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Long-term trends in anthropogenic land use in Siberia and the Russian Far East: a case study synthesis from Landsat

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Abstract

As globally important forested areas situated in a context of dramatic socio-economic changes, Siberia and the Russian Far East (RFE) are important regions to monitor for anthropogenic land-use trends. Therefore, we compiled decadal Landsat-derived land-cover and land-use data for eight dominantly rural case study sites in these regions and focused on trends associated with settlements, agriculture, logging, and roads 1975–2010. Several key spatial–temporal trends emerged from the integrated landscape-scale analyses. First, road building increased in all case study sites over the 35-year period, despite widespread socio-economic decline post-1990. Second, increase in settlements area was negligible over all sites. Third, increased road building, largely of minor roads, was especially high in more rugged and remote RFE case study sites not associated with greater agriculture extent or settlement densities. High demands for wood export coupled with the expansion of commercial timber harvest leases starting in the mid-1990s are likely among leading reasons for an increase in roads. Fourth, although fire was the dominant disturbance over all sites and dates combined, logging exerted a strong land-use pattern, serving as a reminder that considering local anthropogenic landscapes is important, especially in Siberia and the RFE, which represent almost 10% of the Earth's terrestrial land surface. The paper concludes by identifying remaining research needs regarding anthropogenic land use in the region: more frequent moderate spatial resolution imagery and greater access to more finely resolved statistical and other spatial data will enable further research.

Social media abstract

Landsat reveals long-term anthropogenic land-use trends in Siberia and Russian Far East

1. Introduction

The present global era, the 'Anthropocene,' is one of unprecedented human-driven change, with its intensification since the 1950s termed the 'Great Acceleration' (Steffen *et al* 2015, Zalasiewicz *et al* 2015). In the industrializing world, population growth, urbanization, agricultural land conversion, road building, and exploitation of natural resources dominate; in post-industrial regions, the greatest trend is increased consumption. These anthropogenic dynamics have regional to global effects. Yet, it is at the local landscape level that the interactions between humans and Earth's natural features occur, and these create the patterns and consequences that emerge at broader scales (Lambin and Geist 2006).

The globally important and predominantly forested landscapes of southern Siberia and the Russian Far East (RFE) lie within a region of northern Eurasia experiencing considerable recent socio-economic

upheaval (Newell and Henry 2016). In one of the most rapid manifestations of the mid-20th century Great Acceleration recorded globally, industrial-scale agricultural collectives and forestry enterprises were created out of the wilderness, and populations swelled from in-migration (Naumov 2006). Heights of state-sponsored development and resource extraction were reached in the 1970s–1980s (figure 1). Dissolution of the USSR command economy in 1991 led to an extended period of socio-economic instability and depopulation (figure 1, World Bank 2002). Today, changes driven partly by natural resource–hungry Asian and other countries are poised to further shape the region's landscapes (Newell and Simeone 2014, Liang *et al* 2016, Sysoeva 2019).

At the landscape scale, case study sites based on time series of remotely sensed imagery matching key socio-economic eras have become an important approach in mapping and analyzing anthropogenic land use and trends in global regions (Lambin and Geist 2006, Magliocca *et al* 2015). Moderate spatial resolution multispectral sensors such as Landsat (TM/ETM+/OLI at 30 m, MSS at ~60 m; supplementary material table A; available online at stacks.iop.org/ERL/15/105007/mmedia) are often preferable for observing land uses anthropogenic in origin and occurring at small or fragmented feature sizes yet over relatively large landscapes (Zhao *et al* 2009). The Landsat record (1972 to the present) is the primary source of moderate spatial resolution imagery encompassing major socio-economic eras for the former USSR (Gutman and Masek 2012).

Land uses associated with dramatic socio-economic changes are well studied using the Landsat record in other regions of the former Soviet Bloc, especially Eastern Europe. There, analysis of spatial–temporal observations uncovered trends, including those of logging, agricultural land abandonment, other agricultural land change, and reforestation (Kuemmerle *et al* 2008, 2009a, 2009b, 2011). Such results also provide evidence of how trends and couplings in land use have varied by socio-economic era, as well as by country, region, or landscape characteristic (Baumann *et al* 2011, Müller and Kuemmerle 2009a, 2009b, Prishchepov *et al* 2013).

Comparatively less is known from Landsat for Siberian and RFE anthropogenic landscapes (but see Achard *et al* 2006). Incomplete Landsat coverage prior to ~2000, image cloud contamination, poor access to ancillary data, and a geographically large area present obstacles (Bergen *et al* 2008, Loboda 2009, Wulder *et al* 2016). Yet, a handful of local case studies (each up to 1–3 Landsat scenes in area) have investigated one or more anthropogenic land uses of logging, agriculture, rural urban settlements, and roads. (Bergen *et al* 2008) observed declines in clearcut logging post-1990, plus the transition of some agriculture land use to woody encroachment. Several studies suggested that logging targeted remaining old/mature conifer forest (Bergen *et al* 2008, Cushman and Wallin 2000, Dyukarev *et al* 2011). Non-clearcut logging methods were reported by (Shchur *et al* 2017) in west Siberia and inferred by (Johnson 2014) in southernmost RFE, in contrast to large-scale clearcutting in central Siberia (Bergen *et al* 2008). Two case studies quantified the importance of roads and rural settlements (Peterson *et al* 2009, Hitztaler and Bergen 2013). (Pflugmacher *et al* 2011) and other case studies captured fire disturbance but generally deferred its definitive assessment to higher temporal coarser spatial resolution sensors.

While informative within their respective Siberian and RFE sites, the findings from these separate landscape-scale case studies have remained isolated from each other and limited by incomplete representation of anthropogenic land uses. However, through a synthesis combining multiple case study sites and a fuller set of anthropogenic land-use data, we can potentially better answer emergent questions, such as: What are the fundamental characteristics and magnitudes of the region's land uses that are primarily anthropogenic in origin? How do these vary over geographic strata? How do they vary over time by socio-economic eras? And ultimately, what key land-use trends emerge from considering multiple anthropogenic land uses over multiple sites together? Answers to these may also shed greater light on specific questions raised by the earlier studies related to settlement dynamics, agricultural abandonment, logging practices, drivers of road building, and the relative influences of fire and logging.

Therefore, our goal was to complete a quantitative synthesis of existing and new land-cover and land-use (LCLU) data 1975–2010 (approximately decadal) across multiple legacy case study sites, each nominally the extent of a Landsat scene (~185 by 185 km), and with analyses informed by the prior work in these sites. We implemented this synthesis through three objectives:

(a) Create comparable decadal LCLU data inclusive of settlements, agriculture, logging, roads, and fire for eight dominantly forested Landsat case study sites. Also, compile annual time series of province-level socio-economic statistics representative of the above land uses for context.
(b) Quantify trends in anthropogenic land-use proportions and magnitudes over time and by geographic strata; further investigate several specific anthropogenic land-use questions. Considering the multiple sites together, identify key coupled spatial–temporal relationships.
(c) Summarize what questions regarding the anthropogenic landscape have been addressed through Landsat case study data and synthesis to date and what questions are

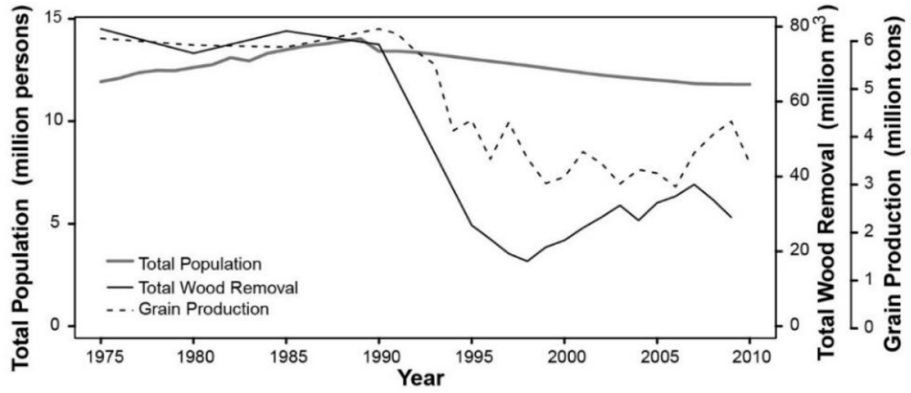

Figure 1. Trends 1975–2010 in population, plus forestry and agriculture indicators, for the combined provinces of Tomsk, Krasnoyarsk, Irkutsk, Zabaykalsky, Amur, Primorsky and Khabarovsk (Park 2013, Rosstat 2013).

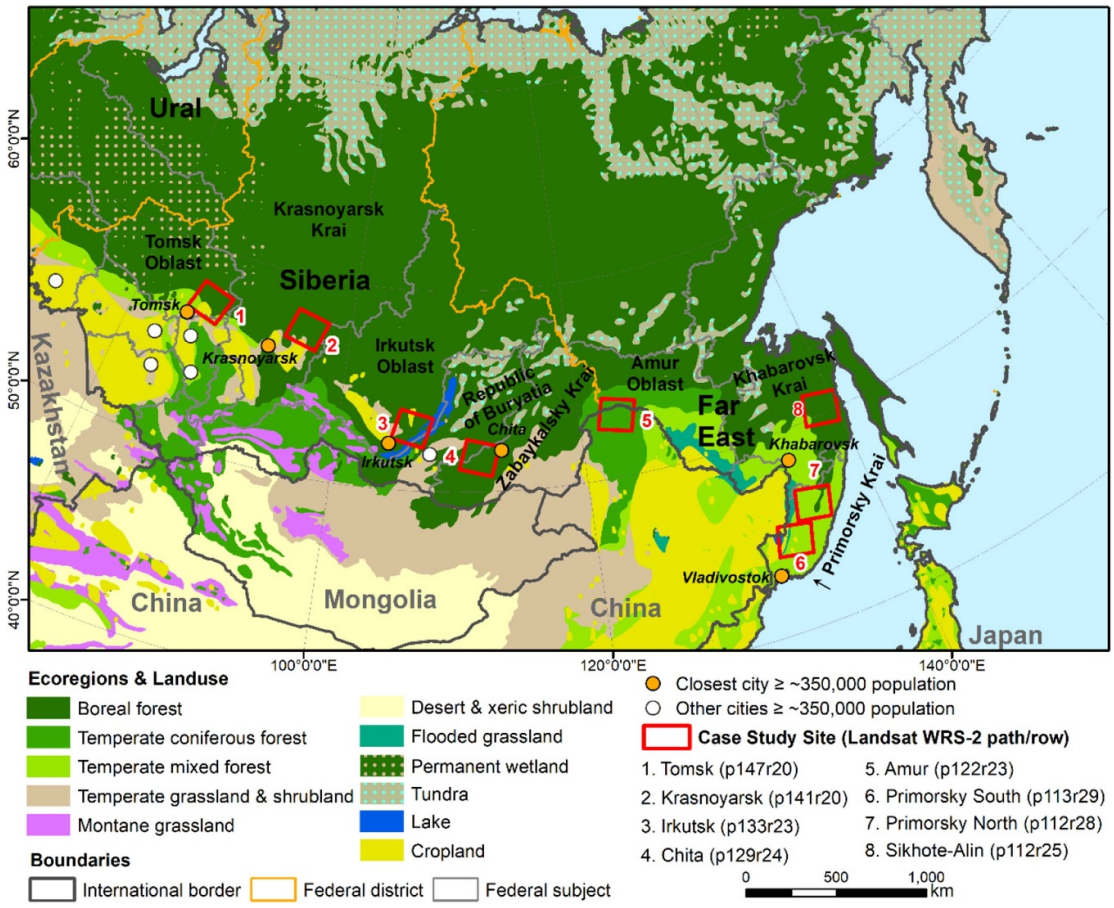

Figure 2. The southern Siberia and RFE case study sites within broader northeastern Eurasia administrative and ecological regions. Ecoregions are potential vegetation types (WWF, Olson *et al* 2001). Also shown are anthropogenic cropland land use from MODIS LAND (Friedl *et al* 2010) and locations of nearby very large metropolitan centers ⩾ ~350 000 population during the study eras.

still outstanding—and how these might be addressed.

2. Study region

Geographically, the lands of the Russian Federation east of the Ural Mountains are partitioned into Siberia and the RFE. Administratively, this area is divided into three Federal Districts: Ural, Siberian, and Far Eastern. Our study focuses on the latter two (hereafter Siberia and RFE) and in particular on the seven Krais, Oblasts, and/or Republics (hereafter provinces) within them that have the most important forest resources of these districts. Due to the short growing season in northern Siberia and the RFE, the majority of productive lands are concentrated in their southern parts (Walter and Breckle 2002), as are our case study sites (figure 2).

At about 2.2 km^{-2}, the population density of Siberia and the RFE is disproportionately low compared to western Russia and is also concentrated in the south (Rosstat 2016, Parfenova *et al* 2019). A few very large metropolises are regional centers of industry and administration; smaller settlements are scattered throughout vast forest-dominated rural areas. Mature forests are mostly coniferous, with species of pine, spruce, fir, and larch (Kortopachinsky and Vstovskaya 2012, Shugart *et al* 1992, supplementary material table B). Young forest consists of immature conifer or early successional birch–aspen. Larch dominates in the east and north, and mixed hardwood–conifer forests occupy southern Primorsky Krai. Wetlands and shrublands are near rivers and lakes or in low areas. Arable lands are less widespread, found in river valleys or as scattered plains. Land dynamics in the past century include agriculture establishment and abandonment, urban settlement, transportation infrastructure, logging, fire, insect infestation, minerals/petroleum extraction, climate change, and post-disturbance forest succession (Kharuk *et al* 2003, 2016a, 2016b, 2016c, 2017a, 2017b, 2017c, Newell 2004, Bergen *et al* 2013, Kukavskaya *et al* 2013).

Of the eight Landsat-footprint case study sites in each of the seven provinces, four are in Siberia and four in the RFE, forming two Region strata: Siberia and RFE (figure 2). Situated in predominantly rural landscapes, the sites were also stratified into Near (to a very large regional metropolitan center $\geqslant$ ~350 000 study era population, to multiple cities and towns) or Remote (not near a very large regional metropolitan center as defined, fewer or smaller nearby cities and towns, rugged physiography). While covering 239 317 km^2, the combined sites are still a small spatial sample; nevertheless, legacy sites had originally been chosen to be reasonably representative of the region's predominantly rural landscapes.

3. Methods

3.1. Data synthesis and augmentation

Our team accessed eight case study sites with ~ decadal Landsat-derived raster LCLU data through ~2000 (table 1, figure 2). These were from the Central Siberia project (CSIB, Bergen *et al* 2003, 2008), Primorsky project (PRIM, Johnson 2014), and Northern Eurasia Land Dynamics project (NELDA, Pflugmacher *et al* 2011). We re-processed the raster data to make LCLU classes as comparable as possible across sites and developed new classifications for 2010. While focusing on anthropogenic land-use classes, we retained the other raster LCLU classes (table 2). Several gaps exist in these time series and we mostly did not retrospectively create missing data. However, we created new classifications for logging and fire for missing dates (table 1). Lacking consistent detailed urban and roads data, we created new decadal vector data for these anthropogenic features for all sites and dates. Together, these formed the SYNTHESIS LCLU dataset. For broader context and a denser (annual) time series, we compiled Russian statistical data at the province level ~1975–2010 for socio-economic indicators representative of the study anthropogenic land uses (Park 2013, Rosstat 2013).

We defined SYNTHESIS raster LCLU classes based on the existing CSIB/PRIM projects class scheme as it most represented anthropogenic land uses (table 2). Some NELDA classes were matched; those that were not were cross-walked or re-classified (supplementary material table C). Re-classification included segmenting some lumped classes into separate classes using the image data. New 2010 raster LCLU classifications were mostly based on the same methods as the legacy data for a given site (Bergen *et al* 2008, Pflugmacher *et al* 2011, Johnson 2014). Training and testing data for 2010 and sites with re-classifications were from high spatial resolution imagery (Google and CNES/Astrium 2014) and the Landsat imagery; unaltered sites retained legacy accuracy statistics. In addition to overall and producers acccuracies, we computed accuracy 95% confidence intervals (CIs) and land area 95% CIs (Rossiter 2004, Olofsson *et al* 2014).

We mapped rural urban settlements and roads manually as vector polygon and line features using 1:200 000 Russian topographic maps and their class schemes plus the Landsat data (table 2, Roskartografia 1985). Map source data was from the 1970s–1980s, and so first we digitized and labeled settlements and roads present on the maps. Settlement mapping used a minimum mapping unit of 0.1 km^2 (10 ha). We overlaid the vector data on the ~1975 Landsat imagery, further customizing road presence to that image date and then to each subsequent date in the study Landsat time series. For urban polygons, we iteratively checked to correct ommission or commission errors. For road length, we also performed a quantitative accuracy assessment for 2010 based on comparison with high-resolution imagery (Google Earth and Digital Globe 2017).

3.2. Quantification and analysis

From the SYNTHESIS raster data, we first quantified trends in the relative proportions and magnitudes of the anthropogenic Cut (logging) and Agriculture classes plus Burn over time for each site. We further pooled these to their assigned region and proximity strata, re-calculating statistics weighted by site terrestrial areas. In the few cases where Cut or Agriculture data was missing from a site SYNTHESIS time series, we estimated these missing values before pooling, using single imputation based on SYNTHESIS data values from neighboring time series dates plus the annual province-level statistics. For the Amur site, we calculated proportions for Russia only and for Russia–China combined.

Table 1. SYNTHESIS data. Source is legacy case studies project. Strata are SIB (Siberia) and RFE (Russian Far East) sites plus N (Near) and R (Remote) sites. Path/row is WRS-2. Date is that of the single or primary image. Sensor is Landsat sensor type. An 'x' denotes available SYNTHESIS data: for raster LCLU this means a complete set of classes; raster Cut & Burn data are either also included in that set or are separately available[a].

Site	Source	Strata	Landsat WRS-2 path/row	Date	Sensor	Vector Urban	VectorRoads	RasterCut & Burn	Raster all LCLU classes
Tomsk	CSIB	SIB/N	p147r20	08/30/75	MSS	x	x	x	x
				09/07/89	TM	x	x	x	x
				07/09/99	ETM +	x	x	x	x
				09/11/10	TM	x	x	x	x
Krasnoyarsk	CSIB	SIB/N	p141r20	06/26/74	MSS	x	x	x	x
				05/14/91	TM	x	x	x	x
				08/18/00	ETM +	x	x	x	x
				08/22/10	TM	x	x	x	x
Irkutsk	CSIB	SIB/N	p133r23	06/21/75	MSS	x	x	x	x
				08/21/89	TM	x	x	x	x
				08/13/01	ETM +	x	x	x	x
				08/30/10	TM	x	x	x	x
Chita	NELDA	SIB/N	p129r24	08/22/76	MSS	x	x	—	—
				05/28/92	TM	x	x	x	—
				060/1/00	ETM +	x	x	x	x
				09/03/10	TM	x	x	x	x
Amur	NELDA	RFE/R	p122r23	05/22/75	MSS	x	x	x	x
				06/15/87	TM	x	x	x	x
				05/15/02	ETM +	x	x	x	x
				07/03/11	TM	x	x	x	x
Primorsky South	PRIM	RFE/N	p113r29	06/30/76	MSS	x	x	x	x
				09/09/89	TM	x	x	x	x
				09/21/99	TM	x	x	x	x
				08/13/09	TM	x	x	x	x
Primorsky North	PRIM	RFE/R	p112r28	08/27/75	MSS	x	x	x	—
				06/27/88	TM	x	x	x	—
				06/07/01	ETM +	x	x	x	—
				09/12/10	TM	x	x	x	x
Sikhote-Alin	NELDA	RFE/R	p112r25	multiple	MSS	x	x	—	—
				08/13/90	TM	x	x	x	—
				05/18/02	ETM +	x	x	x	x
				06/09/13	OLI	x	x	x	x

[a]Two sites do not have any 1975 data due to unavailability of MSS imagery suitable for raster classification.

Table 2. SYNTHESIS LCLU classes.

Raster LCLU classes		
Class #	Class	Definition
1	Conifer	Needleleaved evergreen (pine, spruce, fir); needleleaved deciduous (larch)
2	Mixed	Needleleaved with broadleaved deciduous
3	Broadleaved	Broadleaved boreal (birch, aspen); broadleaved temperate (oak, walnut, etc)
4	Young/Shrub	Post-cut/post-burn regeneration; regeneration from abandoned agriculture; upland shrubland
5	Cut	Logged areas (mostly clearcuts), little onset of herbaceous or woody re-vegetation
6	Burn	Stand-replacing fire scars, little herbaceous or woody revegetation; agricultural fire
7	Insect	Insect infestation (killed or partially killed forest)
8	Wetland/Low	Shrub and herbaceous wetland and riverine floodland; low shrubland and grassland
9	Agriculture	Agriculture (grains and other crops, hay; both active and inactive fields)
10	Urban	Villages, towns, and cities
11	Bare	Permanently bare ground including naturally bare (rocky, sandy) areas
12	Water	Water (rivers, lakes)
Vector LCLU classes		
Class #	Class	Definition
1341	Paved	Paved roads including highways and thoroughfares, with asphalt and cement surfaces
1342	Gravel/Dirt	Gravel and dirt roads including improved (graded) surfaces
1343	Forest/Winter	Minor dirt roads including forest/winter roads and farm roads
111	Large City	Large cities (population from 50 000 to 100 000)
112	Small City	Small cities (population from 20 000 to 50 000)
113	Town	Towns (population of from ~2000 to ~20 000)
114	Village	Villages and rural settlements (population from <100 to ~2000)

Table 3. Raster LCLU land area estimates (km^2) and confidence intervals (95% CIs, in parentheses) for the ~2010 date, all case study sites combined; plus raster LCLU class proportion of the combined sites area (supplementary material table D).

Class	Combined sites area estimates km^2 (CI)	LCLU class proportion	Class	Combined sites area estimates km^2 (CI)	LCLU class proportion
Conifer/Mixed	125 066 (±990)	0.55	Wetland/Low	26 181 (±416)	0.12
Broadleaved	22 347 (±725)	0.10	Agriculture	13 717 (±168)	0.06
Young/Shrub	15 774 (±676)	0.07	Urban	1865 (±219)	0.01
Cut	2977 (±237)	0.01	Bare	1887 (±124)	0.01
Burn	4303 (±290)	0.02	Water	9019 (±72)	0.04
Insect	1757 (±281)	0.01			

From the vector urban data, we first summarized the total numbers (counts) and areas of urban polygons in each of the four SYNTHESIS Urban classes by site and date. From these, we calculated percent increase in count, area, and density for each of the four Urban classes by site and date. To characterize settlement sizes, we calculated mean area (km^2) and standard deviations within each of the four Urban classes by site for the 2010 date. From the vector roads data we computed total lengths and densities for each Road class by site, and then calculated percent increase in road length by road class and site. Finally, we pooled the Urban or Road data (no missing data) by strata for each date, and recalculated area-weighted statistics. For the Amur site, we calculated statistics for Russia and China separately and combined.

In addition to our primary quantifications of anthropogenic land-use trends, we addressed some specific questions raised by legacy studies. To examine

Table 4. LCLU Overall accuracy (%), producers accuracy for Cut and Burn classes, accuracy confidence intervals (95%, CI's). Date is nominal decadal date (actual image date may vary, see table 1); a '*na*' indicates the class was not observed on the landscape at the date; a '—' indicates legacy data not available.

Siberia sites								
Site	Tomsk				Krasnoyarsk			
Date	1975	1990	2000	2010	1975	1990	2000	2010
Overall	90 (± 1)	94 (± 1)	94 (± 1)	89 (± 2)	90 (± 2)	91 (± 1)	93 (± 1)	92 (± 3)
Cut	*65 (± 9)*	*87 (± 6)*	*98 (± 3)*	*80 (± 13)*	*91 (± 6)*	*94 (± 5)*	*79 (± 8)*	*73 (± 18)*
Burn	*73 (± 9)*	*54 (± 10)*	*na*	*100 (± 1)*	*72 (± 9)*	*100 (± 0)*	*60 (± 10)*	*67 (± 21)*
Site	Irkutsk				Chita			
Date	1975	1990	2000	2010	1975	1990	2000	2010
Overall	82 (± 2)	89 (± 1)	89 (± 2)	90 (± 2)	—	—	77 (± 4)	90 (± 2)
Cut	*82 (± 11)*	*95 (± 4)*	*81 (± 8)*	*96 (± 6)*	—	*90 (± 8)*	*84 (± 11)*	*93 (± 7)*
Burn	*80 (± 11)*	*92 (± 6)*	*98 (± 2)*	*100 (± 1)*	—	*75 (± 36)*	*100 (± 2)*	*97 (± 6)*
Russian Far East sites								
	Amur				Primorsky South			
Date	1975	1990	2000	2010	1975	1990	2000	2010
Overall	82 (± 1)	91 (± 1)	92 (± 0)	91 (± 1)	89 (± 3)	93 (± 3)	92(± 3)	92 (± 3)
Cut	*Na*	*100 (± 0)*	*99 (± 1)*	*89 (± 3)*	*79 (± 18)*	*92 (± 13)*	*70 (± 21)*	*95 (± 11)*
Burn	*Na*	*99 (± 1)*	*100 (± 0)*	*100 (± 0)*	*100 (± 10)*	*na*	*na*	*na*
	Primorsky North				Sikhote-Alin			
Date	1975	1990	2000	2010	1975	1990	2000	2010
Overall	—	—	—	93 (± 3)	—	—	89 (± 13)	88 (± 3)
Cut	*94 (± 11)*	*94 (± 3)*	*91 (± 4)*	*86 (± 12)*	—	*90 (± 16)*	*76 (± 13)*	*98 (± 4)*
Burn	*94 (± 10)*	*93 (± 8)*	*80 (±13)*	*100 (± 2)*	—	*96 (± 10)*	*94 (± 6)*	*84 (± 13)*

the relative contribution of agricultural abandonment to regeneration, we computed the proportion of new Young/Shrub class area that had been classed as Agriculture at the previous decadal time step within a representative set of sites. To examine forest type/s at risk for logging, we computed the relative proportions of previous decadal date forest classes within new Cut areas for representative sites. To investigate logging practices, we computed landscape pattern metrics of the Cut class for representative sites. We compared logging (Cut) and fire (Burn) magnitudes over time.

At the province level, we quantified and visualized six socio-economic indicators representative of regional anthropogenic land uses. We used these data to help impute several missing values from the raster land-use data and to provide information on both broader context as well as finer temporal patterns during interpretation of Landsat–derived SYNTHESIS results.

4. Results

4.1. Synthesis dataset

The Landsat-derived SYNTHESIS case study sites cover 239 317 km^2 (224 893 km^2 in the raster LCLU after cloud removal, table 3). Overall classification accuracies of the raster LCLU data ranged from 94% to 77% (table 4, supplementary material table D); older LCLU data had several low per-class producers accuracies. Both Urban and Roads ~1975 vector data had some geolocation error and digitizing generalization. The 2010 roads assessment showed higher per-site ommission than commission statistics (2.6%–5.5% and 0.0%–2.8% respectively; supplementary material table E).

4.2. Urban

Little change occurred 1975–2010 in the mostly rural Urban class area (km^2) in any individual site (supplementary material figure A), with a <3.5% increase all sites combined. The Village class represented most urban land use by both count (table 5) and area density (figure 3). Siberian sites had a higher mean density of villages (figures 3(a), (b)), even though Primorsky South in the RFE (and Near stratum) had the highest density among individual sites. The difference in Village class density was even greater when comparing sites grouped as Near versus Remote (figures 3(c), (d)). The classes of Small City and Large City are found exclusively in Near stratum sites (table 5, figure 3(c)).

4.3. Agriculture

Agriculture was negligible in three sites, just over 20% of one site (Primorsky South), and between ~5%–15% in four. Strata show predominance of the Agriculture class in sites nearer to regional

Table 5. Urban distributions: number of settlements plus mean area (km^2) and standard deviation of each mapped Urban class in each case study site at ~2010. Totals are area-weighted and include only the Russia part of Amur.

	Village			Town			Small City			Large City		
	N	Area mean	Area stdev	N	Area mean	Area stdev	N	Area mean	Area stdev	N	Area mean	Area stdev
Siberia sites												
Tomsk (n)	151	1.50	1.11	5	2.07	2.31	1	21.80	—	0	—	—
Krasnoyarsk (n)	139	1.32	1.40	1	8.97	—	0	—	—	0	—	—
Irkutsk (n)	157	1.74	1.69	1	8.65	—	0	—	—	0	—	—
Chita (n)	63	2.04	1.39	3	7.81	3.97	0	—	—	0	—	—
Class % of Total N and Class area mean/stdev	97.9	1.59	1.40	1.9	4.99	2.35	0.2	21.80		0.0		
RFE sites												
Amur	50	1.42	1.47	0	—	—	0	—	—	0	—	—
Russia (r)	*6*	*1.91*	*1.50*	*0*	—	—	*0*	—	—	*0*	—	—
China	*44*	*1.35*	*1.47*	*0*	—	—	*0*	—	—	*0*	—	—
Primorsky S (n)	160	1.77	1.79	5	5.65	5.88	0	—	—	2	24.77	5.60
Primorsky N (r)	42	2.29	1.87	0	—	—	0	—	—	0	—	—
Sikhote-Alin (r)	13	1.35	0.99	1	3.92	—	0	—	—	0	—	—
Class % of Total N and Class area mean/stdev	96.5	1.85	1.75	2.6	5.36	4.90	0.0			0.9	24.77	5.60

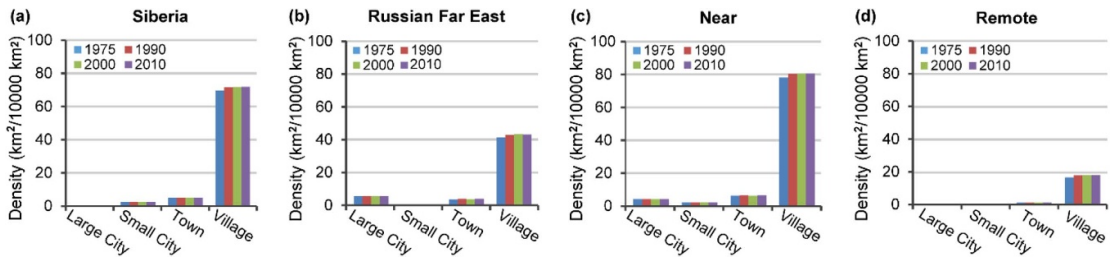

Figure 3. Trends in case study sites Urban land-use density by class and over time grouped by region (a), (b) and proximity (c), (d) strata (only the Russia part of the Amur site is included).

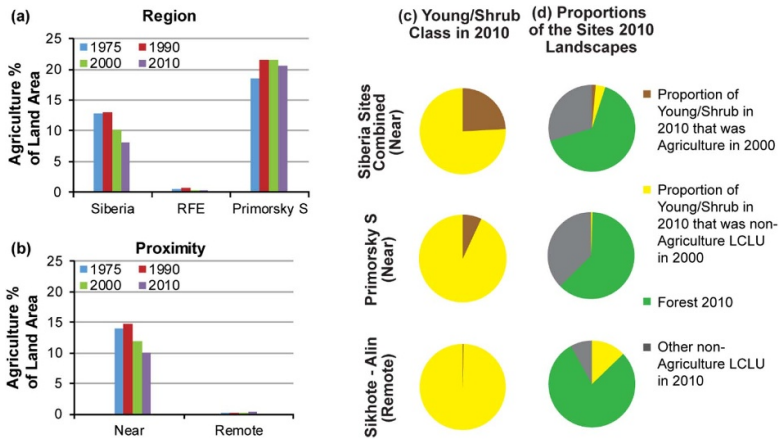

Figure 4. Agriculture as a percent of sites terrestrial land area at the decadal dates and stratified by region ((a); with Primorsky South shown separately and only the Russia part of the Amur site included) and by proximity (b). Also shown (c) for representative sites are the proportions of Young/Shrub vegetation regrowth present in 2010 attributed to agriculture abandonment (brown) between 2000 and 2010 versus Young/Shrub due to other disturbance (yellow). Part (d) shows these two trajectories as proportions of the entire landscape area within the given sites in 2010.

metropolitan centers and other urban areas, with near-absence of Agriculture in more remote and rugged sites (figure 4(b)). Siberian sites had small–moderate agriculture presence that decreased from peaks prior to 2010 (figure 4(a)). Only Primorsky South had a net increase 1975–2010 (figure 4(a)). The portion of Young/Shrub LCLU attributed to abandoned agriculture and defined as woody encroachment is a slight proportion of overall landscapes (figure 4(d)); however, in Near stratum sites it comprised a small or moderate proportion of new Young/Shrub area (figure 4(c)).

4.4. Logging

The Cut class occurred in all sites at all dates. Siberian and Near stratum sites had the highest Cut class proportions through 1990, while those in RFE and Remote stratum sites were greater after 1990 (figures 5(a) and (b)). Analyses showed preference for logging in the Conifer forest class at roughly 1.5–2 times the proportion of that class (figures 5(c) and (d)) with the exception of the Primorsky South site with its valuable mixed hardwoods. The most rugged RFE site (Sikhote-Alin) had the greatest over-representation of logging in the Conifer class. In Siberian sites after the 1990 date, regular patchwork patterns of smaller clearcuts replaced irregularly shaped and often large-sized ones (supplementary material figure B). In the rugged RFE Sikhote-Alin and Primorsky North sites, post-1990 date logging patches were slightly larger and somewhat more irregular in shape than those in Siberia sites. Little pattern of clearcut logging was mapped in the Primorsky South site at any date.

4.5. Roads

The majority of road length was built by the earliest study date (~1975, figure 6). Given that most roads are minor, and that roads after 1975 were mapped from Landsat only, there are errors of omission (supplementary material table E). Nonetheless, a substantial increase manifested in observed total road length and density 1975–2010, and new roads appeared between each mapped date in each site and stratum (figure 6, supplementary material figure C). Remote stratum Primorsky North and Sikhote-Alin sites saw the greatest percent increase in road length after 1990 (table 6), with the majority in the Forest/Winter roads class (figure 6(d)). These minor roads were also created in agriculture areas in the Primorsky South site, and along some utility corridors in all sites. These more recent trends contrast existing roads in ~1975 that have greatest densities in

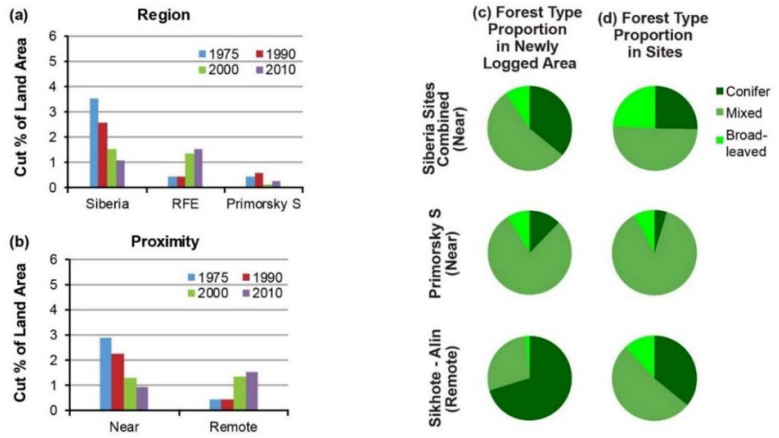

Figure 5. The Cut (logging) class as a percent of sites total terrestrial area at the decadal dates and stratified by region (Primorsky South shown separately and only the Russia part of the Amur site included) (a) and stratified by proximity (b). Relative amounts of conifer, mixed, and broadleaved forest classes that had formerly occupied newly logged areas for representative sites over all available date pairs (c). Also shown are the relative amounts of the three mapped forest types on the sites landscapes averaged over all mapped dates (d).

Table 6. Percent increase in case study sites road length (km) over different eras and by Road class ('Other' combines all improved roads). All increases are relative to 1975 existing roads, and averages are area-weighted. Abbreviations 'n' and 'r' refer to proximity strata.

Site	Forest/Winter road percent increase 1975–1990	Forest/Winter road percent increase 1990–2010	Other road percent increase 1975–1990	Other road percent increase 1990–2010	Total road percent increase 1975–1990	Total road percent increase 1990–2010
Siberia sites						
Tomsk (n)	15.10	6.31	6.45	2.56	11.43	4.79
Krasnoyarsk (n)	20.50	7.48	5.19	1.53	14.33	5.28
Irkutsk (n)	10.63	1.55	6.76	2.89	9.24	2.02
Chita (n)	8.62	1.73	5.26	0.04	7.77	1.31
RFE sites						
Amur	43.33	9.13	55.70	13.66	49.06	11.32
Russia (r)	*8.21*	*1.57*	*4.29*	*6.17*	*7.21*	*2.71*
China	*132.50*	*18.00*	*76.32*	*15.52*	*94.10*	*16.46*
Primorsky S (n)	29.56	5.00	10.57	2.83	6.95	4.49
Primorsky N (r)	45.55	20.47	15.46	5.49	38.60	17.58
Sikhote-Alin (r)	25.20	35.65	26.33	19.32	25.38	33.01
Average[a]	20.42	9.97	10.04	5.10	15.11	8.90

[a]Only the Russia portion of Amur is included in averages.

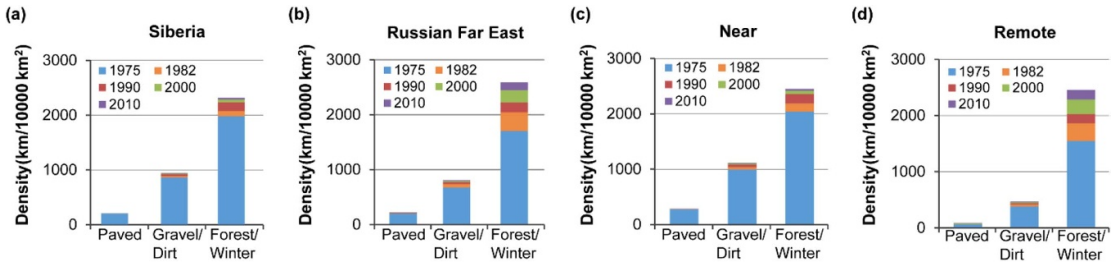

Figure 6. Density of roads in the case study sites by class, over time, and by region and proximity strata (only the Russia part of the Amur site is included).

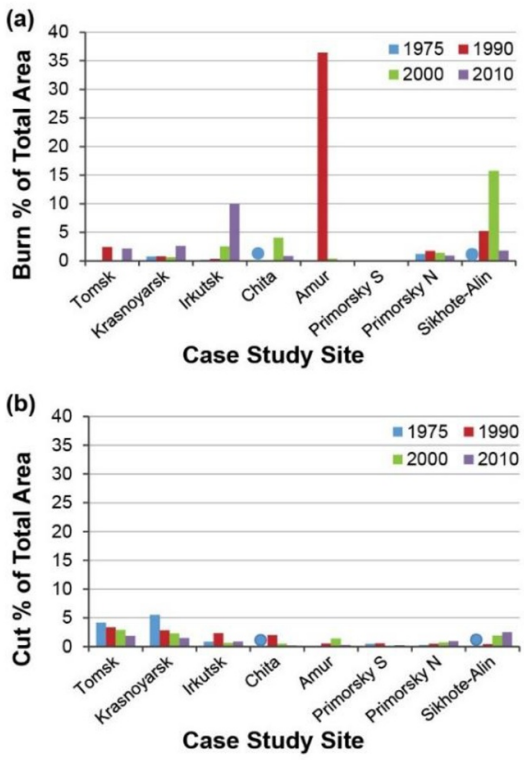

Figure 7. Burn and Cut classes in the case study sites at the same percent area scale for comparison. (Filled circles represent dates with no mapped data; where no bars or filled circles are present, Burn/Cut is negligible at the scale of the chart.) Both Russia and China parts of the Amur site are included.

Siberia and Near stratum sites. Prior to 1990, the percent increase in road length on the China side of the Amur site was greater than in any of the Russia sites (table 6).

4.6. Fire

We compared fire disturbance versus logging for relative influence. The SYNTHESIS Burn class represents mostly stand-replacing forest fires occurring at or near the decadal dates. In five sites, the Burn class comprised <5% of the landscape at all mapped dates (figure 7(a)). In contrast, over 35% of the combined Amur site was burned in 1987 (Cahoon *et al* 1994). Little fire was observed in agriculture areas. Sites with the greatest amount of fire either were Remote stratum sites or Near stratum sites with areas of rugged topography (e.g. Irkutsk). With all sites and dates grouped together, the Burn class does comprise the greatest disturbed area (figures 7(a) and (b)). Yet, some landscapes (Tomsk, Krasnoyarsk, Primorsky South) appeared to be significantly influenced by logging.

4.7. Socio-economic context

Most trends 1975–2010 in the province-level socio-economic indicators (Park 2013) showed abrupt downward changes at about 1990. Trends in the Wood Removal, Sawnwood Production, Grain Production, and Index of Industrial Production indicators exemplify this (figures 8(a)–(c) and (e)). These also show that in forestry and agriculture, subsequent gains after the early post-Soviet era fluctuated. The Index of Industrial Production (which includes mining/oil/gas, not evaluated through this study) exhibited a greater recovery. Province-level Migration Rate (figure 8(d)), was generally negative between 1990 and 2000 except for westernmost Tomsk Oblast. Counter to other indicators, Road Density continually increased over time and in all provinces.

5. Discussion

Considering multiple anthropogenic land uses and strata together, we identified three key spatial–temporal trends centered on (1) urban-era-proximity, (2) agriculture-era-proximity, and (3) forests-era-region-roads.

5.1. Urban-era-proximity

Combined SYNTHESIS spatial data for 750 mostly rural settlements unveiled negligible expansion in area footprint over the 35-year study span. Province-level migration statistics shortly after 1990 show mostly out-migration with exception of westernmost Tomsk (figure 8(d), Heleniak 1997, Heleniak 2001). After 1990 most rural regions of Siberia lost about 30% of their population (Hitztaler 2004, Mueller *et al* 2016), and post-hoc comparison with 2010 census data (Rosstat 2010, Mkrtchyan 2011) showed some small villages within our case study sites entirely lost their populations. This decline is not limited to our region within northern Eurasia but also occurred in Europe (Angelstam *et al* 2003) and may fit with a global rural-to-urban movement (Seto *et al* 2011). This diverges from recent analyses for very large metropolitan centers (outside of our sites) in Siberia showing an increase in urban area (Fan *et al* 2018).

Near stratum sites had far more settlements (figure 3), appearing to align most with the historical distribution of crop agriculture: the same sites with notable agriculture presence (Tomsk, Krasnoyarsk, Irkutsk, and Primorsky South) had a significantly greater density of settlements. This contradicts recent trends in road expansion, which were greater in Remote (and more rugged) stratum sites (figure 6). Thus, in the recent past, rural–urban and agriculture land uses may have been coupled in this region, and rural–urban land use and recent road expansion is probably not particularly coupled.

5.2. Agriculture-era-proximity

Grains are the most widely planted crop type in our study area (Mishina 2015), and government statistics indicate relatively steep declines in production shortly

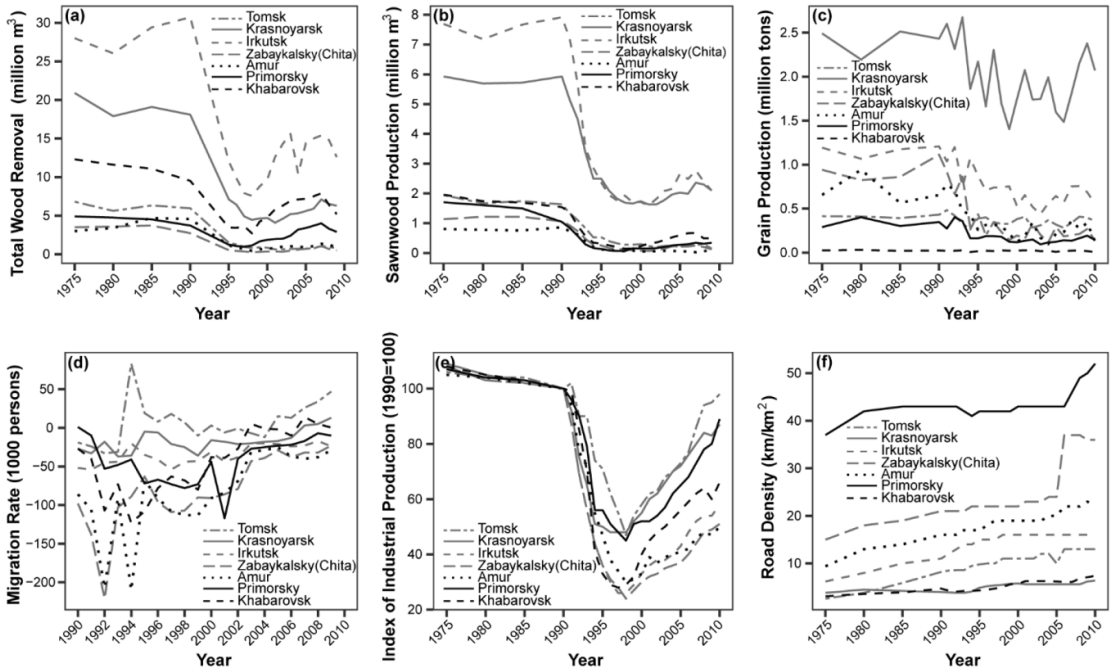

Figure 8. Selected socio-economic indicators at the province level: (a) total wood removal, (b) sawnwood production, (c) grain production, (d) migration rate, (e) index of industrial production (relative to 1990), and (f) road density (Park 2013, Rosstat 2013).

after 1990 (figure 8(c), Deppermann *et al* 2018, Nefedova 2011). SYNTHESIS LCLU data showed downward but less steep trends possibly due to the Landsat–derived data defining the Agriculture class as all land area converted for agriculture whether planted or temporarily bare. An exception to the downward trend in the SYNTHESIS data was the Primorsky South site, near to both China and the fertile Lake Khanka plain.

Crop agriculture in SYNTHESIS sites occurs in southerly reaches, in less rugged physiography, and is virtually absent from Remote (and rugged) stratum sites. Crop agriculture found nearly exclusively in Near stratum sites is coupled with greater village density, with urban areas larger than the Village class, and with very large metropolitan centers close to those sites. This does not mean agricultural practices are unimportant elsewhere. As an interspersed part of village landscapes, small 'private-plot' agriculture is relied on for subsistence or supplementation, giving it a socio-economic importance far outranking its landscape proportions (Pallot and Nefedova 2003, Hitztaler and Bergen 2013).

SYNTHESIS data showed few agricultural fires, even when such fires were observed during the same year and sites by MODIS (MODIS Burned Area Product, Boschetti *et al* 2015). This is likely due to temporally sparse Landsat combined with post-fire cultivation rapidly masking agricultural burn scars. Yet other studies have concluded that more temporally frequent sensors may also miss many smaller agricultural fires due to their coarse (~500 m–1 km) spatial resolutions (Hall *et al* 2016, Zhu *et al* 2017).

5.3. Forests-era-region-roads

Immediately after 1991, wood removal Russia-wide fell dramatically (Obersteiner 1999); the year 2009 saw the first net growth. Our province-level Total Wood Removal and Sawnwood Production indicators similarly show dramatic drops after 1990, followed by some recovery 2000–2010 (figures 8(a) and (b)). SYNTHESIS LCLU results for RFE Remote stratum sites show increased logging by 2000, agreeing with some local statistics within Khabarovsk Krai (Kakizawa 2015, Yamane 2015) where slighter decreases after 1990 were recorded. The latter were attributed to high demand for RFE wood exports from neighboring Japan and, most recently, China (Newell and Simeone 2014, Sysoeva 2019). Combined with this is another post-1990 phenomenon—forest leases. Leases for commercial logging are now widely established within Russian Forest Fund lands (FAO 2013).

Globally, road length has its strongest positive relationships with population density and country GDP (Meijer *et al* 2018). However, high rates of road intensification occur in some of the world's least populated regions but having expanded commercial logging leases (Cordero-Sancho and Bergen 2018). SYNTHESIS data show road building to be highest in the RFE and Remote strata sites, and in the Forest/Winter road type. This might suggest targeting of specific forest areas for the export market, and/or lack of large diameter timber in already accessible sites. In addition, studies in tropical forests show that selective logging may be more road-intensive than clearcut methods (Bell *et al* 2012, Kleinschroth and Healey 2017); over 70% of logging in RFE Primorsky Krai is selective (Russian Federal Forest Service

Table 7. Summary of baseline knowledge of anthropogenic land use at the landscape scale from SYNTHESIS case study sites, plus main outstanding science questions and data or analysis needs.

Addressed by SYNTHESIS	Topics for further research	What is needed to address these
Urban (rural urban)		
• Size and class distribution of small settlements • Proportion of landscape in urban by size class at decadal dates • Variation of urban proportion by type by socio-economic era • Variation of urban use proportion by type over geographic strata of region and proximity • Area (means, stdev) distributions of settlements by size classes	• Used and inhabited urban area versus abandoned or uninhabited urban area • Condition or degradation of settlements area and vegetation regrowth • Comparison of urban area with new global urban products	• Better resolved imagery and methods for observing inhabited versus abandoned urban lands • Methods for observing and quantifying degradation, vegetation regrowth • More finely resolved ongoing ancillary data on population and population change (provided in part in 2010 census)
Agriculture		
• Proportion of landscape in crop agriculture land use at decadal dates • Variation of agriculture land-use proportion over time by socio-economic era • Variation of crop agriculture land-use proportion over geographic strata of region and proximity	• Annual area actually planted to crops • Extent of some confusion of fallow agriculture areas with other LCLU including wetlands • Locations and frequency of agricultural land fires	• Denser time series of moderate spatial resolution imagery for accurate mapping of area and differentiating active and fallow • Finely resolved statistics on crop production
Logging		
• Proportion of landscape recently logged to within several years at decadal dates • Variation of logged proportion by socio-economic era • Variation of logged proportion over geographic strata of region and proximity • Relative amount of logging within different forest types • Observed adherence to sustainable logging patch size and shape regulations	• Exact year of clearcut logging • Actual annual clearcut logging rates • Post-logging succession • Selective harvest proportions and rates • Illegal logging rates and distributions • Comparison of logging area with new global forest change products	• Denser time series of moderate spatial resolution imagery for tracking clearcut logging • Better resolved data and methods for observing selective logging • Consistent, region-wide spatial boundary data for Russian forest management units, leased, and protected areas • Statistical data on forest inventory plus forest harvest and trade, linked to spatial data
Roads and Infrastructure		
• Location of all or most roads • Length and density of roads by road type at decadal dates • Variation in road length by type by socio-economic era • Variation in road length by type over geographic strata of region and proximity	• Roads in leased and non-leased areas • Forest roads persistence • Connection of roads to targeted logging • Connection of roads to wood trade and export statistics • Relationship with mining/oil/-gas extractive installations, pipelines, utility corridors	• Denser time series of moderate spatial resolution imagery for tracking road re-vegetation • Better and updated roads' ancillary data (maps or GIS for thematic comparison) • Spatial boundary data (see Logging, above) • Moderate spatial resolution data over broader areas than case study sites and/or targeted for known major mining/oil/gas, pipelines, utility corridors

2012). Minor roads may also be the only way to access some oil/gas/mining or utility operations and thus coupled with expanding land-use activities more broadly.

In accordance with newer Russian Forest Codes after 1994 (Zaslavskaja 1994), SYNTHESIS data show logging patterns changed, although somewhat more conforming on relatively level Near stratum Siberian sites landscapes. Finally, SYNTHESIS data may suggest some divergence from forest fire as the uniquely dominant regional disturbance (Krylov *et al* 2014). The Near stratum Krasnoyarsk and Tomsk sites both had relatively low fire occurrence combined with relatively high logging at our decadal dates. These findings suggest there are at least some regional landscapes where other anthropogenic activities may strongly contribute to larger landscape patterns.

5.4. What are the outstanding research needs and emerging opportunities?

The next stages of landscape-scale research on anthropogenic land use in this region should focus on mapping and quantifying: (1) annual logging rates, post-logging succession, and relationships to forest leases; (2) selective and illegal logging distribution and impact; (3) agriculture cropland dynamics; (4) anthropogenic agricultural fires; (5) condition and population of settlements; (6) roads (at higher spatial resolution) and their relationships to forest leases and the forest trade; (7) mining/oil/gas, pipelines, and utilities expansion; (8) inter-comparison of landscape findings with global forest and urban change products; and (9) continued evaluation of key anthropogenic landscape trends.

To accomplish these and others (table 7), the following will be advantageous: (1) greater temporal density and coverage of moderate spatial resolution imagery; (2) efficient computational methods to analyze these larger dimensional data; (3) fusion with higher spatial resolution imagery; and (4) greater access to Russian spatial and statistical data. Fortunately, opportunities to address these are maturing via: (1) new data (e.g. harmonized Landsat and Sentinel-2; Wang *et al* 2017, Torbick *et al* 2018); (2) big data computational methods (Gorelick *et al* 2017); (3) finer spatial resolutions of other new sensor data; and (4) greater collaboration and access to GIS and statistical data (Groisman *et al* 2017).

6. Conclusions

Our study provides a closely focused view of the anthropogenic landscape representative of a resource-rich swath of Northern Eurasia over a period of profound change. When we took an integrated look at multiple anthropogenic LCLU types together and over multiple case study sites, key trends emerged.

The rural–urban footprint grew negligibly over the 35-year timespan whereas roads consistently increased in all sites over time. The density of settlements appears to align most with the historical distribution of crop agriculture. This is counter to recent trends in road expansion, which were greater in more remote and rugged sites. This suggests that in the recent past, rural–urban and agriculture land uses may have been coupled, and that rural–urban land use and recent road expansion is probably not particularly coupled. The greatest increase in recent road building occurred in sites that are more remote and rugged, near to Japan and China wood markets, and with now widespread commercial forest leases. Forest regeneration from abandoned agriculture manifested in small to moderate amounts in sites with agriculture. While fire is the dominant disturbance overall, the landscapes of several SYNTHESIS sites were strongly influenced by logging.

The SYNTHESIS results establish a foundation upon which to build more knowledge of landscape-scale anthropogenic land use in this globally important region. Among urgently needed refinements are the deployment of denser time series of moderate spatial resolution imagery to track annual logging and fire rates, differentiate between clearcut and selective logging, capture the extent of agricultural land fires, and monitor agricultural land use dynamics. New studies are needed to assess landscape effects of mining/oil/gas activities and utilities infrastructure. Integrative studies should seek to connect road-building and other infrastructure development to energy consumption and the forest trade.

Data availability

The data that support the findings of this study are openly available at the following URL/DOI: https://deepblue.lib.umich.edu/.

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