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# Taiga Landscape Degradation Evidenced by Indigenous Observations and Remote Sensing

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**Abstract:** Siberian taiga is subject to intensive logging and natural resource exploitation, which promote the proliferation of informal roads: trails and unsurfaced service roads neither recognized nor maintained by the government. While transportation development can improve connectivity between communities and urban centers, new roads also interfere with Indigenous subsistence activities. This study quantifies Land-Cover and Land-Use Change (LCLUC) in Irkutsk Oblast, northwest of Lake Baikal. Observations from LCLUC are used in spatial autocorrelation analysis with roads to identify and examine major drivers of transformations of social–ecological–technological systems. Spatial analysis results are informed by interviews with local residents and Indigenous Evenki, local development history, and modern industrial and political actors. A comparison of relative changes observed within and outside Evenki-administered lands (*obshchina*) was also conducted. The results illustrate: (1) the most persistent LCLUC is related to change from coniferous to peatland (over 4% of decadal change); however, during the last decade, extractive and infrastructure development have become the major driver of change leading to conversion of 10% of coniferous forest into barren land; (2) anthropogenic-driven LCLUC in the area outside obshchina lands was three times higher than within during the980s and 1990s and more than 1.5 times higher during the following decades.

**Keywords:** informal roads; Evenki; indigenous knowledge; development; unsupervised classification; spatial autocorrelation analysis

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## 1. Introduction

One byproduct of economic development in remote areas is the expansion of unofficial, or informal, roads constructed to access logging areas, drilling sites, and pipelines. Informal roads, in addition to industrial easements, also include other roads, trails, and paths, neither constructed, maintained, or regulated the government [1]. Expanding transportation infrastructure can improve accessibility and the extraction of natural resources, benefit social integration [2], and provide food and health security [3]. However, related rapid land cover and land use change (LCLUC) also increases wildlife mortality rates, forest and landscape fragmentation, hydrologic alteration, chemical, noise, light pollution, and can marginalize Indigenous peoples [4,5]. LCLUC impacts in regions undergoing rapid development are exacerbated by climate change. Northern hemisphere high latitudes have experienced air temperatures increasing at twice the global mean rate [6–8]. Ecosystem degradation and loss of biodiversity associated with LCLUC is particularly acute in fragile arctic and subarctic tundra and taiga environments prone to climate change, rich in natural resources, and home to Indigenous and other communities and cultures [9]. For example, in the taiga northwest of Lake Baikal, Evenki Indigenous peoples practice traditional subsistence activities including reindeer herding and husbandry, hunting large mammals and birds, and fishing [10]. These traditional livelihoods are significantly affected by the rapid LCLUC caused by the development of extraction industries, including mining, and logging [11–13], and the increasing number of wildfires, which have impacted millions of hectares of Siberian taiga [14,15]. Both wildfires and development have fragmented once-continuous swathes of animal habitat of vital importance to Evenki subsistence activities (Figure 1).

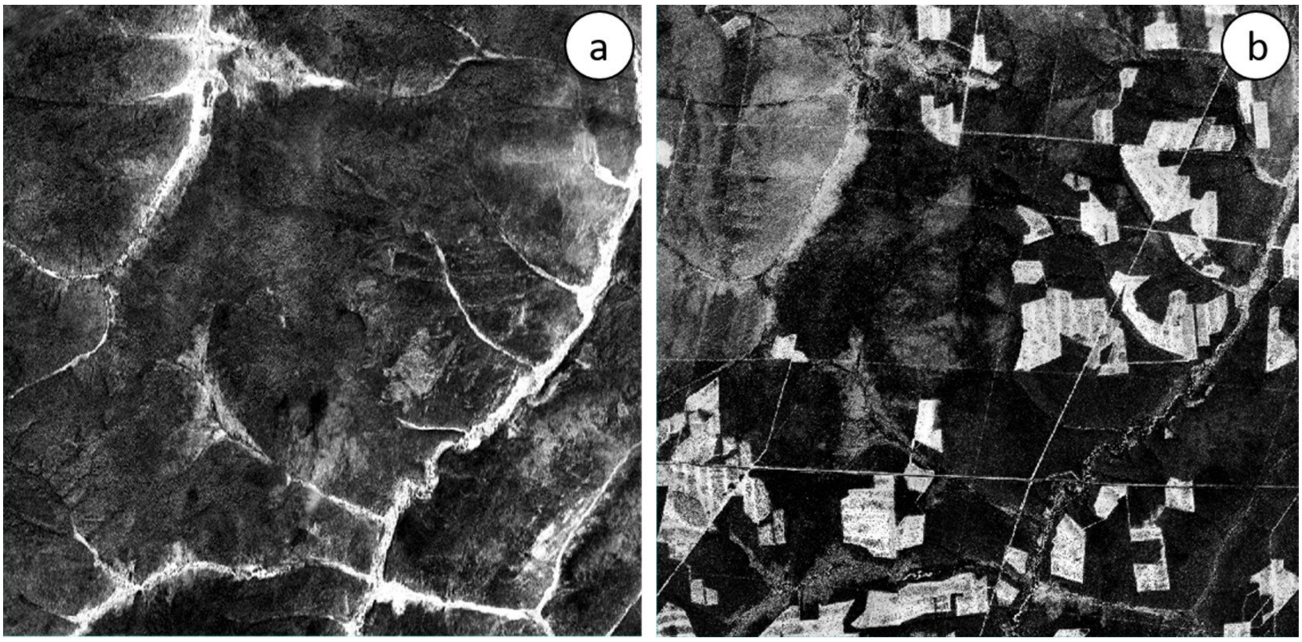


**Figure 1.** (**a**) 1964 CORONA image segment from within the study area, (**b**) the same study area segment in a 2018 Digital Globe image showing drastic LCLUC due to logging, geophysical exploration, and associated expansion of informal road networks.

Numerous studies have addressed LCLUC change in Siberian Forests [12,16,17], including indirect impacts related to political and socio-economic factors, such as population growth, poverty, weak governance, and transition from a planned Soviet to a market economy [18–20], as well as the effects of land use change on Indigenous communities [21]. Previous research in the area of interest has examined the effects of natural resource development on traditional livelihoods, including mining, and regulated and illegal logging [11–13]. These works found that, overall, forest degradation due to human activity has increased in the Irkutsk taiga over recent decades. Researchers found that millions of hectares have been destroyed by wildfires that are increasingly frequently being ignited by humans [12,14]. Meanwhile, a critical analysis of relations between local communities and natural resource extraction companies was conducted using the Irkutsk oil region as a study site [22]. These authors emphasized the intricate nature of the expanding oil industry in the region in terms of benefits and negative impact, where locals do not benefit equally from industrial expansion here, nor does industry represent a sustainable model. However, there have been no studies yet linking LCLUC with specific infrastructure changes, such as road network development.

This paper identifies interconnected LCLUC drivers using a social–ecological–technological systems, or SETs, framework. The SETs framework integrates socio-cultural, environmental, and technological perspectives to better understand complex interactions between environmental change and a variety of land use regimes, in this case, applied to understanding the drivers behind LCLUC observed from unsupervised classifications of Landsat imagery (Figure 2).

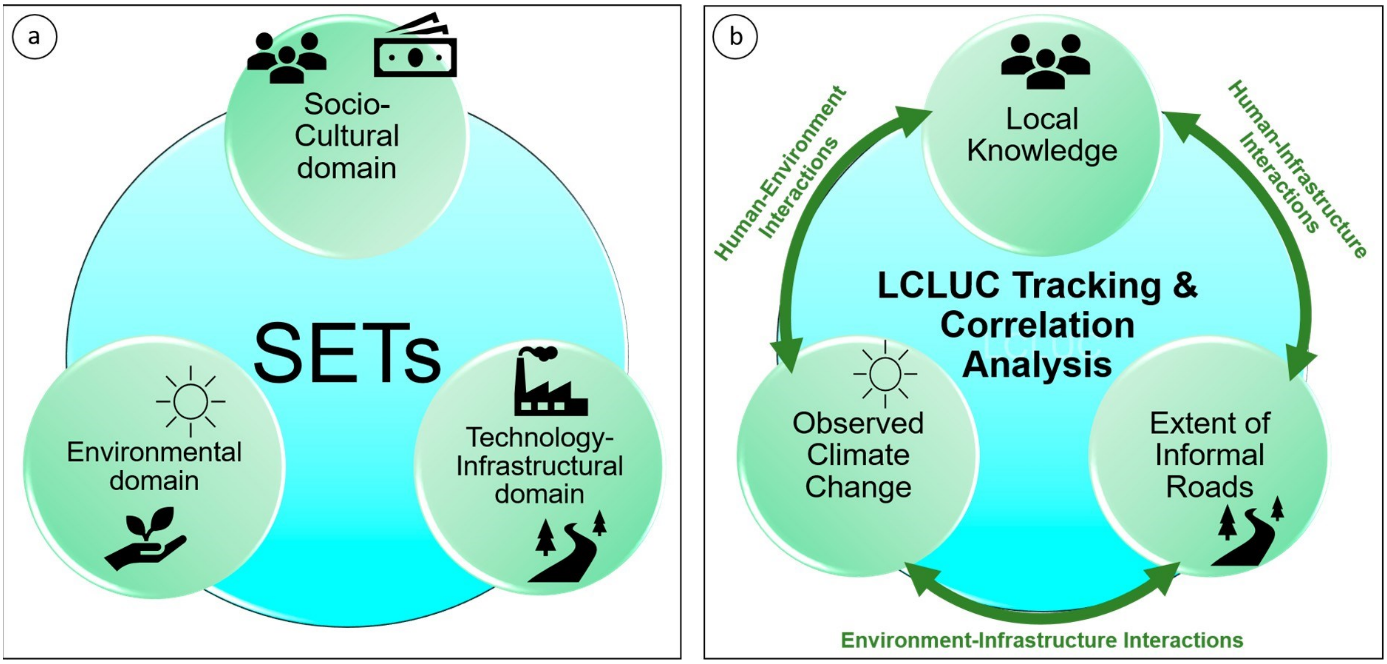


**Figure 2.** (**a**) Sociocultural, environmental, and technological systems (SETs) framework and (**b**) research aspects as applied within the SETs framework.

Each of the three SETs domains are interdependent, and impacts on each domain can produce systemic change [23,24]. In the context of this work, land covers represent landscapes undergoing rapid change under resource extraction facilitated by improved transportation technologies and infrastructure [23]. The primary objective of this research is to understand the complex interactions between landscape and political and economic regimes, ecological succession, and climate change using local and indigenous knowledge in the interpretation of remote sensing and spatial analyses. We explore these general themes by relating statistically significant spatial autocorrelations between particular changes in land cover and the expanding road network to long-term local and indigenous observations, climatic trends, and other published studies to discern the relative impacts of policies (anthropogenic activities) and natural processes. This paper offers an example of an effective application of the SETs framework for interdisciplinary studies and quantified evidence of the extent of landscape change as driven by policy decisions in the taiga surrounding Lake Baikal.

## 2. Study Area

### 2.1. Background on Evenki Obhschinas and Industrial Development

The study area (approximately 21,000 km$^2$) is in the fastest developing economic district of Irkutsk Oblast and includes the Evenki village of Tokma, the city of Ust-Kut, and part of the Yaraktinskoye and Ichodinskoie oil fields (Figure 3). This study area is within boreal forests, or taiga, that have been home to the Evenki Indigenous peoples for millennia [25–27].

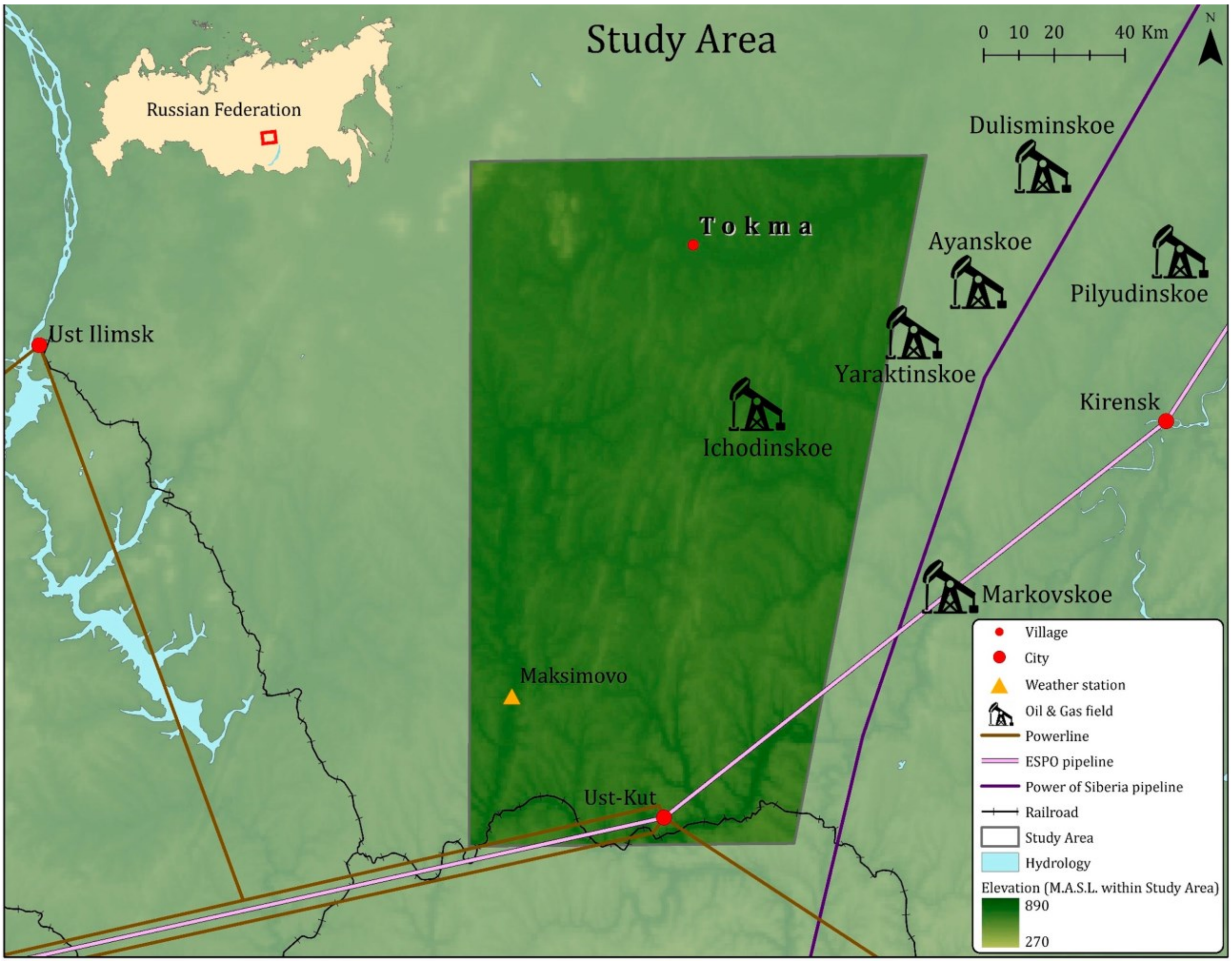


**Figure 3.** Study area within Irkutsk Oblast oil and gas fields. Cartography by Morozova A.O., May 2022. Data sources: [28,29].

Intensive LCLUC in the study area began with industrial development, spurred on by the construction of the BAM railroad in 1974, which attracted other industries [30–32], making Irkutsk Oblast one of the most significant production centers for the development of natural resources, including lumber, oil and gas, in the USSR. During the early stages of the BAM railroad construction, local railroad workers and Evenki collaborated on land surveying. For instance, railway workers rented reindeer from Evenki for the transportation of goods and materials to remote areas along the construction route [33]. However, increased labor migration, construction, and technological developments interfered with traditional land uses, particularly the excessive logging and poaching, which caused reindeer herding in the region to nearly cease, in turn contributing to a decline in the Evenki population [34]. Perestroika, the mid-1980s Soviet economic reformation, brought significant changes to national economic, political, demographic, and social structures by privatizing state-owned businesses. In 1991, the Soviet Union was dissolved [35], leading to a loosening of administrative control and the spread of informal and illegal land uses in the study area. At the same time, it was a period of cultural revival movements for Indigenous peoples. Regional Evenki associations were founded in the 1990s to protect and preserve their culture [36]. A federal law "On Territories of Traditional Nature—Use of the Indigenous small-numbered peoples of the North, Siberia, and Far East of the Russian Federation" was passed in May 2001 establishing the legal basis for allocating and protecting traditional territories for Indigenous communities [37]. According to the new law, Evenki are entitled to preferential rights to land use necessary for conducting traditional economic practices and pursuing traditional lifestyles [38]. The creation of *obshchinas*, a Russian term for non-governmental organizations, to support traditional activities has been the means of ensuring these rights formally, by allocating lands for traditional land use [39].

The favorable geographic location of the study area and its diverse natural resources has attracted international investors, particularly Chinese and Japanese lumber companies, since the 2000s [40]. Two major companies, the Irkutsk Oil Company and Igirma Forestry and Logging Company, are currently operating within the portion of the obshchina's land included in this study. The 2006 construction of the Eastern Siberia–Pacific Ocean (ESPO) oil pipeline connected the region with major Asian markets, promoting oil extraction and exploration in the region. The Irkutsk Oil Company (the main extractive company near the village of Tokma) plans to extend outside investment projects aimed at exploring and developing oil and gas fields [1]. Oil and gas deposits located in and near this study area are expected to become primary sources of Russian oil and gas exports in the near future [41–43]. Additionally, there is a federal plan to develop along the BAM railway, including the development of a new highway and ports to increase accessibility between this region and national and international markets [44]. Past and forthcoming development threatens the taiga, which is already stressed by fire, climate change, pasture expansion, mining, and logging [11]. These largely unfettered land uses in the region necessitate a detailed LCLUC analysis to inform sustainable practices and policy decisions.

### 2.2. Observed Climate Change

The study area has an extreme continental climate, classified as Dfb according to the Köppen Climate Classification System. Compared to similar latitudes in European Russia, Irkutsk oblast has significantly longer winters (snow cover may remain for up to seven months per year) and greater annual temperature variability. The extreme continental climate allows permafrost to persist. Discontinuous permafrost underlies much of the area [45], and elsewhere, soils regularly freeze to depths of up to 3 m in winter [12]. The winter, or cold season, lasts from November 1 (start of the Siberian hydrological year) to April 30, and the warm season from May 1 to October 31. Observations from the Maksimovo Village weather station (57.1° N, 105° E) inside the study area from 1981 to 2010 indicate significantly increasing mean warm season air temperatures. There have been no significant cold season trends in either mean air temperature or precipitation totals (Figure 4). The warming observed during the growing season has the potential to foster wildfires, increasing disturbance frequency in the region, and exacerbating landscape fragmentation.

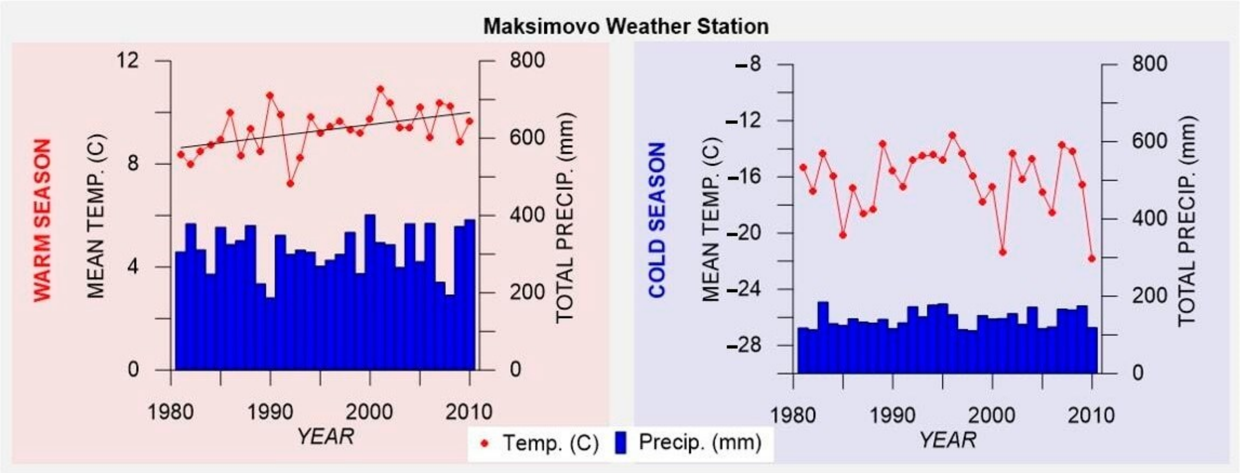


**Figure 4.** Maksimovo village weather station air temperature and precipitation observations from the warm (May 1 to October 31) season (**left** graph) and the cold (November 1 through April 30) season

(**right** graph). Mean seasonal air temperature in °C is plotted as points and total precipitation in mm as bars. Only warm season air temperature displays a significant trend over the 30 years observed ($p$-value < 0.01), indicated with a linear regression trend line. Data source: Russian Federal Service for Hydrometeorology and Environmental Monitoring.

## 3. Methods

### *3.1. Land Cover Classification and Accuracy Assessment*

An unsupervised land cover classification was used because it provides more consistent results for areas with little to no ground truth data [46] and has been successfully applied previously to study forest degradation and fragmentation [47,48]. Moreover, the unsupervised classification ensures higher accuracy, especially in distinguishing different vegetation types, even while using somewhat coarse resolution data such as Landsat. Google Earth, however, offers higher-resolution imagery for reference in classifying unsupervised pixel clusters and validation information in lieu of in situ data [49]. The Global Land Cover Database, created and hosted by Earth Resources Observation and Science (EROS) Center (2018) has 1 km spatial resolution, which is too coarse for an analysis focused on roads and their impacts. The last Global Land Survey (GLS) data sets were produced using a combination of Landsat 7 ETM+ and Landsat 5™ from 2008 to 2012, but do not capture the current land covers that are rapidly changing throughout southern Siberia. Meanwhile, the 2020 Sentinel-2 10 m Land Use/Land Cover product offered by ESRI is inconsistent in terms of spatial resolution and classification with historic maps, making it unhelpful for long-term change observations. Therefore, existing data products cannot be used for studies of land cover changes over several-decade time periods.

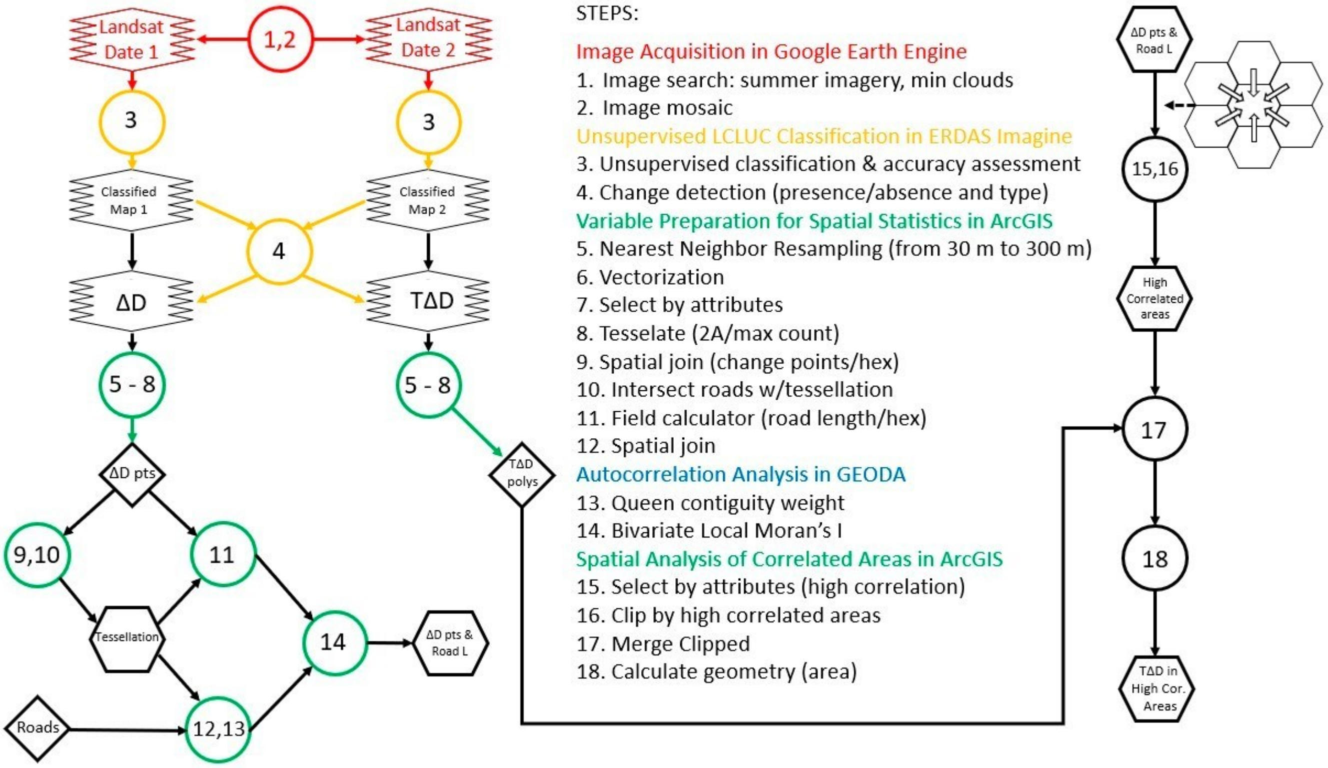
The Figure 5 workflow diagram illustrates step by step the land cover change classification procedure and spatial autocorrelation analysis between two time points, including the specific software packages used. These procedures were replicated for changes detected between decades of interest. Google Earth Engine was used to examine and acquire summertime Landsat scenes representative of the mid-1980s, 1990s, 2000s, and 2010s (Figure 5, Steps 1 and 2). Decadal intervals were chosen to align with major shifts in political and socio-economic regimes. Imagery specifics, including scene ID numbers, path and row designations, and acquisition dates, are provided in Supplementary Materials (see Supplementary Table S1 for data access).

With limited a priori knowledge or ground truth data from the study area, unsupervised classification was deemed appropriate to conduct in ERDAS Imagine v. 16.6.3 software using the ISODATA clustering algorithm. Five hundred spectral clusters were identified for manual classification by referencing true color displays of the Landsat images, geolocated field observations from a transect visited by other researchers, and higher-resolution imagery available from Google Earth and Bing Maps (Step 3).

Accuracy assessments for each of the four classifications were performed in ERDAS Imagine. Random validation points stratified proportionally by land cover class were exported from ERDAS and imported into Google Earth to identify in similar or higher-resolution imagery available through the timeline tool (Figure 5, Step 3). Sensitivity analysis with a weighted Kappa was also performed to measure the agreement between classified data and validation samples (Supplementary Table S2).

### *3.2. Informal Road Digitization*

The extents of recognizable formal, semi-formal, and informal road networks were manually digitized on the basis of 1985, 1995, 2005 and 2015 Landsat images and higher-resolution imagery available through Digital Globe as provided by the Polar Geospatial Center. This massive digitizing effort leveraged crowdsourcing of George Washington (GW) University students and other volunteers coordinated by the GW Humanitarian Mapping Society. These years were chosen based on the availability of clear winter images in which informal roads can be more readily recognized in cleared or trampled snow and to align with decadal land cover classifications. Digitized roads were validated by a research team member who had conducted multiple studies in the area of interest and students who had worked on the project for multiple years.



STEPS:

Image Acquisition in Google Earth Engine
1. Image search: summer imagery, min clouds
2. Image mosaic

Unsupervised LCLUC Classification in ERDAS Imagine
3. Unsupervised classification & accuracy assessment
4. Change detection (presence/absence and type)

Variable Preparation for Spatial Statistics in ArcGIS
5. Nearest Neighbor Resampling (from 30 m to 300 m)
6. Vectorization
7. Select by attributes
8. Tesselate (2A/max count)
9. Spatial join (change points/hex)
10. Intersect roads w/tessellation
11. Field calculator (road length/hex)
12. Spatial join

Autocorrelation Analysis in GEODA
13. Queen contiguity weight
14. Bivariate Local Moran's I

Spatial Analysis of Correlated Areas in ArcGIS
15. Select by attributes (high correlation)
16. Clip by high correlated areas
17. Merge Clipped
18. Calculate geometry (area)

**Figure 5.** Workflow diagram for unsupervised classification of land cover and land use (Steps 1–4) and spatial autocorrelation analysis between changed land covers over classified decades and road network density (Steps 5–18). The Google Earth Engine Code Editor was used to acquire, mosaic, and clip scenes to the study area boundaries. ERDAS Imagine 2020 v. 16.6.3 (Huntsville, AL, USA) was used to conduct the unsupervised classification, accuracy assessment, change detection (ΔD), and identify types of change (TΔD). GeoDa 2019 v. 1.14.0.24 (Chicago, IL, USA) was used for spatial autocorrelation between road network density and land cover changes.

### *3.3. Spatial Autocorrelation Analysis between Land Cover Change and Road Network Density*

A spatial autocorrelation analysis of LCLUC and road network density was performed on transitions between land cover classifications from the 1980s to the 2010s to associate changes attributable to either anthropogenic or natural drivers (climate change or other ecological processes such as succession post disturbance). Models to identify "change" (ΔD) and "type of change" (TΔD) available in the Imagine software (ERDAS Imagine 2020 v. 16.6.3) Model Maker tool were applied to identify change between classifications for each decade (Figure 5, Step 4). The coarsened change rasters from Step 5 (ΔD and TΔD) were converted to consistent hexagonal Theisen polygon tessellation in vector format (Figure 5, Steps 6–9). The tessellation cell size (0.41 km$^2$) was calculated using the Greig–Smith formula [50], where the total study area (21,201 km$^2$) was multiplied by 2 and divided by the total number of points ($n$ = 102,687) in the distribution, or the maximum count of pixels where change was observed to be incorporated in the tessellation. Total road length crossing and within each hexagon was also calculated using the dissolve, intersect tools, and geometry tools followed by a spatial join to append the road length attribute data to the corresponding hexagon (Figure 5, Steps 10–12).

The correlation analysis was performed in GeoDa 2019 v. 1.14.0.24 software to determine spatial relationships between road network density and land cover dynamics based on the hexagon tessellation containing both counts of changed land cover pixels and total road length using a Bivariate Local Moran's I according to a first order Queen's

Case spatial relationship (Figure 5, Step 13). The independent variable was defined as road network length, and the dependent variable was the land use change point count applying a significance filter $p$-value of 0.01. The sensitivity of significant correlation locations to the number of permutations was also assessed and results were based on a 0.05 $p$-value significance filter for 9999 permutations [50,51] (Figure 5, Step 14). A change type model was used to determine the type of land cover change associated with high correlation areas between each out of four decades (Steps 4–6 repeated for the correlation output).

### 3.4. Interviews with Local and Indigenous Residents

Local and Indigenous observations were obtained by means of interviews with eighteen local community members, including Evenki and old settlers, conducted by an author who visited the study area in 2020 and 2021. In-depth, semi-structured interviews focused on road development and its impacts on the environment and subsistence activities. Respondents were recruited using the authors' existing professional networks and snowball methods, with informed consent being provided in accordance with the George Washington Institutional Review Board (IRB) protocol and Ethical Principles and Guidelines for the Protection of Human Subjects of Research. All interviews were transcribed, coded, and analyzed to identify recurring topics using NVivo v. 11 software. Project participant observations from traveling informal roads within the study area in winter and summer seasons were also used in discussing the results of this work.

## 4. Results

### 4.1. Land Cover and Land Use Mapping and Change Analysis

The unsupervised classifications yielded four classification maps spanning 33 years (1986 to 2019) (Figures 6 and 7b).

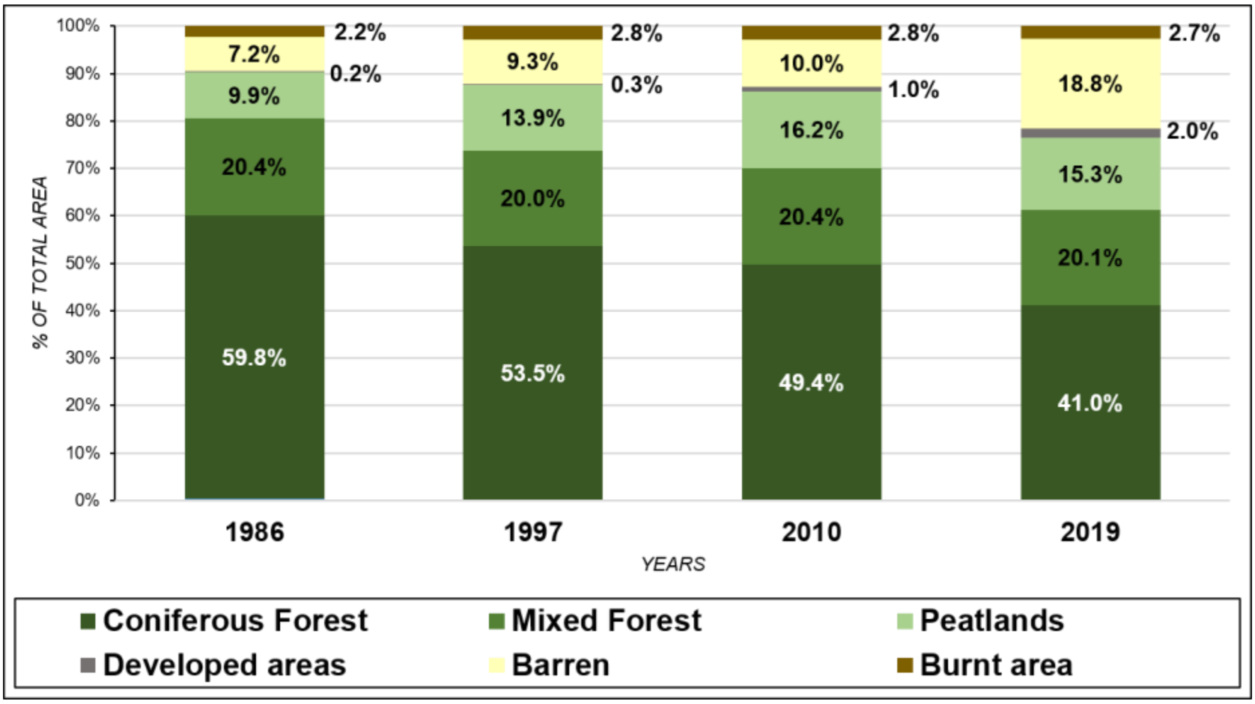


**Figure 6.** Areal land cover proportions classified for each time period (1980s through 2010s) in the study area. Surface hydrology occupy less than 0.3% of the study areas and remained relatively consistent over the observation period and therefore is not displayed on graphs.

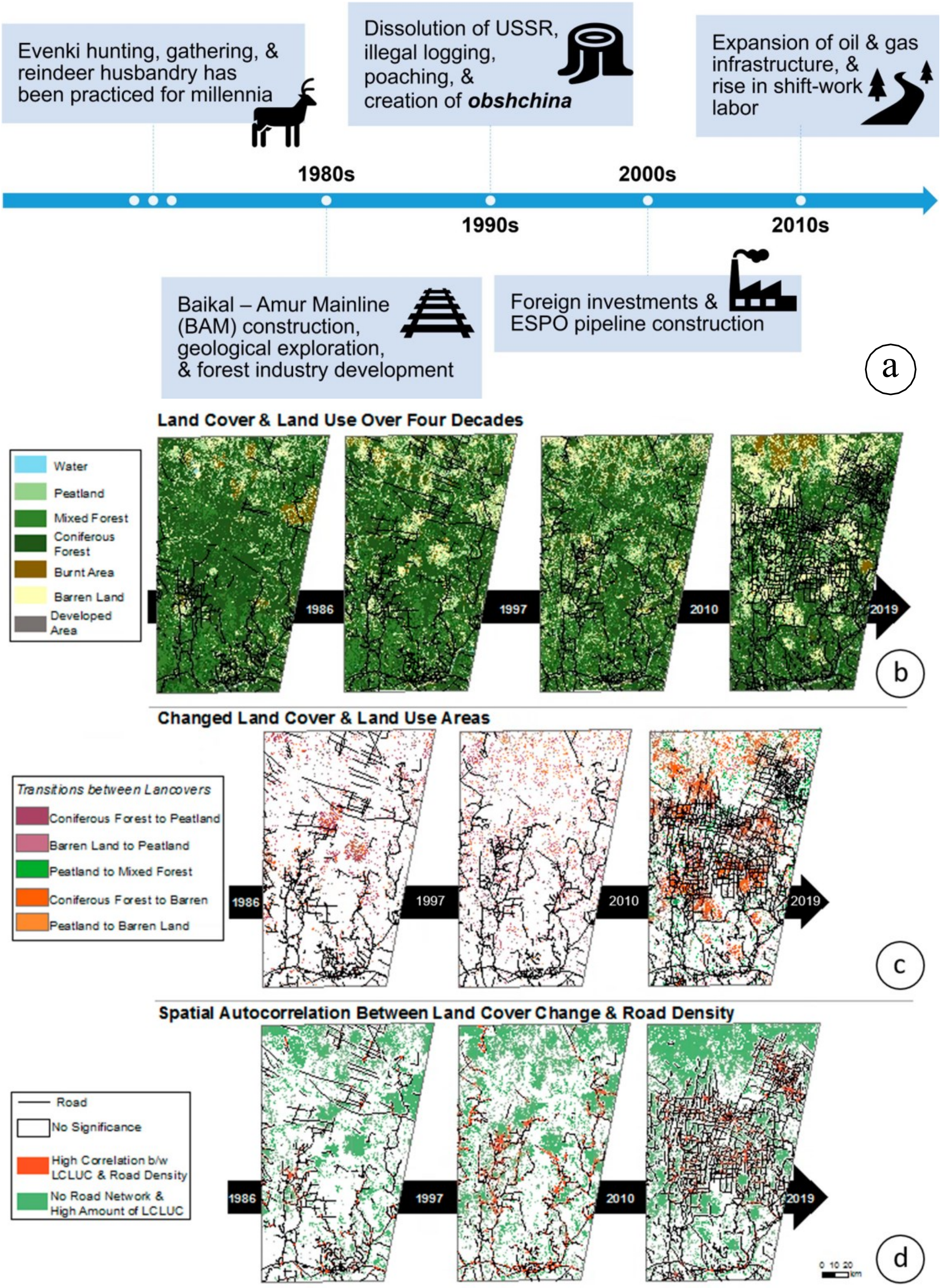


**Figure 7.** (**a**) Socio-economic and political history of land use regimes in the study area; (**b**) land cover and land use change observed (years listed indicate Landsat acquisition) from the mid-1980s to 2019 with rapid expansion of the manually digitized informal road network; (**c**) land cover changes constituting at least 3% of the total study area between classifications; (**d**) spatial autocorrelation between observed land cover change and road density, where orange areas are areas of land cover change significantly correlated with dense roads, or anthropogenic drivers, and green areas are changes significantly correlated with a lack of roads, or natural drivers.

The generalized timeline of land use regimes (Figure 7a) provides historical context for documented landscape disturbances including pervasive clear cutting and road ex-pansion due to deregulation following the dissolution of the Soviet Union that proliferated with new foreign investment into the 2010s. Areal proportions of classified land covers from each decade shown in Figure 6 highlight how coniferous forests decreased by 19%, or approximately 4030 km$^2$, while mixed forest stands have remained relatively un-changed. Peatlands increased by 5% of the total study area (approximately 1060 km$^2$) and barrens increased by 12% (approximately 2540 km$^2$). Built up areas also increased by 1.8% (about 382 km$^2$). The rapid development in this region is better captured by the manually digitized informal roads which expanded by roughly 4,400 km. Surface hydrology includes lakes and ephemeral streams [52] occupying less than 0.3% of the study area at any time point examined and were therefore not displayed.

### 4.2. Land Cover Change and Road Density Spatial Autocorrelation Analysis

Classifications were deemed acceptable for further spatial analysis after accuracy assessments were conducted. Calculated Kappa coefficients for all classifications >0.8 were interpreted as representing a strong agreement between predicted and observed land covers [53,54]. Additionally, overall accuracies for these four classifications were greater than 86% (Supplementary Table S2). A $p$-value of 0.01 was chosen as a significance filter during the correlation analysis between road development and LULCC, considering that this might be due to random error or phenomena that may not be related. Subsequent change detection and correlation analysis are illustrated in Figure 7b,c. Symbology on the change detection maps include purple hues to symbolize land cover transitions likely climate driven, green for ecological succession, and orange for change likely due to anthropogenic activities (e.g., wildfire or development). These change maps show three distinct trends: (1) fire activity and industrial development leading to transition from coniferous forest and peatlands to barren land; (2) peatlands transitioning to coniferous and mixed forest (likely secondary succession and the transition from pioneer or intermediate returning to climax vegetation communities); and, the most dominant trend, (3) deforestation where coniferous forest has transitioned to barren or peatland.

Figure 7d cluster maps show the spatial autocorrelation of land cover change compared to road network density. Orange on these maps represents areas with significant LCLUC in close proximity to dense informal roads. Green areas represent LCLUC correlated with a lack of roads in immediate surroundings, or changes interpreted as likely due to natural or climate change. Regardless of road network presence, coniferous deforestation is apparent throughout and across large extents.

### 4.3. Analysis of Interviews in the Study Area

Interviews with Evenki and other experts familiar with the study area confirm trends observed from the remote sensing and spatial analysis and reveal many concerns about continued logging and oil and gas development (Table 1). In terms of road network development, these concerns were largely based on observations that roads are being widened by companies to improve access for large vehicles. Subsistence activities along these roads and wildlife habitat are disturbed by this construction and locals can no longer use the routes once industry increases their use and/or restricts access to roads for outsiders.

Considering the results of the spatial statistical analysis in the context of local long-term observations demonstrates the limited control of Indigenous communities over their traditional lands in terms of any of the three SETs domains, socio-economic, environmental change, or infrastructure development. Decades of largely unfettered land use have negatively impacted Evenki traditions and livelihoods in ethno-tourism, hunting, and fishing. The Irkutsk Oil Company and Igirma affirm provision of financial and material support to the Tokma residents. However, locals consider this to be little compensation for the severity of damages inflicted on the environment. With limited access to education, Evenki were less likely to be hired by service, sales, or mining industries. Today, only a few Evenki are employed by these companies, and those few are employed as either security guards or janitorial staff removing any financial benefit for Evenki to counter the damages incurred on their traditional lands [33]. The Evenki obshchina's leadership are now trying to bring employment discrimination and environmental degradation issues to government and public attention. These leaders must also compete for government funding and job opportunities, causing disagreements within Indigenous communities themselves, exacerbating an already-vulnerable people in cases manipulated by both local administrations and companies [34].

**Table 1.** Quotes from interviews with local and Indigenous residents illustrating interconnected domains of the SETs framework via drivers of change and related impacts. Interviews were conducted by Dr. Kuklina, August 2021.

| | | **Change Driver** | | |
|---|---|---|---|---|
| | | **Human** | **Environment** | **Infrastructure** |
| **Impacted SETs Framework Domain** | **Human** | "We don't see these people [outsiders] … There are so many of them, they have the type of equipment capable of mowing down so much in two days—the area becomes unrecognizable … " (70-year-old male Tokma resident, March 2020) | "They [extractive industries] negotiated a security agreement with us. Two hunters work in shifts: one works for a month then switches with the other. Living conditions are rough … " (55-year-old female, Magistralny, August 2021) | "You can't leave firewood unattended there. Nothing can be left in areas that can be reached by roads. You don't want to leave anything behind, not even dishes or a spoon. Things that are left get stolen!" (30-year-old male, Vershina Khandy, 30, August 2019) |
| | **Environment** | "They cut down the good forest, you see. Animals are leaving. There is so much noise … The Siberian moose is almost gone now, so to say. The reindeer is gone, too. Well, there is still reindeer, but very few … " (70-year-old male, Tokma, March 2020) | "They say that Manchurian elk appeared in the forest as soon as loggers started to cut the trees. We had never had any … They say that they [Manchurian elk] are pushing them [moose] away and for some reason they are replacing the moose … " (70-year-old male, Tokma, March 2020) | "It is common to see bears walking along the road and wapitis and deer, typically crossing the roads. Black and wood grouse are often seen flying over the roads. Sometimes the wood grouse walks along the road undaunted … " (55-year-old female, Magistralny, August 2019) |
| | **Infrastructure** | "The road that runs along the pipe is considered administrative, and it is hard for residents to get on it. There are usually barriers with security guards along the road … It is dangerous to allow people on the service road, but there isn't an alternative road … " (Interviews with representatives of Ust-Kut municipality, August 2019) | "The movement of the all-terrain vehicles makes it easy for the wolves to move around the area … Therefore, deer cannot inhabit here; it is either driven out by wolves or vehicles." (40-year-old male, Magistralny, August 2021) | "They seem to be expanding the service roads by using adjacent informal roads, previously used by geologists, and now used by hunters for setting up traps. As a result, upon returning to the area, you often find a new road that is 7 times wider than before, with no hunting traps." (50-year-old male, Tokma, March 2020) |

## 5. Discussion

Accuracy assessments for each of the eight land cover classifications (four decadal classifications for each of the two study areas) were performed in ERDAS Imagine 2020 v. 16.6.3 software by generating random points stratified by class. This method is the most widely used, as it allows a minimum number of sample points within each class. Classes occupying less area (e.g., water and burnt areas) were given a minimum of 10 samples compared to classes occupying greater spatial extents that were assigned 50 random sample points. Validation points generated in ERDAS Imagine software were exported to an Excel file and added to the Google Earth for identification at a higher-resolution imagery sometimes available using their timeline tool.

The contingency, or confusion, matrices generated for each classification included producer's, user's, overall accuracy, and Kappa agreement statistics. The Tokma study area classifications demonstrate low user's and producer's accuracies for built-up areas, peatlands, and barrens (Supplementary Table S2). Sparsely vegetated areas classified as barren are spectrally similar to some peatlands depending on moisture which may account for some of these accuracy issues. There is some confusion between the two types of forest, which could be related to the transition zones from boreal taiga forest to mixed forest. Most fire activity was accurately classified, and was rarely mistaken for barren areas and open soils.

Considering the classification issues, a sensitivity analysis with a weighted Kappa was also performed to measure the agreement between the classified data and the validation samples. Given that all Kappa coefficients for the eight individual classifications were greater than 0.8, this can be interpreted as suggesting a relatively strong agreement between the predicted and observed classifications. Additionally, given all of the overall accuracies were greater than 86%, all were deemed acceptable for further change detection and correlation analysis.

LCLUC analysis shows significant deforestation across the study area, specifically the conversion of coniferous forests to barrens or peatland regardless of proximity to roads. Areas of high correlation between LCLUC and dense roads in the north-east are attributed to the Yaraktinskoe oil and gas field development. The detected fire activity can be attributed to natural sources including lightning strikes, but is increasingly due to anthropogenic sources such as exhaust sparks thrown from roads in dry peatlands [55]. For more detailed analysis on significant changes in area occupied by each land cover for the decadal time steps observed and likely associated driver refer to the related master's thesis [56].

Several studies have determined that the main types of disturbance in boreal forest cover include direct (e.g., fires, infrastructure expansion, logging, and mining) and indirect causes (e.g., political and socio-economic factors, such as population growth, poverty, and weak governance) [11]. Overall, human-driven deforestation has increased rapidly in the Irkutsk taiga, especially in the late 1990s and early 2000s [12,18]. However, available studies within the study region lack the socio-cultural component that would make it possible identify the pressing issues and Indigenous narratives addressed in this work. Meanwhile, this information is crucial for understanding links between land cover and land use. In particular, analysis of interviews helped to better establish the cause of deforestation and link it to the road network expansion. The latter has not yet been a focus of regional researchers. Moreover, it made it possible to indicate the effects of environmental protection within the territories dedicated to the Evenki traditional land use. While existing research on the territories of traditional land use is usually quite pessimistic [37], we find them to be effective to a certain degree. Additionally, we find it critical to draw the reader's attention to the disproportionate impact of these territories by natural change which can be considered part of the climate change—indirect human impact generated by industrial development elsewhere. As a result, this research emphasizes the necessity of collaborative research with Indigenous communities to improve quality of LCLUC studies both in the study region and elsewhere.

The beginnings of spatially extensive land use changes over the 33-year observation period are related to the transition to a market economy in the 1990s, when all state-owned and cooperative farms were corporatized. The legal rights attributed to small-numbered Indigenous populations, especially in terms of recognition of land use and property rights, are in reality rarely honored. Extractive industries operating in traditional land use areas are required to receive consent from the respective obshchina(s) prior to any development, but this requirement is not enforced [57]. Limitations on preferential rights for small-numbered Indigenous peoples are compounded by minimal funding to support Evenki socio-economic development [34]. The strong connections between the three SETs framework domains are evident when considering the cumulative LCLUC documented by this work within the Evenki obshchina's regionally designated territories for traditional land use (Figure 8).

Table 2 provides an alternative quantification of anthropogenic and naturally driven change observed within and outside the obshchina included in the study area. Obshchinas were established in sync with the increase in development following the dissolution of the Soviet Union. This provided an opportunity for obshchina members to effectively shield some key areas for subsistence activities from development by the oil and gas industries [58].

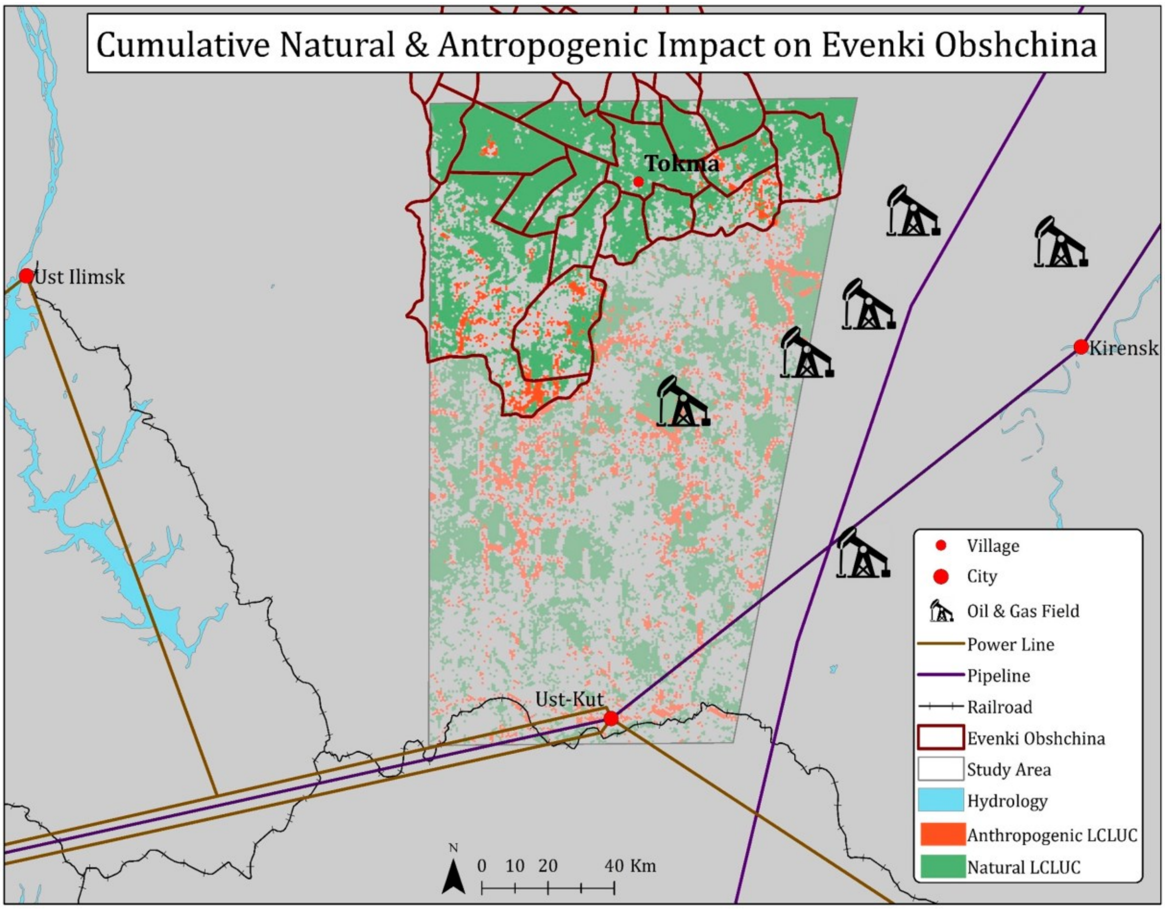


**Figure 8.** Cumulative LCLUC within obshchinas in the study area. Similarly to Figure 7d, green and orange areas on the map represent LCLUC interpreted as anthropogenically driven, or correlated with roads (orange) and those interpreted as naturally driven, or not correlated with roads (green).

**Table 2.** Cumulative anthropogenic and natural impact on total territory of obshchina and individual farms.

| **Driver** | **Anthropogenic** | | **Natural** | |
|---|---|---|---|---|
| | Within obshchina | Outside of obshchina | Within obshchina | Outside of obshchina |
| Years | 1986–1997 | | | |
| Changed Area % | 0.6 | 1.7 | 32.8 | 18.1 |
| Years | 1997–2010 | | | |
| Changed Area % | 3.6 | 5.7 | 42.8 | 22.6 |
| Years | 2010–2019 | | | |
| Changed Area % | 2.6 | 4.0 | 50.6 | 18.72 |

As a result, anthropogenic-driven LCLUC had an impact three times higher in the area outside the obshchina's land than within it during the 1980s and 1990s, and this figure was more than 1.5 times higher during the following decades. This relative difference in impact by area is significantly reduced in the 2000s and 2010s. The analysis suggests that additional restrictions for industrial development within the territories of Evenki traditional land use are effective, and decrease the degree of human disturbances. Simultaneously, however, obshchina territory appears to be disproportionately impacted by natural change drivers throughout all the observed time periods. The largest anthropogenic impact observed within the obshchina was between 1997 and 2010, when large capital businesses operating in the region redistributed properties between private business groups and state corporations. From 2010 to 2019, there was also evidence of increased wildfires within the study area, possibly due to either natural processes or anthropogenic activities.

Infrastructure development, and particularly the rapid expansion of informal road networks to support the Irkutsk Oil Company wells and pipelines and Igirma logging sites, have a variety of impacts, improving short-term mobility for some and restricting them for others through landscape fragmentation and increased security. Outside of private industry development, federal financial assistance prioritizes the extraction industries. Federal funds, including those allocated for Indigenous communities, are largely aimed at restoring infrastructure to build regional capacity rather than environmental protection, restoration, or education and health services [33]. Regional capacity building has included repairing power lines and emergency buildings, private residential housing construction, and purchasing water trucks. The collision of subsistence community land use interests with government-supported industrial development does not bode well for the adoption of equitable and effective sustainable land management policies.

## 6. Conclusions

This research demonstrates the importance of considering a holistic suite of LCLUC drivers and an effective application of the socio-cultural, environmental, and technological, or SETs framework, to marry Indigenous and local knowledge with remote sensing. Interactions between domains are demonstrated by changes in land use and land cover. In particular, Evenki traditional land use activities have been increasingly disturbed by economic development and changes in political and land use regimes. The importance of the technology–infrastructural domain is exemplified in this study area by construction of the BAM railroad which promoted oil and gas exploration through rapid deforestation and significant rural and urban development during the 1970s and 1980s. Transportation network development, while fundamentally changing traditional lifestyles, has facilitated communication and transport of goods, and improved access to services [34]. The national economic crisis of the 1990s, accompanied by poaching and illegal logging, led to depletion of subsistence resources. During the 2000s and 2010s, the oil and gas industries grew dramatically, expanding the informal road networks within the Evenki obshchina. These disturbances to taiga landscapes are likely to continue with the development of informal roads, leaving local communities with limited ability to use, monitor, or protect subsistence resources [43]. Climate warming will further complicate SETs domain interactions and exacerbate land cover change through positive feedback mechanisms. While development is currently a primary LCLUC driver in the study area, climate change can potentially supersede anthropogenic drivers in time given the severity of projections.

Holistic approaches such as this offer insights into complex interrelationships between different regional and global actors influencing landscape change and the breadth of impacts on sensitive environments and peoples. The limitations of the SETs framework and particularly biases exist when examining each of the incorporated domains (socio-cultural [59] and technology–infrastructural [60]) in addition to the environmental (e.g., Foody 2002). Future research should incorporate more local and Indigenous knowledge to address local concerns and provide invaluable contextual information such as long-term observation as seen in this application of the SETs framework. In addition, informal road network expansion in remote areas has still been insufficiently explored and documented [1]. Incorporation of higher-resolution imagery and map validation using ground truthing are needed for more accurate maps and quantification of change.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15031751/s1, Supplementary Table S1: Landsat imagery acquisition data, Supplementary Table S2: Confusion matrices for (A) 1986, (B) 1997, (C) 2010, and (D) 2019 classified thematic maps of the study area, including the overall, user's, producer's, and kappa accuracy statistics.

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**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study. Respondents were recruited using the authors' existing professional networks and snowball methods with informed consent in accordance with the George Washington Institutional Review Board (IRB) protocol and Ethical Principles and Guidelines for the Protection of Human Subjects of Research.

**Data Availability Statement:** The data presented in this study are available in [56].

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