that three categories of covariates capturing a) supply-side (environmental), b) demand-side, and c) governance/administrative conditions in the regions are all important and jointly explain considerable variation in the three main categories of forest-cover change, i.e., forest loss to logging, forest loss due to fires, and forest gains. Examining these specific categories of forest-cover change, we find that covariates capturing the demand side of the economy and administrative characteristics of the regions are significantly associated with rates of logging and reforestation. In contrast, supply-side variables—particularly those related to the ecology of the region—have high explanatory power for patterns of forest fire loss.

The broader question we set out to answer is: what are the effects of the transition from state socialism to a market economy on forest-cover change? Comparing the relative importance of the covariates for the three categories of forest-cover change in the decade during the transition versus the decade after the transition allows us to draw at least one tentative conclusion. Our main finding is that economic forces become much more important for forest-cover change in the 2000s compared to the 1990s. Regional income per capita, for example, is only weakly correlated with logging loss and forest gain during the transition, but becomes a strong predictor after the transition, when income may have played a stronger role in structuring the incentives of economic actors. Similarly, the suitability of land for crop production emerges as a strong correlate of logging and fire loss in the decade following the transition. This finding is consistent with the increased importance of agriculture (and thus comparatively smaller importance of logging) in regional economies in the 2000s, as well as the greater risk of forest fires in regions with intensive agricultural activities. Further, the transition to a market economy appears to have allowed for the adoption of technology suitable for logging and processing the most readily available types of forests, which are deciduous. The relative area of evergreen forests, which were predominantly harvested during the socialist era, is no longer associated with higher logging loss in the 2000s. Finally, urban population emerges as a key determinant of forest gain in the 2000s, implying that the general post-socialist trend of urbanization may have benefited forests in Russia.

Beyond these economic variables, the relative size of the forest bureaucracy emerges as one of the key correlates of forest-cover change in both periods that we examine, but the bureaucracy's role is ambiguous. On the one hand, larger bureaucracies may provide the public goods necessary for economic development—in both periods we examine, the rate of logging loss is greater in regions with more forest bureaucrats per forest area. On the other hand, regions with larger forest bureaucracies experienced more forest fires in the 1990s and less forest gain in both the 1990s and 2000s. Too many employees may render bureaucracies ineffective, especially in a context of weak state institutions and political uncertainty. Clarifying the conditions under which size and organization of the bureaucracy benefit or harm public goods provision in forest and other policy contexts is an important topic for future research.

Another important political/administrative correlate of forest-cover change is the autonomous status of Russian regions. Forest loss due to logging was substantially higher, and forest gain was significantly lower, in autonomous regions during the early years of Russia's transition. Furthermore, forest gains remained low in these regions, even as their autonomy withered in the context of a stronger federal government in the 2000s. Future research can explore the specific features of autonomous regions that affect economic activities and management of common resources, including forest-cover change.

Our main findings complement the conclusions of Alix-Garcia et al. (2016), whose analysis uses similar data at the national level. Looking at logging loss and forest re-growth on abandoned agricultural land in post-socialist countries, Alix-Garcia et al. (2016) find that a country's history of land use and changes in land ownership explain a significant portion of forest change in the post-socialist period. Our analysis demonstrates that, holding these country-level variables constant, ecological, administrative, and economic factors emerge as important correlates of forest cover change at the regional level within Russia, as discussed above.

Looking beyond these specific empirical findings, this paper, which stems from an interdisciplinary project, helps to bridge the divide separating scholarship on remote sensing, ecology and social science of land use. It supplements ecological research by bringing administrative and political factors to the fore of the analysis, rather than just speculating about their potential effects, and suggesting possible channels that connect them with forest cover outcomes. At the same time, it complements social science by examining forest-cover change as a dependent variable influenced by socio-economic factors, rather than—as is typical of prior work—the reverse. Further studies that tease out the mechanisms behind key correlations identified in this paper would be the next fruitful steps for both branches of scholarship.

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CRediT authorship contribution statement

Delgerjargal Uvsh: Methodology, Software, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Scott Gehlbach:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Peter V. Potapov:** Resources, Data curation, Writing - review & editing. **Catalina Munteanu:** Software, Writing - review & editing, Visualization. **Eugenia V. Bragina:** Resources, Writing - review & editing. **Volker C. Radeloff:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

None.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2020.104648.

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