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Exploring natural and social drivers of forest degradation in post-Soviet Georgia

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ABSTRACT

The Caucasus Mountains harbor high concentrations of endemic species and provide an abundance of ecosystem services yet are significantly understudied compared to other ecosystems in Eurasia. In the country of Georgia, at the heart of the Caucasus region, forest degradation has been the largest land change process over the last thirty years. The prevailing narrative is that legal and illegal cutting of trees for fuelwood is primarily responsible for this process. Yet, since independence from the Soviet Union in 1991, the country has undergone rapid socioeconomic and institutional changes which have not been explored as drivers of forest change. We combine newly available land-cover change estimates, Georgian statistical data, and historical institutional change data to examine socioeconomic drivers of forest degradation. Our analysis controls for concurrent changes in climate that would affect degradation and examines variation at the regional (state) level from 2011 to 2019, as well as at the national level from 1987 to 2019. We find that higher winter temperature and drought are associated with higher degradation at the regional scale, while major institutional changes and drought are associated with higher forest degradation at the national level. Access to natural gas, the major energy alternative to fuelwood, had no significant association with degradation. Our results challenge the narrative that poverty and a lack of alternative energy infrastructure drive forest degradation and suggest that government policies banning household fuelwood cutting, including the new Forest Code of 2020, may not reduce forest degradation. Given these results, improved data on wood harvesting and more research on the commercial drivers of degradation and their links to economic and political reforms is needed to better inform forest policy in the region, especially given ongoing risks from climate change.

1. Introduction

Forest degradation is a major contributor of carbon emissions, though it is often missing from carbon accounting and is a hidden cause of ecosystem damage globally (Bullock et al., 2020; FAO, 2019). Degradation and deforestation together contribute 11 % of global carbon emissions (FAO, 2019), and degradation's share of that is between 25 and 40 % (Aragão et al., 2014; Pearson et al., 2017). In contrast to deforestation, degradation occurs when forests undergo changes in their structural and functional characteristics without resulting in a change in land-cover type, i.e., conversion from forest class (Lanly, 2003). Outcomes of degradation include negative impacts on multiple ecosystem services, such as carbon storage and cycling, habitat quality, and overall forest health (Vásquez-Grandón et al., 2018). Since this study is part of a larger project investigating land cover and land use change in the Caucasus, we use definitions consistent with other studies in the project. Forests are places with more than 10 % tree cover, excluding orchards; forest degradation is a reduction in tree cover due to natural or anthropogenic drivers without becoming deforested (<10 % tree cover); deforestation is the conversion of forest to non-forest; and forest

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disturbance refers to combined land cover changes from forest degradation and deforestation (Chen et al., 2021a, Chen et al., 2021b).

Despite its importance, understanding of the drivers of forest degradation has been limited due to the subtle and gradual nature of degradation compared to abrupt and acute land changes, such as deforestation. For example, degradation is more difficult to detect and monitor with remote sensing compared to deforestation (FAO, 2018), primarily due to the more smaller shift in the spectral signature of the forest canopy following degradation. In addition to the difficulties associated with the physical monitoring of degradation, precisely identifying the underlying drivers is difficult as they are often multifaceted, divergent, and partially overlap with deforestation drivers. Population growth, poverty, armed conflicts, and institutional changes influencing use of and access to forests are major long-term drivers of forest degradation in many developing countries (Muller and Zeller, 2002; Vu et al., 2014; Zeb, 2019). An "overuse" of forests (causing forest degradation) may be incentivized by high discount rates for the future arising from chaotic political environments, unresponsive labor markets, poverty, and weak property rights (Bluffstone, 1998).

These challenges may be exacerbated during societal transitions such as the collapse of the Soviet Union, when people become more insecure physically and politically and support for natural resource protection, including conservation institutions, is reduced (Bragina et al., 2015). Indeed, a growing body of research has examined how major economic and institutional changes since the end of the Soviet Union have affected forest cover and use in former member states (Dear et al., 2012; Quinn, 2017). Prior work in Eastern Europe has identified that forest cover generally increased in the region after the collapse of the Soviet Union due to a collapse in timber markets (Gutman and Radeloff, 2017). However, in Ukraine, Baumann et al. (2011) identified stable forest-cover levels due to ongoing timber harvesting pressure. Several studies have identified an increase in illegal forest use in the post-Soviet era in Russia, Ukraine, and Romania as a result of weakening law enforcement (Eikeland et al., 2004; Kuemmerle et al., 2009; Sieber et al., 2013; Vandergert and Newell, 2003). These activities usually result in forest degradation rather than complete forest conversion. In Russia after the collapse of the Soviet Union, road density, forest type (evergreen or deciduous), and total forest area were the principal drivers of both legal and illegal timber harvesting, however, major regional differences in political and economic shifts were also important sources of harvesting variation (Wendland et al., 2011).

Despite a growing body of research on forest processes in the former Soviet Union (fSU) region, the drivers of forest degradation in the Caucasus' subalpine meadows, coniferous forests, beech forests, and hornbeam-oak forests (Zimina, 1978) have been scarcely analyzed. Unlike the broader fSU region, where commercial timber harvesting drives forest-cover change, the primary hypothesized driver of degradation in the Caucasus is legal and illegal domestic fuelwood extraction, which increased by 250 % after independence, with the majority of the increase occurring after 2000 (Garforth et al., 2016; Torchinava and Iordanishvili, 2010). For example, an international black market in illegally harvested timber removed between 2.5 and 6 million cubic meters of timber per year from Georgian forests between 1991 and 2004, approximately-three times the legal limit (Macharashvili, 2009). Other potential drivers of these changes are the stark institutional shifts the country has experienced in recent decades and biophysical factors, such as droughts and climate variations, which may affect forest health.

We fill a major knowledge gap about land system dynamics in the Caucasus by analyzing the socioeconomic factors influencing forest degradation in the country of Georgia. Like other forested fSU countries, Georgia is an illustrative case to answer these questions due to its position as a "natural" experiment for examining the impacts of rapid political, economic and institutional shifts on land cover and land use as a result of the collapse of the Soviet Union (Baumann et al., 2012; Gutman and Radeloff, 2017; Kuemmerle et al., 2006; Prishchepov et al., 2013, Prishchepov et al., 2012). Yet it is also potentially unique from prior studies focused on Russia and Eastern Europe due to the political and cultural history of the Caucasus, particularly its past under the influence of various regional powers and Georgia's recent efforts at integration into the European Union and NATO.

A recent analysis using satellite data shows that forest degradation is the most prevalent land-cover change process over the last 30 years (Chen et al., 2021a, Chen et al., 2021b) and the major challenge to ensuring the conservation of the Georgian forest ecosystems and their functions (Garforth et al., 2016) (Fig. 1). These new data indicate that a net total of 11 % of the 1987 forest area had been degraded by 2019, which is high considering previous forest loss estimates of 0.8 % ± 0.6 % between 1990 and 2000 (Olofsson et al., 2010). Our study focuses on forest degradation, the reduction of forest canopy cover, and not deforestation, since it plays a minor role in the study area. Specifically, we ask: ***1) What were the natural and human drivers of forest degradation in Georgia between 2011*** **and** ***2019? 2) What were the relative effects of institutional changes since 1991 on forest degradation in Georgia?*** We answer these questions using two approaches: i) a panel regression model examining the region-level drivers of degradation based on data from the Georgian census for 2011–2019, and ii) a time series model at the national-level incorporating climate, macroeconomic, and institutional variables from 1987 to 2019.

2. Background

2.1. Georgia

Georgia is situated in the Caucasus mountains in western Asia. Rich in forests, it has undergone rapid economic, social, and institutional changes over the last 30 years. Georgia's high level of biodiversity, endemism, and forest cover (2.8 million ha, comprising 40 % of the national area) make responsible management and protection of its biomes a conservation priority. The country contains 22 microclimates and varied terrains in a small area including alpine mountains, arid shrublands, steppes, and temperate mixed forests (Olson et al., 2001). To date, 368,000 ha (13 %) of forests are under the Agency of Protected Areas, with other Georgian agencies adding marginally to the nominal protected forest area (GEOSTAT, 2021).

Only 2 % of Georgian forests are in the lowlands, with the vast majority in mountainous regions that are particularly threatened by climate change, with few options for species to move as temperature regimes change. Degradation may exacerbate pressure on forest ecosystems as reduced forest functions increase trees' susceptibility to disease, reduce habitat, and disrupt nutrient cycles.

Rates of forest degradation and deforestation in Georgia are similar to the patterns of Eastern European countries, with mostly constant levels of declines in disturbance shortly after the collapse and a noteworthy increase in the early 2000 s (Potapov et al., 2015). Moreover, after the dissolution of the Soviet Union, Potapov et al., 2015 also found large-scale, fast-paced forest regrowth in many of the fSU countries. Yet, compared to other affected regions, the Caucasus region experienced comparably low rates of forest change in the period 1987–2015 with roughly equal rates of forest loss and gain (Buchner et al., 2020).

Georgia has experienced two major institutional shifts during our study period of 1987–2019. Prior to 1991, the country was part of the Soviet Union. After independence the country was in political turmoil which eased towards the turn of the millennium. In November 2003, the bloodless Rose Revolution removed the last of the Soviet-era government leaders from power and ushered in the current period, characterized by market liberalization and orientation towards political, economic, and security arrangements with the West. There have been large demographic changes in Georgia since independence from the Soviet Union, with population declining by 25 % since 1991 (Castren, 2018).

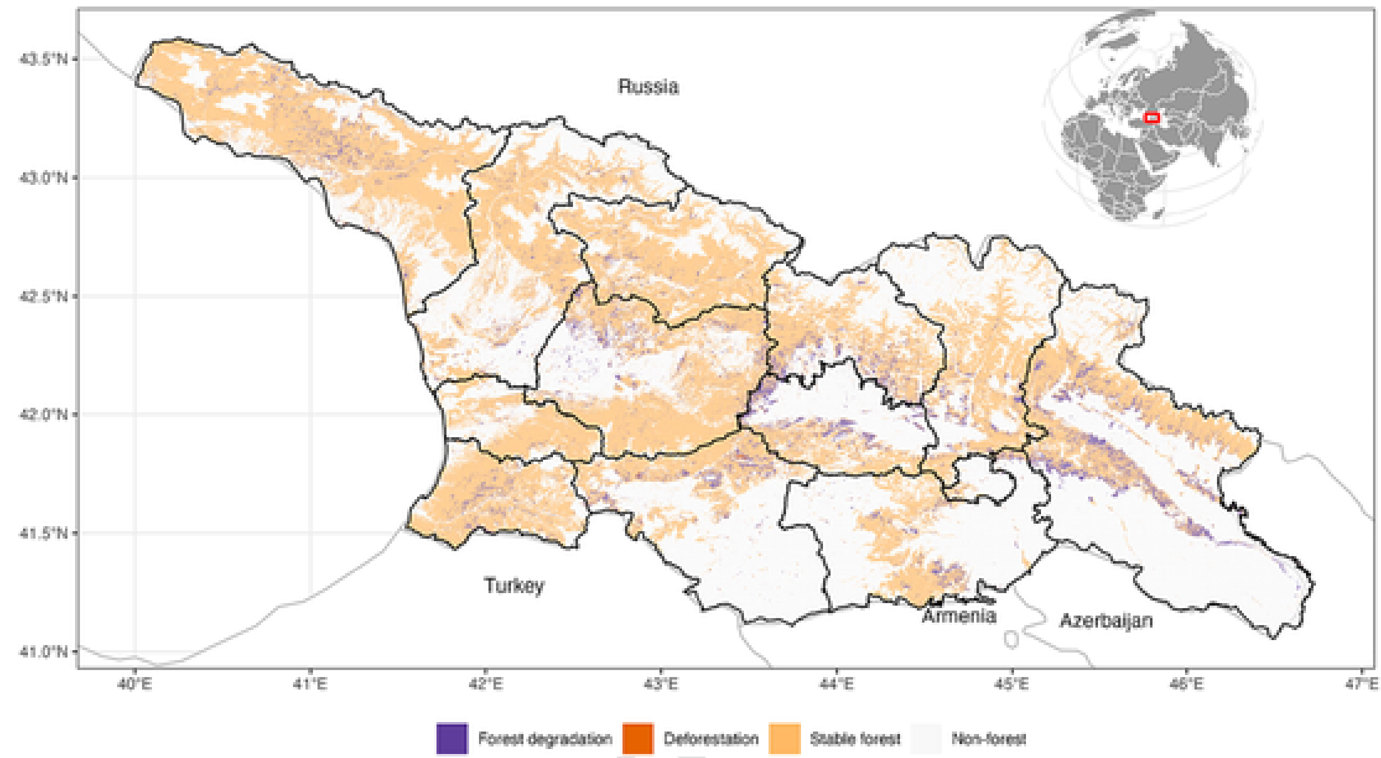

Fig. 1. Net forest degradation and deforestation in Georgia between 1987 and 2019 (Data from (S. Chen et al., 2021).

Forest degradation is especially acute in rural Georgia where poverty rates are higher, and it is believed that much of the forest disturbance in Georgia is driven by small-scale logging for household use, often referred to in Georgia as "social cuttings," and illegal cutting for fuelwood (Olofsson et al., 2010; Torchinava, 2016). These household energy decisions are heavily affected by the country's difficult relationship with Russia. The 2009 war between Russia and Georgia left 20 % of the country occupied by Russian or Russian-backed forces who restricted natural gas supplies to Ukraine and parts of Europe in a struggle over prices and political affiliations (i.e., Ukraine's and Georgia's desires to join NATO) (Kramer, 2009). In 2017, Georgia signed an agreement to transport Russian natural gas through their country to Armenia in exchange for payment and gas supplies (Rukhadze, 2017). Yet, the lack of control over these supplies provides an additional incentive for Georgians to use fuelwood instead.

All forest in the country is publicly owned. Before 2019, forest land could be owned or leased by local enterprises, but the new Forest Code, passed into law in 2020, transferred all control to government agencies (Torchinava, 2020). Some license holders with active agreements are permitted to continue forest activities until the expiration of their licenses. The law (which will enter into force in 2023) also bans all small-scale logging for household needs.

2.2. Potential drivers of forest degradation

We conceptualize human use of forests as a function of access to forests and demand for forest resources. Both access and demand include components that span human, economic, and institutional factors. Biophysical conditions, population dynamics, markets, infrastructure, and policy incentives are all recognized factors that influence forest cover and use (Binswanger, 1991; Cvitanović et al., 2016; Lambin et al., 2001; Moran, 1993; Repetto and Gillis, 1988), thus we include biophysical controls including forest area, slope, and drought, which can affect tree health and resilience to insects and disease. For anthropogenic changes, we draw on peasant theory by Chayanov, access theories (Ribot and Peluso, 2003) among others, and the institutional analysis and development (IAD) framework by Ostrom (Chayanov, 1966; Tucker and Ostrom, 2005). The IAD framework focuses on the "action situation," a composite of participants, positions, actions which respond to information, costs and benefits of actions, and outcomes of the actions taken. Its roots are in rational choice, collective action, common property, and social capital theories. We integrate the basic components of the IAD Framework by including biophysical data, community attributes (regional economic and demographic data), and rules-in-use through the use of institutional placeholder variables. These variables are referred to as exogenous in the framework. They are shaped by existing environmental conditions and in turn create the situation in which actors make decisions and create new outcomes (McGinnis, 2011).

2.2.1. Access to forests

Access to forests is influenced by physical access (e.g., road infrastructure) and legal access (e.g., use rules, forest laws, and enforcement (Robinson et al., 2010). The Caucasus Environmental NGO Network (CENN) found in 2016 that though the National Forestry Agency permitted 600,000 cubic meters of firewood per year, demand was calculated at 2.4 million cubic meters (CENN 2019, personal communication). Yet, individual households are not the only consumers of fuelwood in Georgia, the public sector also plays a large role and within this sector, public schools are the largest consumers of firewood (CENN, 2016a,b). Under situations where common pool resources such as forests have few institutional restrictions on access, users tend to adopt optimal foraging strategies. These strategies result in land use based on *access* factors such as distances from roads and settlements, slope, elevation, and patterns of enforcement (Gibson et al., 1998; Nagendra et al., 2008; Schweik, 2000).

Institutions are the formal and informal rules recognized by a group of people in a given context (Dietz et al., 2002; Tucker and Ostrom, 2005). Institutions shape the environment, and biophysical factors can change how institutions affect environmental outcomes. Forests ungoverned by institutions, whether institutions are absent, unenforced, or poorly defined, are more likely to be degraded if these forests contain commercially valuable species or if population growth near the forests increases subsistence or other uses (Tucker and Ostrom, 2005). The factors which support the development and persistence of effective institutions for the management of common-pool resources are standing questions in global environmental change. The goal of this research is not to evaluate whether private, public, or common property regimes are better at promoting positive forest management, but how specific rules-in-use in Georgia have affected forests as these specific rules and their contexts may have evolved since the Soviet period.

2.2.2. Demand for forest resources

Peasant theory holds that household land-use behaviors are driven by meeting subsistence needs. After subsistence needs are met, leisure time will be prioritized rather than making more surplus to generate income (Chayanov, 1966). In Georgia, 96 % of rural households rely on wood heating, which is common in countries from Pakistan to Ghana to India, where links to forest degradation have been widely noted (Cooke et al., 2008; CRRC and Zurabishvili, 2013; Heltberg et al., 2000; Sola et al., 2017; Swinkels, 2014; Zeb, 2019). Thus, we expect that household forest-use behaviors are partially driven by the ***demand*** of households to collect as much firewood as needed to provide sufficient energy for heating, cooking and a buffer supply. Theoretically, households may not always obtain as much firewood as they would like, as various institutions and infrastructural impediments limit ***access*** to forests to harvest fuelwood. As with all land-use processes, both household demand and access to forests are influenced by broader structural factors, including biophysical, culture, market, and institutional changes, among others (Cortner et al., 2019). From the pattern of forest degradation in Fig. 2, we initially expected that political chaos from the dissolution of the Soviet Union and the civil wars in Georgia from 1991 to 1995 drove an increase in forest degradation.

In the Georgian context, where rural households are poor relative to their urban counterparts, demand for fuelwood is likely to be influenced by household income and the prices and availability of alternative heating sources (Cecelski et al., 1979; Heltberg et al., 2000). Energy insecurity was further exacerbated during the political chaos of the post-independence years, especially in rural alpine regions (Radvanyi and Muduyev, 2007), increasing reliance on harvested wood. Wood harvesting in alpine regions is difficult, damages alpine habitats, negatively affects household health by being burned indoors, and is largely criminalized by the state (Government of Georgia, 1999; Lampietti et al., 2003). Given these disadvantages, we expect that regions with higher access to natural gas will have lower rates of forest degradation. At the regional level, degradation may be higher where the population density is greater, since this could increase total demand for energy; however, increasing population does not necessarily lead to forest degradation. People in areas of increasing population may realize the threat posed to shared resources and adjust institutional arrangements accordingly in the presence of a scarce resource under pressure (Tiffen and Mortimore, 1994; Varughese, 2000).

2.2.3. Biophysical conditions and trends

Climate stressors and other biophysical factors are also potential drivers of the large-scale degradation observed. The close tracking of deforestation and degradation in Georgia suggests that deforestation there is the result of advanced degradation processes. Drought conditions, including a 2010 extreme heatwave in European Russia, have affected forests and crops in the wider region (Loboda et al., 2017; Martin-Benito et al., 2018). Climatic shifts can result in both tree stress and forest retreat as well as tree growth (Kulakowski et al., 2011). Short-term extreme events like drought can also cause spikes in tree mortality and negatively affect agricultural production, which in turn may drive hu-

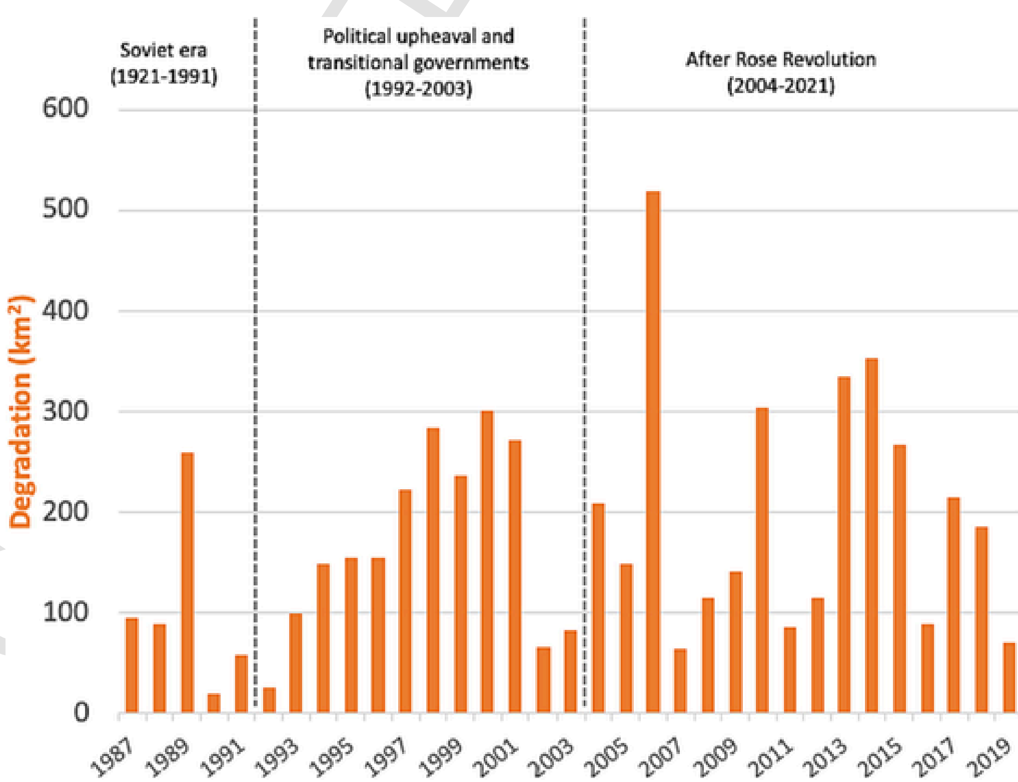

Fig. 2. Forest degradation and institutional periods 1987–2019. Area estimates of forest degradation are from (S. Chen et al., 2021). Burned areas are excluded from the chart and our analysis since they are extremely small (e.g., max burned area classified as deforestation = 8.5 km2 in 2008) and do not change the pattern presented. During the 33-year study period, the total area classified as having undergone the land cover change of forest degradation was 3541 ± 556 km2, and the total area classified as having undergone deforestation was 158 ± 98 km2. Those are the 95 % confidence intervals for each land cover change area. The map from which degradation values were sourced had an overall accuracy of 91 %.

man behavior that impacts forests adjacent to agricultural areas (Lipper et al., 2014). Land use and climate change may interact (Oliver and Morecroft, 2014), which can make assessment of the relative contributions of land use and climatic variables difficult. Increased temperatures, changes in the precipitation regime, and extreme events (fires, storms, floods, draughts, pathogens and pests) from climate change are expected to impact forest species growth and distribution in Georgia (MEPA, 2021).

Based on exploratory interviews with farmers, rural inhabitants, and Georgian forest experts in the fall of 2018 and literature, we built a conceptual map of hypothesized drivers of disturbance and change in Georgian forests (Fig. 3). The conceptual map focuses on harvesting for fuelwood and other household needs while allowing for the possibility that natural disturbances such as drought, pests, disease, and fire (backgrounded by climate change) could also play major roles. We exclude degradation caused by fire, since there is not a natural fire regime in Caucasus forests, the major burned area in the last two decades was likely caused by conflict instead of harvesting (Bahrampour, 2008; Snoy et al., 2008), and the burned areas relative to other degradation are extremely small, no more than 2 % of the total degraded area in any year of the study period based on statistics calculated from the relevant shapefiles provided by Chen et al., 2021a, Chen et al., 2021b.

3. Data

3.1. Exploratory interviews

In October 2018, two members of the research team traveled to Georgia. We conducted nine interviews across four government agencies, four farms, and an important forest area and observed land-cover and land-use changes in four regions. Interviews were semi-structured, with a prepared list of questions but no strict requirement to answer all questions or proceed linearly through the list. These interviews and existing literature informed our conceptual model (Fig. 3) and variable selection. The variables included in the regression models are used to operationalize this conceptual model. The final set of variables included in the various models we tested depended on data availability, an assessment of multi-collinearity between variables, and our judgments about the interpretability of the models (given temporal overlaps between some potential institutional changes). A sample interview guide, descriptive statistics, assumptions, and additional information about the explanatory variables can be found in the Supplemental Information (SI).

3.2. Forest degradation data

We acquired maps of stable forest, forest degradation, and deforestation from 1987 to 2019 at 30 × 30 m resolution (Fig. 1) from Chen et al., 2021a, Chen et al., 2021b. The map was created using the Continuous Change Detection and Classification-Spectral Mixture Analysis (CCDC-SMA) algorithm (Chen et al., 2021a, Chen et al., 2021b). CCDC-SMA used all available Landsat images of Georgia from 1984 to 2019. In the SMA model, each pixel is regarded as a combination of four pure materials (called "endmembers"): green vegetation (e.g., green leaves), non-photosynthetic vegetation (NPV) (e.g., stumps and dead leaves), soil, and shade (e.g., shadows). The fractions of these endmembers in a pixel can be calculated using a SMA model. In CCDC-SMA, these fractions of endmembers and a spectral index, the normalized difference fraction index (NDFI) (Bullock et al., 2020; Souza et al., 2005), were calculated for all Landsat observations. CCDC-SMA fits harmonic models to the observed values of fraction of endmembers and NDFI to make predictions. A change is detected if the observations are significantly different from the predictions. An example of CCDC-SMA model fits at a forest degradation site in Georgia can be seen in the.

The overall accuracy of the map was 91 %, with a user's and producer's accuracy of forest degradation of 69 % and 83 %, respectively (Chen et al., 2021a,b). Burned areas, a negligible fraction of overall degraded or deforested area, were manually delineated and excluded

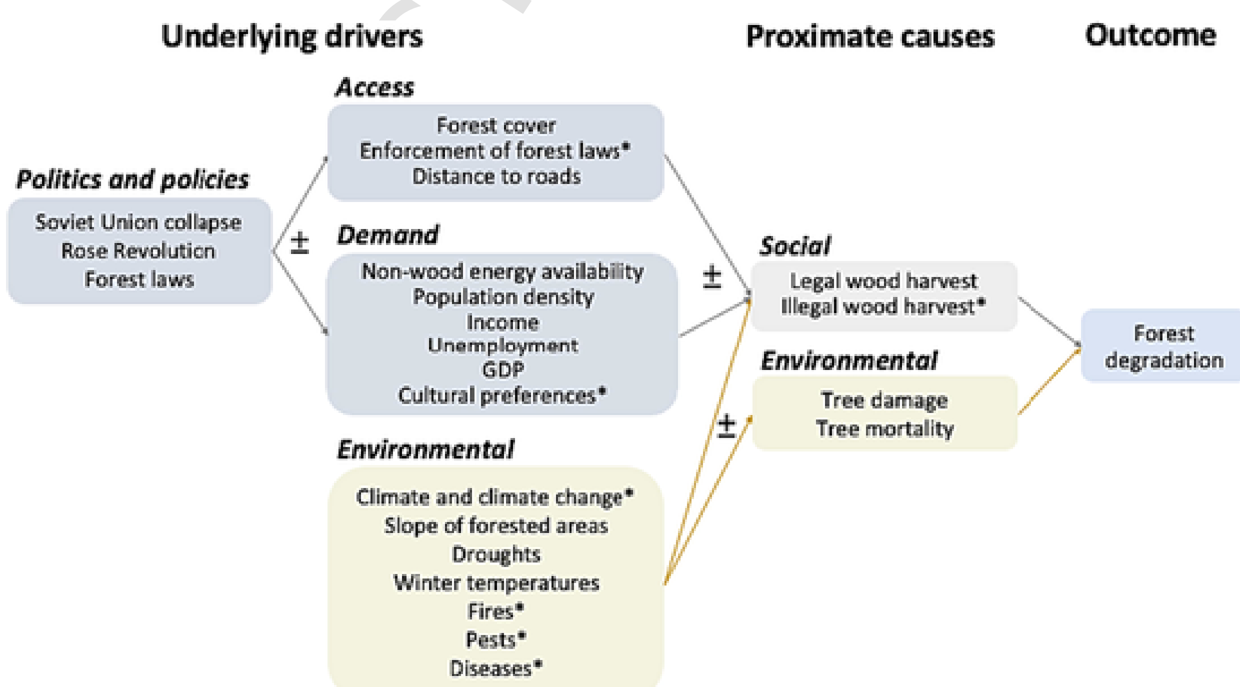

Fig. 3. Conceptual diagram of underlying drivers and proximate causes of forest degradation in Georgia. The * indicates the variables that are theoretically important but not included in our study. The forest area affected by fire is negligible, so it is excluded from the analysis. We do not have adequate data for forest law enforcement, traditions and cultural preferences, pests, or diseases, so we excluded them from the analysis. While some climate-related variables are included, we do not include comprehensive climatic variables (e.g., soil moisture, mean surface temperatures) and instead restrict this part of the analysis to climate indicators that directly affect tree health (i.e., drought) or expected fuel demand (i.e., winter temperatures).

from the analysis (Chen et al., 2021a,b). We aggregated the resulting forest cover, degradation, and deforestation data at the regional and national levels to match the levels of analysis. The smallest units of our analysis are the regions of Georgia, which are equivalent to "states" in the United States or "provinces" in Canada. This is the most detailed of Georgia's administrative units where pertinent socioeconomic data were available.

3.3. *Access to forests*

Physical access to forests was approximated by computing the straight-line distance from each forested pixel in the 1986 land-cover map of Georgia to the nearest road in a 2015 map of the country's road network, shown in Fig. 7 in the SI. Using the SRTM 90 m Digital Elevation database (Jarvis et al., 2008), we calculated the mean slopes of forested areas in each region. Data on legal access, i.e., the enforcement of forest laws, would have been important to measure accessibility, but no consistent spatial–temporal data were available. Yet, physical access, e.g., remoteness, may approximate monitoring and enforcement of forest laws (Robinson et al., 2010).

3.4. *Demand for fuelwood*

As proxies for household demand for fuel we include proximate drivers, i.e., *wood harvest* estimates of *legal* cuttings, and underlying drivers including *population density*, *income*, *unemployment*, and *gas access* from the Georgian census. These statistics are collected by and made publicly available on the website of the National Statistics Agency of Georgia (GEOSTAT) (https://www.geostat.ge/en). Few data were available for the full period of interest (1987–2019), and if available, often only at the national level. Continuous records at the regional level were often only available for the period 2011–2019. This scarcity of long-term records is a result of the multiple political transitions, conflicts, and the switch from paper-based to digital records (Radvanyi and Muduyev, 2007). Changing governments and inconsistent forest statistics collection are similar challenges to those faced in former "Eastern Bloc" countries (Potapov et al., 2015). Similarly, socioeconomic statistics for Georgia during the Soviet period were unavailable. Due to a lack of census statistics for Abkhazia and South Ossetia, due to political conflict, and the distinctly urban character of Tbilisi, the capital district, these regions were excluded from the analysis. Data for the proportion of households with access to piped natural gas supply gave aggregated values for the regions of Samtskhe-Javakheti, Guria and Mtskheta-Mtianeti for the years 2011–2018, i.e., these regions have the same value for households with natural gas each year. These values are currently used in the data set for the panel models.

Since demand for fuelwood used to heat homes is not only a function of socioeconomic status, but also temperature, we developed an estimate of *winter coldness*, calculated as the mean of the mean monthly minimum temperatures for the three coldest months of each calendar year. Temperatures were obtained from the Copernicus Climate Change Service Data Store's ERA5 dataset (Hersbach, et al., 2018).

3.5. *Nation-wide institutional changes and climatic changes*

Institutional changes were coded as binary variables, identifying prior- and post-change years of the relevant institutional change. All institutional changes were modeled as structural shifts, meaning they were represented in the data with a "1″ for the occurrence year and every successive year and "0" for all years before the occurrence (Table 2). Institutional changes examined included the collapse of the Soviet Union (1991), the Rose Revolution (2003), representing the end of Soviet-era leadership, and government policies relevant to forests. From 1999 to 2020, the first Forest Code of independent Georgia was in force. During this period, licenses for commercial harvesting were issued (2005–2011). Later, the Ministry of Environmental Protection and Natural Resources was established (2012) along with the reintroduction of regular management level inventories of forests. The National Forest Concept was developed in 2013 and active till 2019, and a new Forest Code was adopted in 2020. Of these policies, we include the first Forest Code, the period in which commercial harvesting licenses were issued, and the National Forest Concept. These variables are included in a separate regression model from the model which includes the major structural changes of the Soviet Union Collapse and Rose Revolution due to time overlaps that confounded our ability to assess whether the policies had any detectable influence on degradation.

To represent the influence of climate, we included a drought proxy, the Standardized Precipitation Evapotranspiration Index (SPEI), a multi-scalar drought index sensitive to global warming (Vicente-Serrano et al., 2010). Recent research in the Caucasus on the effects of drought on tree mortality and health suggested that a three-month scale was for drought analysis was the most appropriate (Martin-Benito, 2021; Martin-Benito et al., 2018), which is the drought value used in our analysis, computed through the package SPEI in R.

4. Methodology

To answer the research questions posed in the Introduction, we developed models at both the regional-level and the national-level. For question one, "*What were the natural and human drivers of forest degradation in Georgia between 2011* and *2019?*", we use the regional-level analysis, which employs panel data over a 9-year period to assess the influence of spatial variations in socioeconomic factors on degradation outcomes. In the regional panel model the observational units are ten regions (i.e., states) of Georgia with annual values for each variable over the period 2011–2019. To answer the second question "*What were the relative effects of institutional changes since 1991 on forest degradation in Georgia?*", we needed a longer time period, so we use a national-level analysis to try to detect changes from macroscopic indicators (i.e., the collapse of the Soviet Union, the Rose Revolution, GDP, population). The national time series model extends for 33 years from 1987 to 2019. The response variable for both models is the log of the area in square kilometers of forest degradation. This corrects for right-skewed degradation values and achieves a normal distribution of the model residuals (see SI).

The regional panel model tested fuelwood demand and forest access in addition to control variables as predictors of forest disturbance similar to previous land-cover/land-use change studies (e.g. (Alix-Garcia et al., 2016; Bluffstone, 1998; Munteanu et al., 2014; Vu et al., 2014)).

The general form of the model is as follows:

$$\ln(Degradation_{it}) = \beta_1 Demand_{i,t} + \beta_2 Access_{i,t} + \beta_3 Controls_{i,t} + \varepsilon_{i,t}$$

where $Degradation$ is the remotely sensed area estimate in region i at time t and $Demand, Access$ and $Controls$ represent the variables from Tables 1 and 2. The error term is represented by $\varepsilon_{i,t}$.

The panel model is as follows:

$$\ln\left(degradation_{i,t}\right) = legalwoodharvest_{i,t} + naturalgasaccess_{i,t} + populationdensity_{i,t} + unemployment_{i,t} + householdincome_{i,t} + wintertemperature_{i,t} + threemonthSPEI_{i,t} + \varepsilon_{i,t}$$

In the regional model, $Demand$ is a set of variables which our theoretical framework and the literature suggests influence demand for fuelwood, and $Access$ is a set of variables thought to be likely to influence people's access/ability to use the forest. $Controls$ includes a set of environmental variables. Some variables were eventually discarded from the final models due to collinearity or model requirements. Correlation

Table 1
Variables examined in regional-scale analysis.

Variable by type	Source
Outcome:	
Forest degradation excluding burned areas (km^2)	(S. Chen et al., 2021)
Proximate causes – human:	
Legal wood harvest (m^3)	(GEOSTAT, 2021)
Underlying drivers – demand:	
GDP per capita (constant 2010 U.S. dollars)	(The World Bank Group, 2021)
Rural population (percentage of the total population)	(The World Bank Group, 2021)
Winter temperature (mean temperature of the three coldest months of the year in °C)	(Hersbach, et al., 2018)
Population density (persons/km^2)	(GEOSTAT, 2021)
Household earnings (average monthly nominal earnings in Georgian lari)	(GEOSTAT, 2021)
Unemployment (% unemployed of active labor force)	(GEOSTAT, 2021)
Households with natural gas (%)	(GEOSTAT, 2021)
Underlying drivers – access:	
Forest-to-road distance (km)	National Forestry Agency of Georgia
Mean slope of forested areas (°)	(Jarvis et al., 2008)
Control:	
Water deficiency (Standardized Precipitation Evapotranspiration Index)	(Beguería and Vicente-Serrano, 2017; Harris et al., 2021)
Forest area as detected and classified through remote sensing (km^2)	(Chen et al., 2021)

matrices for regional- and national-level variables are included in the SI.

Due to the overlap of the forest policies tested with the Rose Revolution time period, we made two models for the national analysis, which are as follows:

$$\ln degradation_t = ruralpopulation_t + wintertemperature_t + SovietUnioncollapse_t + RoseRevolution_t + threemonthSPEI_t + forestarea_{t-1} + \varepsilon_t$$

$$\ln degradation_t = ruralpopulation_t + wintertemperature_t + ForestCodeI_t + licensesissued_t + NationalForestConcept_t + threemonthSPEI_t + forestarea_{t-1} + \varepsilon_t$$

Explanatory variables were included in the final models based on our hypotheses, theoretical framework, past literature, and statistical considerations. We chose an individual fixed effects model so that we could compare differences in the explanatory variables over time within each region while controlling for time-dependent shocks that might have affected all regions. This resulted in the removal of some variables from the final model. For example, forest-to-road distance was omitted from the individual fixed effects model because it does not vary over time. The slope of forest areas was ultimately removed from the models since it was extremely correlated with forest area given the way it was calculated, and highly correlated with unemployment. GDP was omitted from the final national regression because it was strongly correlated with the proportion of total population that was rural, which was a more relevant variable to our theoretical framework.

The national models do not include a felled wood variable like the regional model since data were not available for the full time period. All analyses were carried out using R software, version 4.1–4.2.1, in RStudio, version 2021–2022.07.1 + 554. Full correlation tables and matrices for all potential regional and national variables are in the SI.

Table 2
Variables examined in national-scale analysis.

Variable	Notes	Source
Outcome:		
Forest degradation excluding burned areas (km^2)		(S. Chen et al., 2021)
Underlying drivers - demand:		
Soviet Union collapse	0 for years < 1991, 1 for years >= 1991 (representing structural change)	Historical
Rose Revolution	0 for years < 2004, 1 for years >= 2004 (representing structural change)	Historical
GDP per capita (constant 2010 U.S. dollars)		(The World Bank Group, 2021)
Rural population (percentage of the total population)		(The World Bank Group, 2021)
Winter temperature (mean temperature of the three coldest months of the year in °C)		(Hersbach, et al., 2018)
Underlying drivers - access:		
Forest Code	0 for years < 1999, 1 for years >= 1999; represents the introduction of Georgia's first post-independence Forest Code	(Torchinava, 2020)
Licenses	1 for 2005–2011, 0 for all other years; represents the Georgian government's issuance of forest harvesting licenses to private companies	(Torchinava, 2020)
National Forest Concept	1 for 2013–2019, 0 for all other years; represents the introduction of the National Forest Concept, the main framework for the country's forest sector reforms prior to 2020	(Torchinava, 2020)
Control:		
Water deficiency	Standardized Precipitation Evapotranspiration Index	(Beguería and Vicente-Serrano, 2017; Harris et al., 2021)
Forest area	As detected and classified through remote sensing (km^2)	(Chen et al., 2021)

5. Results

5.1. Regional model results

Results of the regional panel linear model are shown in Fig. 4 with standardized coefficients, allowing the effects of the explanatory variables can be compared to one another, but do not represent the effect size on the response variable. The models shown used either individual fixed effects (IFE) or random effects (IRE) and had adjusted R^2 values of 0.07 and 0.09 respectively. The IRE model is included to examine the influence of the one time-invariant variable, forest-to-road distance, which was thought to be a key indicator of forest access and human use as a driver of degradation. These results are cautiously interpreted below given the limitations of our data and regression design in detecting causal effects.

5.1.1. Human causes and drivers of degradation

There is only limited evidence to support the ideal that wood harvest is a major direct cause of degradation. Legal wood harvest was significant and positively associated with degradation in the IRE model, but not in the IFE model. This is likely due to the fact that the legal harvest varies a lot across regions but not across time within regions (see Fig. 9 in the SI), and since the IFE model uses the mean of all within-region values for each year, the effect of the legal harvest on degradation is not visible.

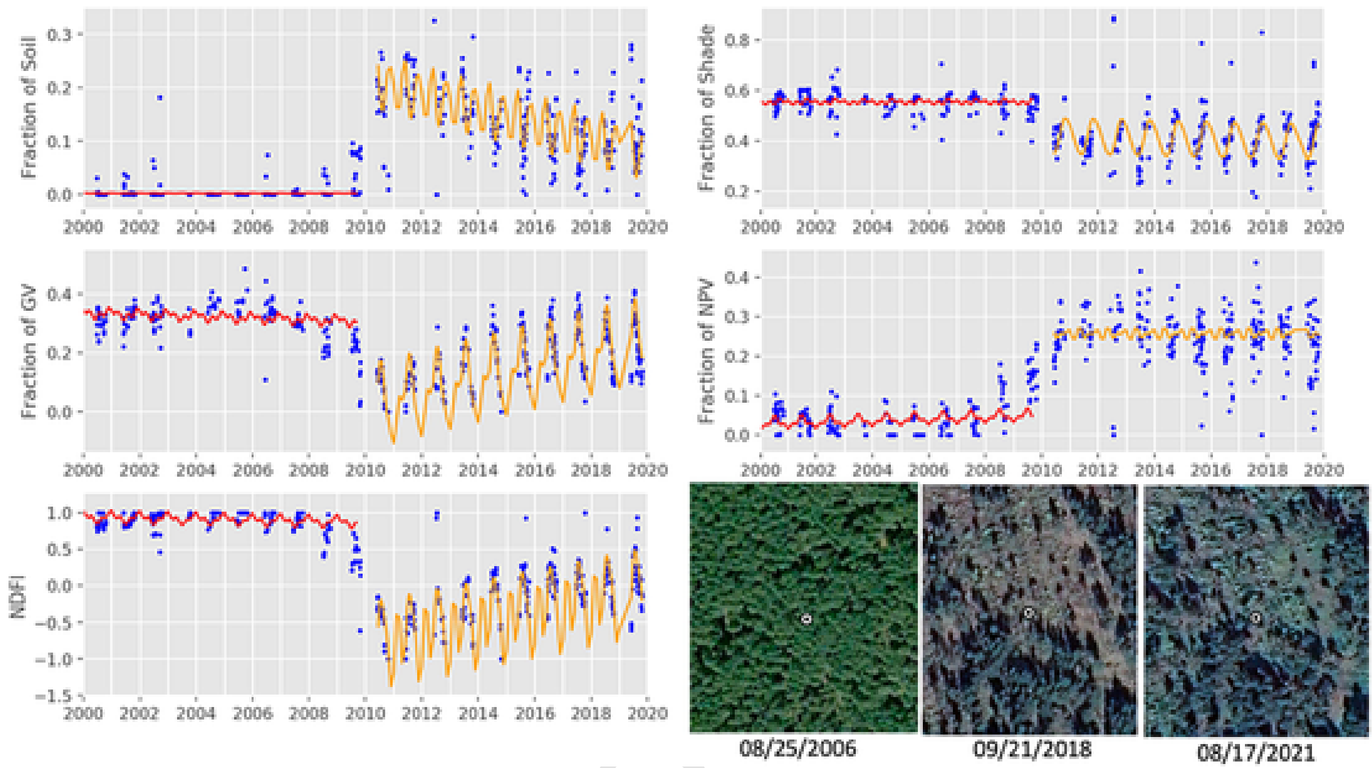

Fig. 4. An example of CCDC-SMA model fits at a forest degradation site in Georgia. Example location: 42°23′9″N, 45°40′15″E. In the time series plot, the blue points are Landsat observations, and the colored lines are the CCDC-SMA model fits, where different colors indicate different segments. In the high-resolution images, the white circles show the center of the pixel. The red segments before 2010 indicate the stable status of the dense forest. The break in 2010 resulted from significant change of the fractions of endmembers and NDFI indicates the degradation event. The dates below the images are image acquisition dates.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

There is no evidence to support the idea that smallholders are driving this process through illegal wood collection or condoned social cuttings. None of the hypothesized underlying human drivers (i.e., none of the access or demand for fuelwood indicators) were significant aside from winter temperature. However, with higher winter temperatures were associated with higher forest degradation, which is not as we had hypothesized (based on the theory that colder winters would lead to higher fuelwood extraction).

5.1.2. Environmental causes and drivers of degradation

There is more evidence to suggest that tree mortality is a direct cause of degradation. Drought, represented by the three-month SPEI, which is a well-known driver of tree stress and eventual death, was significant in both models. This suggests that drier conditions during the growing season increased forest degradation, as indicated by the negative effect direction of three-month SPEI. This is because, after centering and scaling the explanatory variables, negative scaled (low unscaled) SPEI values mean dry conditions and positive scaled (high unscaled) SPEI values mean wetter conditions.

5.2. National model results

The results of the national-level models are shown in Fig. 5 with standardized coefficients. Each model version explains approximately 30 % of the variation in forest degradation over the period 1987–2019 at the national level. Two models were used, one that included the collapse of the Soviet Union and the Rose Revolution, modeled as structural changes, and another that included the three forest-relevant policies under investigation. Given the lasting effects of the dissolution of the Soviet Union in 1991, modeling the change as a structural shift was considered the most plausible modeling implementation. Likewise, the deliberate and ongoing program of reforms and orientation towards market liberalization since the Rose Revolution in 2003 guided our decision to model it as a structural change (see Fig. 6).

5.2.1. Importance of institutional drivers of degradation

There is only limited evidence to support the ideal that wood harvest is a major direct cause of degradation. Only one of the variables describing changes to legal access to forests from Model 2, National Forest Concept, was significant, with a large relative effect size compared to other independent variables in the model. The collapse of the Soviet Union and changes in rural population were not significant predictors of forest degradation. The Rose Revolution was associated with a large increase in degradation, but there is a large standard error on this coefficient.

5.2.2. Environmental causes and drivers

The national model results support the regional evidence that tree mortality is a direct cause of degradation. Drought, as represented by lower SPEI scores, is again significantly positively associated with degradation and therefore one of the most likely underlying degradation drivers. Winter temperature was also significant in Model 1with a positive effect on degradation similar to the regional models.

6. Discussion

6.1. Climate factors are the dominant driver of degradation and there is little support for the household social-cuttings hypothesis

According to one representative of a Georgian environmental NGO we spoke to during our exploratory interviews, few Georgians with natural gas actually use it for heating, and the fuelwood black market provides a main source of income for thousands of people. Unfortunately, we cannot directly assess the influence of illegal harvests since they are

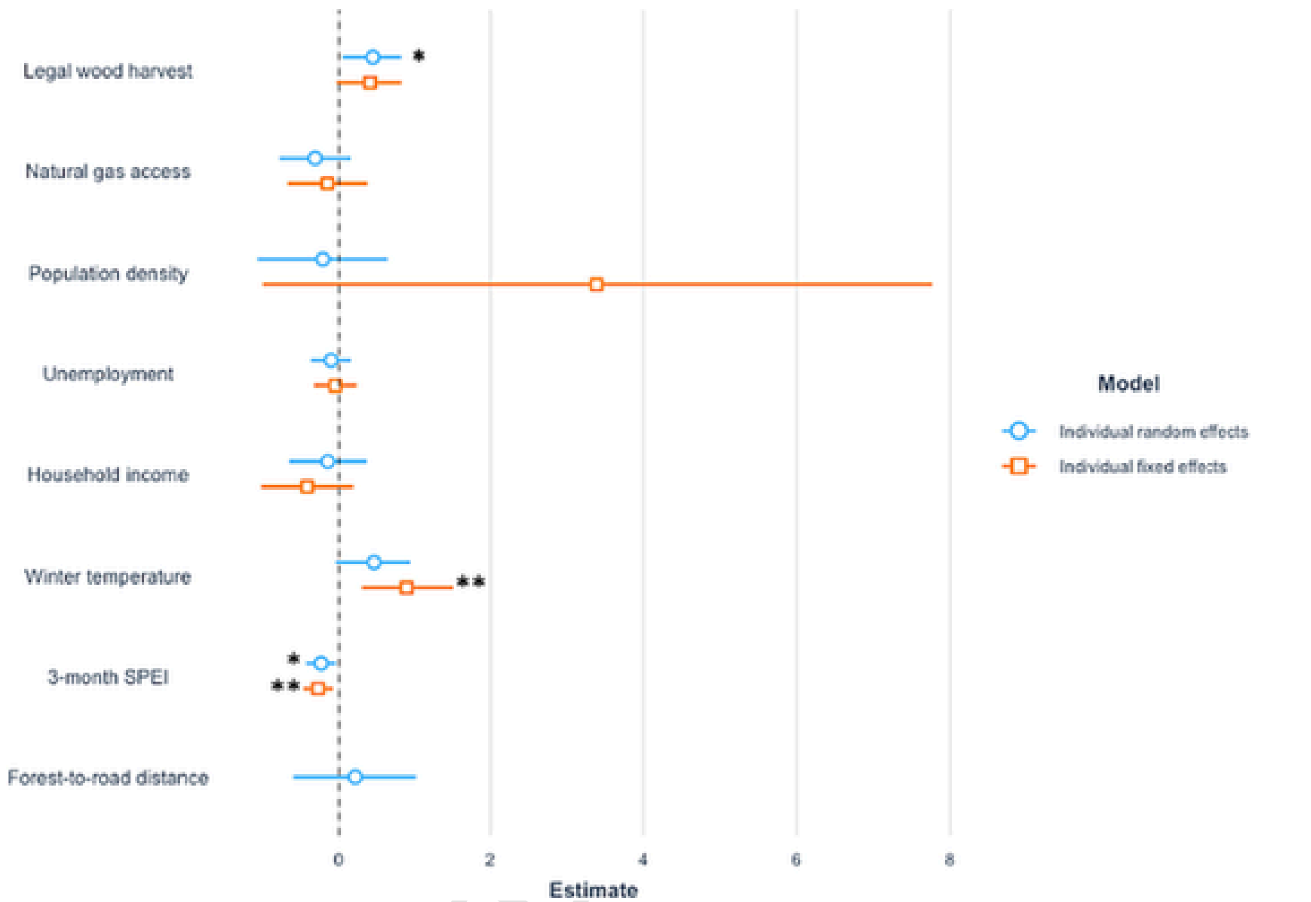

Fig. 5. Panel linear model results coefficient plot. Individual fixed effects model and individual random effects model shown. Scaled and mean-centered explanatory variables. Coefficient values shown with hollow blue circles or orange squares. A variable is significant where the error bar (blue or orange line) for the coefficient does not cross the 0 line. ** $p < 0.01$; * $p < 0.05$. Please see details in Table S2 in the SI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

unreported, so instead we looked at underlying variables that would support a "social-cutting" hypothesis. Yet none of the variables that would support such a hypothesis are significant in our analysis. Differences in the legal harvest across regions does explain differences in degradation between regions, but, given their consistency over time amid large-scale rural population and economic change, these legal harvests are more likely associated with state-planned cuttings, rather than spontaneous individual household use.

The positive coefficients for winter temperature do not fit a cold-driven demand theory if we accept that most households burn wood in the same year it is harvested (Torchinava, 2020). Instead, the positive association of degradation and warmer winter temperatures suggests a climatic explanation. Warmer winter temperatures could induce tree stress through multiple pathways, including disruption to dormancy periods and a failure to break pest cycles (World Bank, Adb 2021).

SPEI, the drought index employed, was consistently important at both the regional scale and across years at the national scale. Whether drought is a more influential driver of degradation than human actions is still unclear. At the national level, drought had a similar effect size to winter temperature, and in a similar direction, that is, drier and warmer temperatures were associated with increased degradation. This confluence of the two variables, one an aggregated monthly minimum mean temperature, and the other an index calculated from temperature, precipitation, and latitude, points to the important role played by climate in forest degradation. Under the most likely scenarios of future climate change, the effects of drought and temperature will likely increase in strength.

Privatization of the energy sector, among other parts of the Georgian economy, was a stark difference from the Soviet era when energy was a public good. The transition, occurring in parallel with many other changes in Georgian society, left many without reliable or affordable access to energy for long periods. During this time, Georgians recall that many windbreaks and accessible stands of trees on the edges of urban areas were cut for fuelwood (Gutbrod, 2019; Torchinava, 2020). As the country stabilized and urban areas developed, most citizens of cities were able to access electricity and gas for heating. However, many of the rural parts of Georgia had emptied out as people either moved to cities or emigrated to other countries. This demographic loss and the shocks of the communist-capitalist transition left rural areas behind their urban counterparts (Alvi, 2018). In addition to the urban–rural divide, those living below the poverty line in rural Georgia are much more likely than their wealthier neighbors to be dependent on a single source of income, and most of the time that income is dependent on forest products (Castren, 2018; ENPI, 2016).

The Georgian government has invested heavily in gas infrastructure, yet this will do little to abate degradation if people consider it too expensive or unattractive to substitute gas for fuelwood. In addition, if it is a common livelihood option for thousands of people, legal enforcement against illegal cutting may cause harm by criminalizing one of limited options for earning income. ENPI-FLEG, a program financed by the European Commission and the Government of Austria, aimed to improve forest law enforcement and governance in seven countries including Georgia (ENPI, 2018). Their work with local stakeholder groups and the Georgian government recommended a path away from gas to avoid increasing energy dependence on other countries. Instead, the program

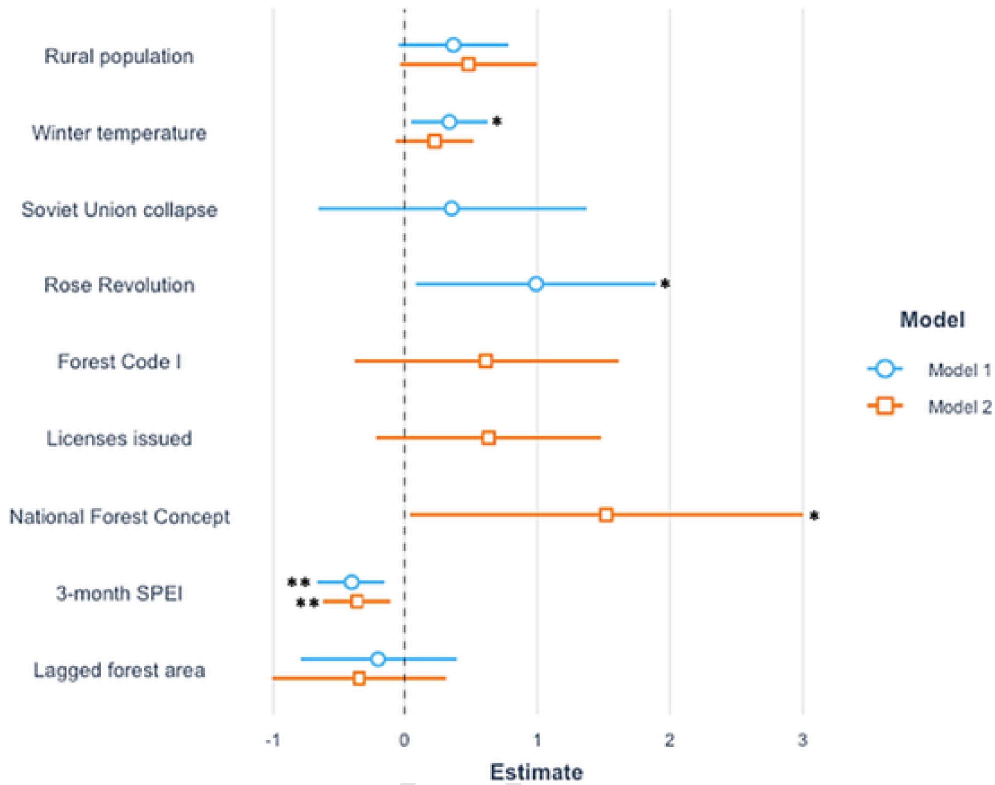

Fig. 6. National regression model results coefficients plot. A variable is significant if its error bar does not cross the 0 line. ** $p < 0.01$; * $p < 0.05$. Please see details in Table S4 in the SI.

reports envisioned replacement of fuelwood with briquettes made from recycled local materials, primarily biowaste from agriculture and wood, and equipping public schools with central heating systems fueled with natural gas (CENN, 2016a).

In light of these transformations, it is surprising that huge changes in GDP and population as a result of the collapse of the Soviet Union do not seem to have an effect on forest degradation. We expected forest degradation to inversely track GDP, with poverty increasing reliance on domestic forest wood for fuel, and to directly track population, with higher populations consuming more domestic forest wood. When looking at trends over time (Fig. 2), forest degradation follows a very different pattern than GDP or population. This seems to support the idea that macroeconomic trends and the initial political transition in 1991 were overshadowed as drivers of forest degradation by other factors.

Nevertheless, in the national models, the Rose Revolution in model I and the National Forest Concept in model II were both significant drivers of degradation, both with a positive relationship to degradation. It should be noted that this does not necessarily point to the Rose Revolution itself as the driver of change in forest degradation, but rather that it marks a period in which institutional, economic, or other structural changes occurred that had an effect on forest degradation within the framework of our analysis. Since the National Forest Concept, which was in effect 20213–2019, overlaps with the period of the Rose Revolution's structural impact, we cannot clearly separate their influence. It is especially notable that the National Forest Concept is associated with *increased* forest degradation, since it included sustainability and protection as key elements. However, it may have also encouraged additional use by calling for "increasing the contribution of timber harvesting and processing to the national economy…" and "increasing contribution to the national economy from the exploitation of nontimber forest products and use of forests by their functional purposes…" (MENR Georgia, 2014). This would support a hypothesis that planned state cuttings are indeed important drivers of degradation even if household demand for fuelwood is not.

6.2. Policy implications

As the latest Forest Code is adopted and implemented throughout the country, we should pay attention to how enforcement is carried out in fuelwood-dependent communities, what options are presented to them, and how the tension between the illegality of forest cutting and the demand by government schools for wood for heating will be resolved. There is a planned mechanism under the new Forest Code passed in 2020 to create a mechanism for the sustainable provision of fuelwood and timber through NFA-operated business service yards (Torchinava, 2020). If market liberalization as a result of the Rose Revolution was the major institutional factor driving forest degradation, then it remains to be seen whether forest policy alone can meaningfully shift forest outcomes.

6.3. Future research needs

As questions of Earth system governance loom ever larger in the scholarly community and in policy discussions, research to investigate findings like the effects on forest degradation of the Rose Revolution and the policy reforms which followed will be important. These relationships should be investigated for robustness, particularly to better understand the mechanisms by which this political-institutional shift and the policies that followed could have impacted laws, economics, management, and norms around forests. The oil and gas price increases resulting from the Ukraine invasion will present another interesting natural experiment. If social cuttings are indeed a relevant driver of degradation, they would surely increase during the 2022–2023 winter season.

Our results also indicate that it is crucial to better understand the effects of winter temperatures and drought on montane temperate forests. Very little research on this subject has been done in the English language for the study region. From a forest management perspective, it will be useful to look to the findings of the ongoing forest inventory to assess how remotely sensed estimations differ from the inventory and to better understand the characteristics of degraded regions. Once forest degradation is available at the broader Caucasus scale, it will be possible to examine the importance of institutional and economic differences across countries.

7. Study limitations

As noted in the data and methods sections, there were severe constraints on the socio-economic data available, from shorter than desired time periods (data beginning in 2011 for the regional model), to exclusions based on politically-driven lack of data (Abkhazia and South Ossetia/Tskhinvali regions), to inherent uncertainty in variable accuracy (illegal harvesting). Since our approach was regression analysis for theory-testing, we elected to present models based on theoretical and practical considerations. The models we use are standard for exploring hypothesized drivers of land change, but do not allow for the evaluation of causality, since we do not look at specific event treatments or examine a specific causal chain, e.g., using structural equation models. Unfortunately, after our theoretical elaboration, many variables that we would have liked to include were not available or available only for one year or a few years instead of the full time period we desired. Additionally, model limits meant we had to drop variables in some cases, which are noted in the results section. We refer readers to the Supplementary Information to review these.

Overall, the three-month SPEI index was the most robust independent variable to changes in model specifications indicating that a lack of water availability is a major underlying driver of degradation through its effects on tree mortality. While there is little research on the Caucasus about this issue, it is supported by numerous other studies in temperate forests (Huang et al., 2015). The non-significance of many socio-economic drivers of degradation is surprising based on the prevailing narratives by experts we interviewed during the exploratory stage and do not match the theory related to smallholder-driven degradation processes. This result is interesting, yet considerable uncertainty remains given the lack of other published research on the region against which we could compare our results. It may also point to overall poor data quality for the socio-economic variables or to issues of scale, since we were limited to region (i.e., state) level estimates, which may overlook important sub-regional variation.

8. Conclusion

Increasingly apparent effects of climate change (IPCC, 2019) and the ongoing challenge of attaining the Sustainable Development Goals requires rigorous information about land-cover and land-use change in critical bioregions. Mountain ecosystems are important reservoirs of biological and cultural diversity, play unique and irreplaceable roles in watersheds, and are often undeveloped due to their unsuitable terrains. In the Anthropocene, understanding the drivers and impacts of human behavior within ecosystems is essential to designing and creating land systems that support multiple demands. Georgia and the Caucasus bioregion offer a useful recent institutional history that illuminates the potential of new land-cover change detection and classification techniques as well as the need for nuanced institutional analysis to incorporate diverse stakeholders in the governance of land.

In Georgia, as in other regions, it is easy to encounter a narrative that poverty alone pushes households to illegally cut trees for fuelwood, causing pockets of forest degradation over large areas. However, the available and relevant proxies for household access and demand for fuelwood examined in this study do not support this hypothesis. Instead, there is some uncertain evidence that forest degradation might primarily be driven by climatic factors, particularly drought, and institutional change after the Rose Revolution which we could not clearly isolate and test. Forest transition theory predicts that institutional reform and increasing GDP may relax pressure on the environment. Yet, the available data within the selected analytical framework did not strongly align with this. Future studies may show that it is the case, with delayed effects of institutional reforms as they become established and affect the intended biophysical systems, i.e., forests.

Given traditional reliance on many communities in Georgia and other fSU forests for wood, pastures, and foraging, as well as new opportunities for sustainable forest-based livelihoods (e.g., tourism), policies promoting transparent and multi-objective management of forests are urgently needed. However, these policies need to be based on sound scientific evidence about the existing drivers of ecosystem degradation and rural livelihoods or else they may further harm already relatively poor communities, while failing to improve ecological outcomes. The new Forest Code will ban household cuttings after 2023, yet our analysis provides little evidence to support the theory that such a ban would actually help reduce forest degradation. In addition, the law could pose significant harm to people without access or means to obtain energy from sources other than fuelwood. These impacts of this on rural livelihoods and forests should be carefully studied as the relative contribution of small-scale harvesting in the overall matrix of degradation drivers has not been clearly established.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2023.102775.

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