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Climatic- and anthropogenic-induced land cover change around Norilsk, Russia

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ABSTRACT
Increasing atmospheric temperatures over the last 30 years has prompted land cover change in sensitive Arctic environments and exacerbated change in large urban-industrial centers on permafrost. Norilsk, Russia, the largest city built on permafrost north of the Arctic Circle, has a long history of development and industrial activity providing an opportunity to evaluate the climatic- and anthropogenic-induced land cover change. Land cover changes in three areas representative of natural and anthropogenic landscapes in the vicinity of Norilsk were examined over a 30 year period of documented warming focusing on three time periods corresponding to distinct socio-economic conditions: the mid- to late 1980s, the early 2000s, and the 2010s. Temperature increases resulted in consistent and significant greening and a slight increase in surface water extent in the nearby area unaffected by human activities. The areas modified by human activities within the city and downwind from local pollution sources experienced an expansion of barren ground due primarily to sulfur-dioxide-laden pollution. Subsequent decreases in emissions in this area correspond with marginal revegetation, or a likely process of secondary succession with the expansion of tall shrubs. These findings show that both climatic warming and industrial development exert significant influence on Arctic land covers.

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Introduction

High-latitude regions are warming significantly faster than the global average, a trend accentuated on the Taymyr Peninsula of Siberia, warming at a rate of 0.08°C yr^{-1} (e.g. Anisimov, Kokorev, & Zhil'tsova, 2013; Roshydromet, 2014). The environmental changes associated with a warming climate have significant impacts on Arctic and sub-Arctic ecosystems. Numerous studies indicate ongoing climate-induced change in the structure, composition, and functioning of tundra and boreal forest biomes manifested through increased photosynthetic productivity (e.g. Beck & Goetz, 2011; Epstein et al., 2012; Macias-Fauria, Forbes, Zetterberg, & Kumpula, 2012) and/or latitudinal and altitudinal treeline shifts in Arctic and sub-Arctic regions (e.g. Kharuk, Ranson, Im, &

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Naurzbaev, 2006; Kullman, 2002; Lloyd, 2005; Shiyatov, Terent'ev, & Formin, 2005) generally referred to as 'Arctic greening.'

Significant ecosystem changes in the Eurasian Arctic have also been associated with anthropogenic drivers related to developmental, social, economic, and institutional transformations, which exert additional pressure on highly sensitive Arctic environments (e.g. Andrew, 2014; Forbes, Fauria, & Zetterberg, 2010; Kumpula, Pajunen, Kaarlejärvi, Forbes, & Stammler, 2011; Stammler, 2005). The effect of human-induced ecosystem changes is exemplified in the vicinity of Norilsk (69°N, 88°E). Founded in 1935 in an area with rich deposits of non-ferrous metals, Norilsk is one of the largest metallurgy complexes in Russia and the most significant point-source polluter in the Arctic (e.g. Derome & Lukina, 2011). Numerous studies have addressed the extent and severity of pollution-related ecosystem damage around Norilsk (e.g. Kozlov & Zvereva, 2007; Nilsson, Blauberg, Samarskaia, & Kharuk, 1998; Vlasova, Kovalev, & Filipchuk, 1992; Zubareva, Skripal'shchikova, Greshilova, & Kharuk, 2003). For example, it is estimated that the total area that experienced vegetation mortality due to pollution emitted from Norilsk's smelting operations increased from approximately 5000 ha in the 1960s to 200,000 ha in the mid-1970s to 1,400,000 ha in the mid-1980s (Kravtsova, 1999). Later estimates of the total area affected by ecosystem damage range from 400,000 ha (Kozlov & Zvereva, 2007) to two million ha (Derome & Lukina, 2011). Simultaneously, the Norilsk region has undergone significant atmospheric warming over the last three decades (Streletskiy, Sherstukov, Nelson, & Frauenfeld, 2015) providing a unique opportunity to analyze a complex interplay between human- and climate-induced drivers of Arctic land cover change.

Satellite-based remote sensing provides a useful tool for assessing land cover change. However, the use of satellite imagery is complicated for Arctic applications due to issues including the consistently high cloud cover, data gaps, and polar night (e.g. Kumpula et al., 2011; Stow et al., 2004; Wallace, 2012). The dense time stacking methodology (Kennedy, Cohen, & Schroeder, 2007; Schneider, 2012; Streletskiy, Tananaev et al., 2015) presents an opportunity to overcome the challenges posed by high-latitude environments to remote sensing-based impact studies. Nyland (2015) applied the Landsat dense time stacking technique to analyze long-term broad-scale spatial vegetation and surface hydrology changes in the Lower Yenisei River Region of central Siberia. In this paper we utilize the maps produced by this methodology to (1) quantify significant changes to land covers in the Norilsk industrial complex and the surrounding region; (2) identify specifics of both climatic- and anthropogenic-drivers for these changes; and (3) to explicitly characterize Arctic vegetative change induced by pollution as a process of secondary succession. Land cover changes were examined at pivotal time periods corresponding to distinct socio-economic conditions in Norilsk over the last 30 years, including the final years of the Soviet Union's planned economy and government subsidies to the far north (1985–1987), the market transition and privatization of Norilsk Nickel and subsequent market bust of 1998 (2000–2002), and the most recent period of relative economic stability (2012–2014).

Study area

The study area, centered on the Norilsk urban-industrial complex, is located within the drainage basin of the Yenisei River at the junction of two major physiographic regions: the West Siberian Plain and the Central Siberian Plateau.

The region has a subarctic climate (Peel, Finlayson, & McMahon, 2007). Daily mean temperatures ranged from −52.5°C to 27.2°C from 1966 to 2016. Where monthly mean temperatures during the warmest month (July) ranged from 10.1°C to 19.1°C, and the coldest month (January) ranged from −38.8°C to −14.6°C. Annual precipitation averages 461 mm yr^{-1} for the same period, the majority falling as snow (World Meteorological Organization Station ID# 23073). Snow depth is highly variable across the region due to microtopography and complex orographic effects associated with the nearby Putorana Plateau (Streletskiy, Shiklomanov, Kokarev, & Anisimov, 2015). Over the last 30 years (the remote sensing time period for this study) the mean annual air temperature has increased at a rate of 0.045° C yr^{-1} and annual total precipitation has increased on average by 2.7 mm yr^{-1}.

The natural environments surrounding Norilsk are dominated by tundra and taiga landscapes. Marshy, predominantly coniferous taiga forest consists largely of Siberian Larch (*Larex sibirica*), Siberian Spruce (*Pecea ovobata*), and Silver Birch (*Betula pendula*). The tundra landscapes are dominated by mosses (*Sphagnum* genus), lichens (*Cetraria islandica*), grasses (*Poa* spp.), and low shrubs, including blueberries (*Vaccinium uliginosum*), dwarf birch (*Betula nana*), and alder (*Alnus fruticosa*) (Vlasova et al., 1992).

The greater Norilsk region is located within the zone of continuous permafrost (Yershov, Kondrat'yeva, Loginov, & Sychev, 1996) although taliks (thawed ground) are found under large water bodies such as lakes and rivers. Permafrost temperatures monitored in Norilsk prior to major construction in the 1960s at 10 m depth (the approximate depth of zero annual amplitude) ranged from −0.5°C to −7°C in natural environments and from −2.5°C to 0.5°C beneath built-up areas as of the 2000s (Streletskiy, Shiklomanov et al., 2015).

Norilsk was recently found to be a 'hot spot' of permafrost warming with significant increases in active layer thickness (the upper, seasonally thawed, soil layer), at an average rate of 4 cm yr^{-1} from 1963 to 2013 and greater than 6 cm yr^{-1} from 1999 to 2013 (Streletskiy, Sherstukov et al., 2015). A Circumpolar Active Layer Monitoring (CALM) site located in forest tundra outside city limits experienced a 12 cm increase in average active layer thickness over 1 ha from 2005 to 2015 (CALM site# R32). The increasing length of the growing season, thickening of the active layer, and increased snow depth are the primary factors cited for facilitating shifts in the spatial extent of larger plant species, and especially woody shrubs. These changes promote growth with greater access to liquid water and nutrients, and protection for these taller plants from the extreme winter temperatures and abrasion from wind-blown snow (e.g. Blok et al., 2011; Forbes et al., 2010).

Exacerbating these environmental changes is intensive industrial activity. Norilsk is the world's largest producer of nickel and palladium (greater than 20% and 40% of global production respectively), and a leading producer of platinum and copper (Groisman, Gutman, Shvidenko, Gergen, & Baklanov, 2012). Historically, Norilsk has boasted three smelting factories; a nickel plant (est. 1942), a copper plant (1949), and the Nadezhda Plant (1979), which processes ore from one open pit and seven underground mines (Kozlov, Zvereva, & Zverev, 2009). Norilsk has also been considered the largest point-source polluter throughout the global boreal region for the last 60 years as a result of emissions from its smelting operations (e.g. Bergen et al., 2012; Kharuk, 2000; Kozlov et al., 2009). However, the Nickel Plant, the oldest of these facilities, was closed in June 2016 as part of a long-term modernization effort (Norilsk Nickel MMC, 2016).

Methodology

The assessment of climatic- and anthropogenic-induced land cover changes in the vicinity of the Norilsk urban-industrial complex is based on quantified differences between three land cover maps developed by Nyland (2015) for the Lower Yenisei River using the 'dense time stacking' methodology (Kennedy et al., 2007; Schneider, 2012). This method ignores the established use of an anniversary date for change detection and includes scenes from a range of time periods and those normally rejected due to data gaps and high amounts of cloud cover. Scenes are stacked, ensuring greater spatial coverage in areas obscured by clouds or data gaps in any single scene. This stack can also be combined with ancillary data allowing for a more nuanced classification scheme to be developed.

This methodology was conducted using ERDAS Imagine Software, where all available imagery for three-year time spans were combined for two adjacent Landsat TM scenes covering a total area of approximately 60,750 km^2 for the lower Yenisei River. Methodological testing showed that three-year time periods allow for temporal consistency and a sufficient number of images to the included within each time stack, thereby compensating for data gaps and cloud cover issues. Imagery was combined with calculated Normalized Difference Vegetation Index (NDVI), digitized urban areas, and a digital elevation model to classify land covers and produce three maps representing the mid-1980s (15 images from June 1985 to September1987), the early 2000s (10 images from March 2000 to October 2002), and the contemporary period (11 images from April 2012 to July 2014). The five land cover classes mapped were (1) water; (2) bare ground; (3) open forest, or tundra; (4) closed forest, or taiga; and (5) built-up areas based on training sites visited with hand-held GPS units during the summers of 2013 and 2014. These vegetative classes were based on a previous *in situ* dendrochronology study in the nearby Putorana Mountains (Kirdyanov et al., 2012).

The thematic accuracy for each map was calculated from a stratified random sampling of 650 points (with a minimum of 130 points per class) visually assessed and labeled using higher resolution data from Google Earth, ground truth collected with a hand-held GPS during 2013 and 2014 field seasons, and local knowledge of larger areas of change, particularly within the city of Norilsk. The three maps produced have overall accuracies ranging from 85% to 89%, determined to be acceptable for further analytical work. However, while providing more spatial coverage for change detection during these three time periods, relatively small changes detected should consider class-specific accuracies (Table 1(a–c)) and therefore treated with caution (Nyland, 2015).

The five land cover classes correspond to categories used in a dendrochronology study in the nearby Putorana Mountains, where the determining factor defining 'open' and 'closed' forests is the density of individual trees. A closed forest has abundant single tree growth and an understory of shrubs, while an open forest has spread out tree individuals or clustered multi-stem individuals up to 20 m apart with herbaceous and moss layers between (Kirdyanov et al., 2012). It was determined using preprocessed data linked to Google Earth through the ERDAS Imagine platform that at the 30 m spatial resolution of Landsat imagery, this land cover is indistinguishable from tundra and therefore considered as one class, as it was by Kirdyanov et al. (2012).

Analysis of changes in the spatial extent of these five land covers in the Norilsk region was done by examining three 50×50 km^2 case study areas (CSAs) selected to represent

Table 1. Verification data (known land covers). Shaded cells forming a diagonal on the table highlight the numbers of correctly classified landcovers during validation.

Classification data	Water	Barren	Tundra/Open forest	Closed forest	Built up	User's accuracy (%)
(a)						
Water	122	3	4	1	0	93.85
Barren	15	84	30	0	1	64.62
Tundra/Open forest	2	1	118	9	0	90.77
Closed forest	0	0	12	118	0	90.77
Built up	0	2	8	4	116	89.23
Producer's accuracy (%)	87.77	93.33	68.60	89.39	99.15	
Overall accuracy	85.86%		Kappa statistic	82.31%		
(b)						
Water	125	1	4	0	0	96.15
Barren	5	98	25	0	2	75.38
Tundra/Open forest	1	4	115	10	0	88.46
Closed forest	0	0	6	124	0	95.38
Built up	1	5	6	3	115	88.46
Producer's accuracy (%)	94.70	90.74	73.72	90.51	98.29	
Overall accuracy	88.77%		Kappa statistic	85.96%		
(c)						
Water	121	2	5	2	0	93.08
Barren	7	106	16	1	0	81.54
Tundra/Open forest	3	1	111	15	0	85.38
Closed forest	4	0	12	114	0	87.69
Built up	2	5	7	1	115	88.46
Producer's accuracy (%)	88.32	92.98	73.51	85.71	100	
Overall accuracy	87.23%		Kappa statistic	84.04%		

vegetation conditions and human activities characteristic of the region: (1) the Putorana Plateau escarpment, an undisturbed area unaffected by anthropogenic modification and pollution, was selected as a control to assess only climate-induced change; (2) the populated area centered on the city of Norilsk and its satellite communities was selected to represent an area under immediate anthropogenic influence (industry, infrastructure, recreation); and (3) the area directly downwind of the smelting factories (to the southeast of the city) was selected to represent the impacts of pollution on the natural environment, but without direct surface disturbance from anthropogenic activities (Figure 1).

The undisturbed case study area (CSA1) is located approximately 100 km north-northeast of the city, covering the environmental gradient between the lacustrine valley and the Putorana Plateau. This location captures the topographic gradient and places the CSA outside the pollution zones associated with Norilsk mining and metallurgy activities. While the pollution 'boundaries' are not well defined due to changes in intensity of emissions and seasonal circulation patterns, this area has maintained its natural land cover. Analysis of heavy metal content in lichens and other vegetation types indicates that concentrations of metals in this area are at or near natural levels (Arctic Monitoring and Assessment Programme [AMAP], 2002; Baklanov et al., 2012; Zubareva et al., 2003).

CSA2 and CSA3 represent land covers affected by anthropogenic activity, as they are within the maximum pollution zone (AMAP, 2002; Baklanov et al., 2012; Vlasova et al., 1992). CSA2 includes the entirety of the Norilsk industrial complex with natural land covers largely transformed by human activities, including urban development (Norilsk, its satellite communities of Talnakh, Khaerkan, Oganer, Snejnogorsk) including mines, factories, roads, and other infrastructure. The area also contains summer cabins, small agricultural plots, and other recreational activities surrounding the city and satellite communities, including a winter ski resort. CSA3 is southeast of the city, in the direct path of

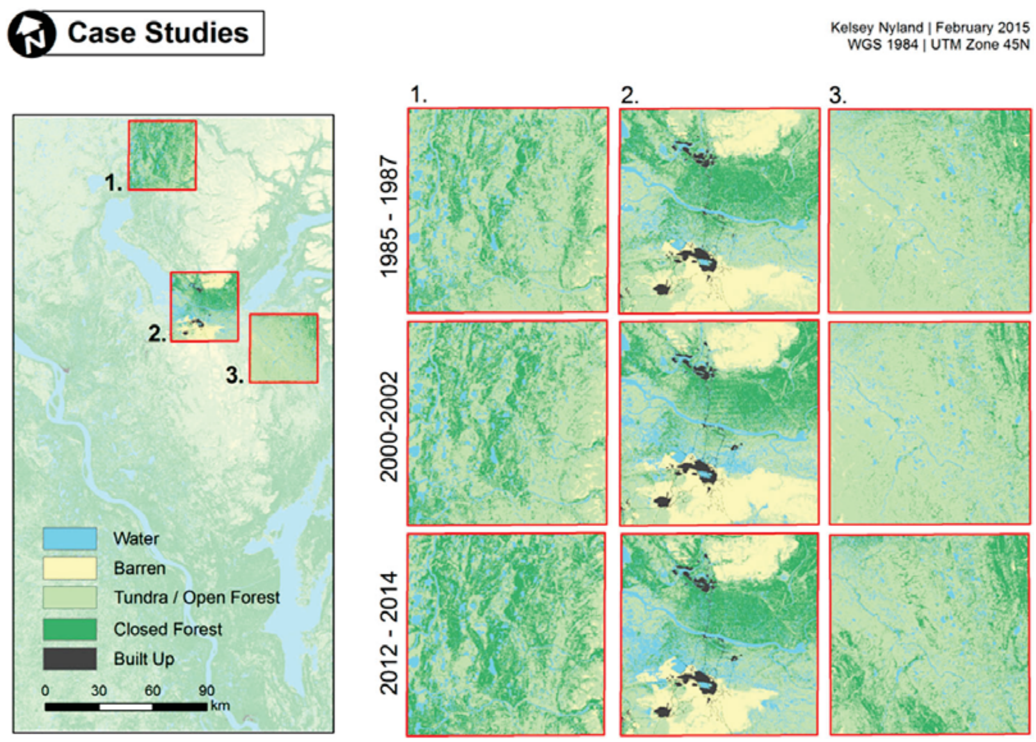

Figure 1. Map of the lower Yenisei River region previously mapped and case study areas representing (1) case study area (CSA) 1, an undisturbed area, (2) CSA2, Norilsk and its satellite communities, and (3) CSA3, an area in the direct path of pollution (downwind) from the Norilsk smelting operations. The right side panel shows each case study through the three time periods.

prevailing northwest winds that transport pollution generated from the smelters through the valley (Walter et al., 2012). While outside any direct human activity, this area allows the impacts of pollution on land cover changes to be discerned.

Using raster algebra tools in ArcMap version 10.1, land cover changes over the 30-year timespan were estimated for each of the CSAs based on the maps described above. Fieldwork conducted in the Norilsk region in July of 2011 and 2013–2015, in addition to personal communications with locals and researchers of Norilsk, were used to validate the land cover changes observed from the three maps.

To complement the detected land cover change mean annual temperature and total annual precipitation was calculated for the 1984–2013 period from the NASA-MERRA (Modern-Era Retrospective Analysis for Research and Applications) product as weather stations are not present in all three CSAs. Reanalysis data used were bounded by coordinates (70.41°N, 84°E) and (68.91°N, 90°E) totaling 16 cells at 1/2 by 2/3 degree resolution. Data for individual CSAs were also examined (2–3 MERRA cells each). Absolute values differed between the areas, but trends were in close agreement, therefore a larger number of pixels covering all three areas were aggregated to examine regional trends.

Results

The spatial extent of the five mapped land cover classes in the three observed time periods was calculated for each of the three CSAs as a percentage of the total CSA (2500 km^2)

(Figure 2). Distinct land cover and climatic changes detected for each CSA are discussed below.

CSA1: The undisturbed site

The most notable change in the control CSA was the 17% expansion of closed forest (425 km^2), resulting in relatively similar extent of both open and closed forests (45% and 43% of the total case study area or 1125 km^2 and 1075 km^2 respectively) as of 2012. This is drastically different from the mid-1980s, when open forests covered 63% of the area. Lakes and ponds occupy primarily the western portion of the area or at the base of the Putorana Plateau escarpment rising from west to east (Figure 1). There was a 50 km^2 or 2% increase in the extent of these water bodies over the last 30 years (Figure 2(a)). Barren ground, characteristic of the eastern part of the area on top of the plateau, was reduced significantly, now occupying a quarter of the area it did in the mid-1980s. However trends in surface hydrology and barren ground should be considered with respect to the accuracy of the classification algorithm, as these changes were relatively small and within only a few percentage points.

During the same 30 years mean annual air temperatures at screen height (2 m) have markedly increased at an average rate of 0.06°C yr^{-1} across all three CSAs based on NASA-MERRA data. Meanwhile, total annual precipitation for the region did not show significant change beyond annual variation (Figure 3). Consequences of warming temperatures thawing permafrost, thickening active layer, and increasing water availability to plants fosters the proliferation of larger woody species and the previously discussed 'Arctic greening' phenomena throughout all three CSAs.

CSA2: Norilsk proper and its satellite communities

Built-up areas within CSA2, including industrial and mining facilities and the road network, currently occupy 100 km^2 or 4% of the total area. Barren ground occupies 475 km^2 or 19% of the area. While there was only a 1% (25 km^2) increase in built-up area since the mid-1980s, there has been a relatively large (100 km^2) expansion of barren ground to the southeast of the city between the mid-1980s and the early 2000s. However 200 km^2 (8% of the total area) of barren ground was replaced by the open

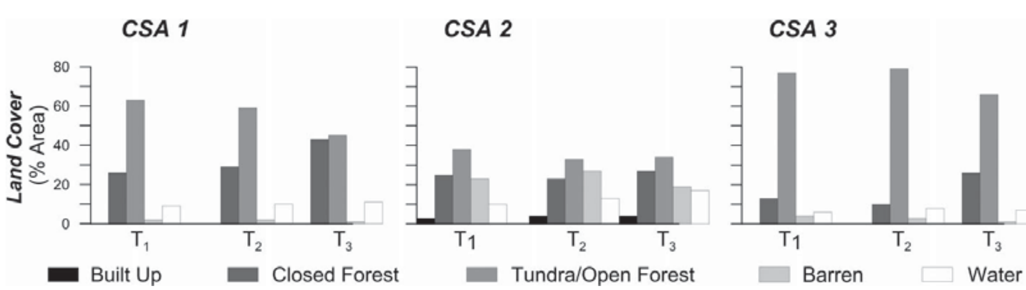

Figure 2. Adjacent bar graphs show the percent coverage of the five classified land cover classes across the observed time periods; 1985–1987 (T1), 2000–2002 (T2), and 2012–2014 (T3) for (a) CSA1 (the undisturbed area); (b) CSA2 (Norilsk and its satellite communities); and (c) CSA3 (downwind from the Norilsk smelting operations). Different land covers and the proportions of the CSA occupied are represented by different colors in the stacked bars.

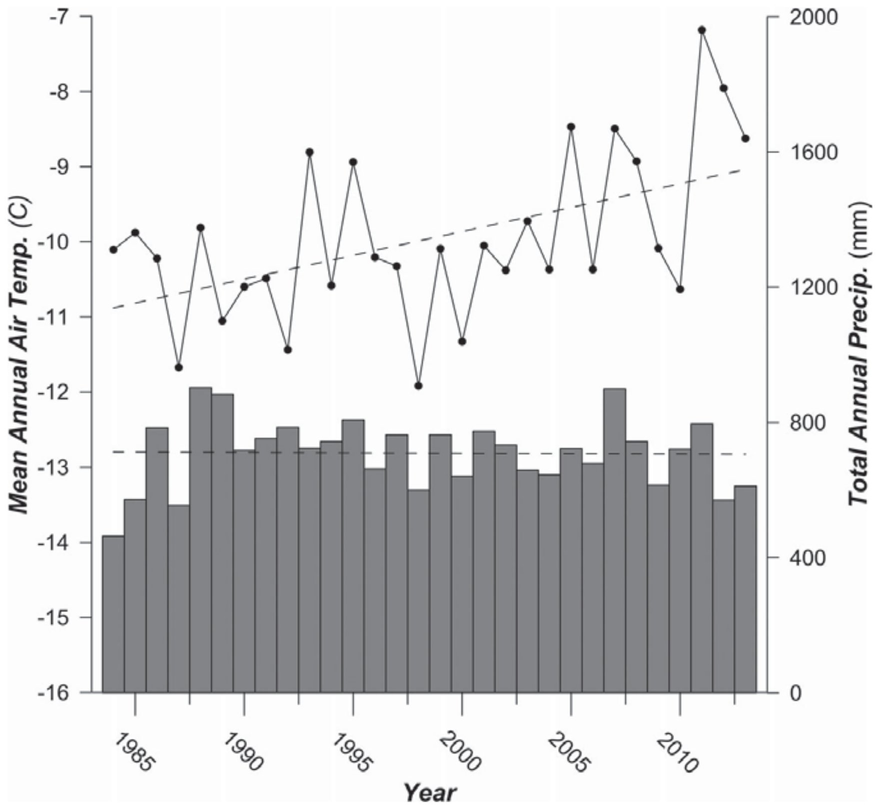

Figure 3. NASA-MERRA data and respective linear trend lines are shown for mean annual air temperature (°C) and total annual precipitation (mm) over the observed 30-year time period.

forest category by the last 2012–2014 period. An initial 175 km^2 decrease in both forest and tundra cover was followed by a 125 km^2 expansion. Water bodies increased consistently over the period of analysis by 175 km^2, which is similar to the undisturbed control area. The expansion of the area occupied by surface water is attributable to the increase in areal extent of preexisting lakes and ponds to the northwest of the city, and to formation of new ponds in the southeast.

CSA3: Downwind polluted site

Similar to the undisturbed area, closed forests within CSA3 underwent a substantial (16%) increase in extent between the early 2000s and the contemporary 2012–2014 period. However, open forests have remained a dominant vegetation class, accounting for 66% or 1650 km^2 in the 2012–2014 period. The progressive decrease in barren area in this case study area is also similar to CSA1 (Figure 2(c)). The area occupied by water shows some variability but no significant changes over the 30-year period.

Discussion

Climate-induced land cover change

Land cover changes that occurred within CSA1, the undisturbed site, show a pronounced greening trend over the 30-year period, manifested by the significant expansion of closed forests. Similar findings based on remote sensing analyses have been reported in other Arctic regions (e.g. Bhatt et al., 2013; Frost & Epstein, 2014) and are supported by a number of *in situ* studies, including the Polar Urals (Shiyatov et al., 2005), the eastern portion of the Taymir Peninsula (Kharuk et al., 2006), and in Alaska (Lloyd, 2005).

The expansion of larger shrubs and trees in the Arctic significantly lowers the surface albedo and increases regional heat absorption, contributing to warmer near-surface air temperatures and to the warming trend observed. However, vegetation monitoring over recent decades has shown that albedo change produced by albedo has a negligible impact on summer air temperatures compared to the albedo effects from a longer snow-free period (Chapin et al., 2005) evident from observed decreases in total annual precipitation and especially the slight decline in maximum annual snow depths in all three CSAs. Despite a slower change over time, the greening trends (tundra to shrub to forest conversions) are expected to continue and will eventually play a more significant role in the albedo feedback mechanism (Hinzman et al., 2013). Vegetation also acts as a thermal insulator for the ground thermal regime and changes in species complexes have significant implications for the degree to which atmospheric signals can impact ground temperatures.

Detected increases in water extent support previous studies of changes in surface hydrology in the Arctic. For example, Smith, Sheng, MacDonald, and Hinzman (2005) reported the formation of new lakes and the expansion of existing ones within the continuous permafrost zone in West Siberia over a similar time period. Increases in the number and areal extent of lakes can be attributed to thermokarst development, that is, subsidence-caused depressions filling with ground ice melt water (Karlsson, Lyon, & Destouni, 2014; Muskett & Romanovsky, 2011; Smith et al., 2005). Increases in the number and areal extent of lakes can be attributed to thermokarst development as precipitation did not increase over the study period.

Characterizing and quantifying land cover change such as these occurring in floristic tension zones, or transition areas like that from taiga to tundra in the Norilsk region, are key to improving vegetation and Earth system models (e.g. Pearson et al., 2013). Examples of ecosystem models applied to northern Eurasia for assessing Arctic vegetation change include BIOME4, ArcVeg, and TreeMig (Goetz et al., 2010). Biome4 is a continental to global scale, spatially oriented vegetation model driven by temperature, precipitation, and solar radiation (e.g. Kaplan et al., 2003; Kaplan & New, 2006). Based on a 2° C increase in global average temperature under several greenhouse gas emissions scenarios, shrub expansion and a shift in treeline are projected for the Taymyr Peninsula by 2026–2060 (Goetz et al., 2010; Kaplan & New, 2006). The climate-driven 1 km^2 resolution TreeMig forest model applied to a transect of Siberian lowlands also projected a latitudinal shift in treeline similar that detected in this study (Goetz et al., 2010; Lischke, Zimmermann, Bolliger, Rickebusch, & Löffler, 2006). The fine-resolution (1 m^2) ArcVeg model (Epstein, Walker, Chapin, & Starfield, 2000; Goetz et al., 2010) was developed to assess impacts of climatic warming on biomass and plant community composition based on nutrient availability. The model application to the Yamal Peninsula of Siberia indicates an increase in woody plant biomass, especially dwarf-erect and evergreen shrubs, with a corresponding decrease in the biomass of mosses and lichens (Goetz et al., 2010).

The proliferation of woody shrubs and trees projected by three Arctic vegetation models, for northern Eurasia correspond to general climate-induced changes observed by this study in the vicinity of Norilsk. However, more detailed, site-specific modeling approaches are needed to characterize secondary succession processes associated with anthropogenic disturbance (e.g. pollution) detected around Norilsk.

Anthropogenic land cover change

Results from CSA2 (Norilsk and its satellites) and CSA3 (downwind/polluted site) captured climate-induced changes compounded by the intensive anthropogenic activities in Norilsk. In CSA2, the initial slight increase in built-up area was due to the most recent development in Norilsk, a community called Organer, in the late 1980s. The road network was extended to this area and partial foundation and building construction had been initiated when all work ceased due to the loss of resources following the collapse of the Soviet Union in 1991.

Larger increases in the extent of water bodies in CSA2 and CSA3 as compared to CSA1 can be largely attributed to material being continually added to industrial waste-retention lakes in and near the smelting factories. New lakes that formed to the southeast of the city in industrial barrens in CSA3 are more likely to be the result of permafrost degradation, similar to what is occurring in CSA1, with the loss of insulative vegetation and increasingly warmer summer temperatures (Nyland, 2015).

Perhaps the most drastic impact on the environment surrounding Norilsk stems from SO_2-laden air pollution and particulate matter emitted from the local smelting factories. The process in CSA2 and CSA3 is likely one of secondary plant succession initiated by pollution, where the zone to the southeast of Norilsk quickly transitioned to barren ground early in the observation period and was then reclaimed by tundra/open forest covers, following changes in annual emissions (AMAP, 2002; Vlasova et al., 1992; Walter et al., 2012; Zubareva et al., 2003). Secondary plant succession is the process by which a disturbance reduces the extent of a previously established vegetative community that is eventually recolonized by more resilient species, in the case of Norilsk those resistant to SO_2-laden pollutants (Horn, 1974).

The third and largest smelting factory, Nadezhda Plant, began operation in 1979 just before the time period captured by the first land cover map used here. Following this, total airborne emissions (measure SO_2 and particulate matter as reported by Norilsk Nickel MMC) nearly tripled by 1983, after which emissions declined precipitously (Figure 4). SO_2 is consistently the greatest component of total airborne emissions (>95% of total annual emissions each year reported) from the Norilsk smelters; this and the heavy metals emitted cause damage to plant tissues, acidifying and leeching nutrients from the soils, eventually killing large swaths of the larch forest stands classified as closed forest (AMAP, 2002; Vlasova et al., 1992). The significant reduction in closed forest extent seen in the transition between the mid-1980s and early 2000s is likely a result of an increasingly exposed understory being classified as open forest, and in the more devastated areas as barren ground.

By the early 1990s the vegetative damage southeast of Norilsk was described as 'total vegetative damage' (AMAP, 2002) and 'catastrophic damage' (Vlasova et al., 1992). Where the following species were documented as being particularly affected by pollutants emitted from the smelters in Norilsk: lichens (*Cetraria* spp.), larch (*Larix gemelinii*), Siberian spruce (*Picea obovata*), and marsh labrador tea (*Ledum palustre*) (Vlasova et al., 1992).

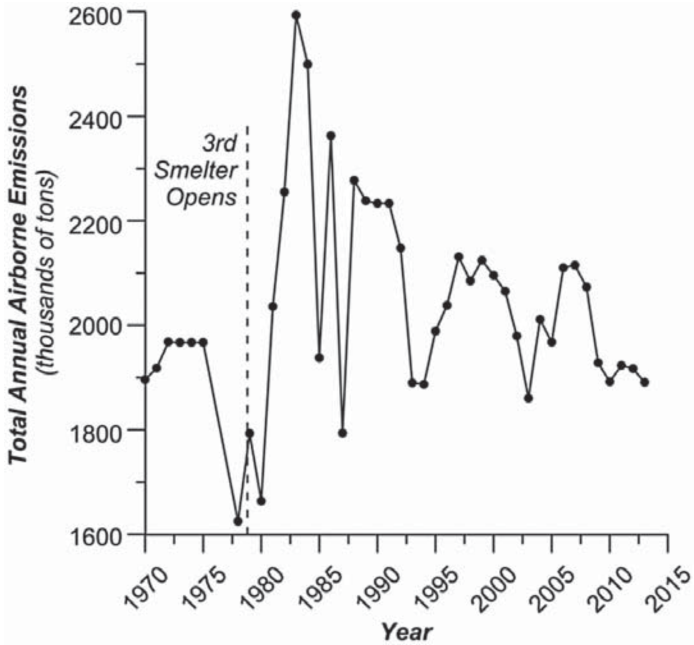

Figure 4. Total annual airborne emissions (sum of total SO_2 and particulate emissions) from smelting factories in Norilsk. The sharp increase in emissions in the early 1980s is attributable to the opening of the third smelter, Nadezhda, in 1979. Source: Norilsk Nickel Annual Reports and Kozlov et al. (2009).

In a survey of vascular plants conducted in July 2002 (Kozlov et al., 2009), some species were found to survive in areas close to the factories despite being in areas considered to have maximum pollution (within 2.5 km of sources). Species identified included dwarf birch (*Betula nana*), Siberian alder (*Duschekia fruticosa*), willows (*Salix* spp.), blueberries (*Vaccinium uliginosum*), horsetail grass (*Equisetum arvense*), and other grasses (*Poa* spp.). It is likely that the spatial trends noted in CSA1 and CSA2 are due to the removal of the taller canopy of the original larch forests opening the area to the succession of more pollutant resistant species, such as those documented by Kozlov et al. (2009). The possibility of secondary succession explaining the later greening is also tentatively supported by a test vegetation plot planted by the local company Norilsk Nickel. In this test plot they have successfully replanted dwarf birch (*Betula nana*), alder (*Duschekia fruticose*), and grass (*Poa* spp.) in a barren area immediately abutting a slag retention pond. However, increases in field-layer vegetation cannot necessarily be directly related to declines in the upper tree canopy (Zvereva & Kozlov, 2012).

The persistence of common field-layer species is in accordance with general trends in vegetation change documented around other smelting facilities, referred to as a ‘downward pattern of vegetation decline’, where only the upper canopy is adversely affected (Zvereva & Kozlov, 2012). *In situ* research conducted in the Fennoscandia region confirms the Arctic flora succession previously described. These studies focused on land cover changes due to emissions originating from smelters in Nikel and Zapolyarnyy, Russia, also production divisions of Norilsk Nickel MMC. Here, emissions cross the border into Finland and Norway where they have triggered similar plant succession processes (e.g. AMAP, 2002; Høgda, Tømmervik, Solheim, & Marhung, 1995; Tømmervik, Johansen, & Pedersen, 1995). These studies found that where pollution initially damaged tree cover and ground vegetation, several native shrub species such as crowberries (*Empetrum nigrum* ssp.), bilberrys (*Vaccinium myrtillus*), and grasses (*Poa* ssp.) (Tømmervik et al., 1995) all increased (AMAP, 2002).

Conclusion

This study compared remotely sensing-based land cover maps from time periods representative of significant changes in socio-economic conditions to; (1) quantify significant land cover changes in the vicinity of Norilsk industrial complex; (2) identify dominant climatic- and anthropogenic-drivers of these changes; and (3) to characterize secondary succession of Arctic vegetation induced by industrial pollution.

The effects of climatic forcing alone, as seen in CSA1, the undisturbed area north of Norilsk, produced a steady 'greening' effect, where larger woody plant species spread northward and the treeline advanced to higher elevations, in accordance with changes observed elsewhere in the Arctic. Increases in surface hydrology were also found, but within the accuracy of the method, and therefore cannot be considered significant. CSA2 and CSA3, encompassing the city and its satellites and a polluted area downwind respectively, represent locations where climate-driven changes are compounded by anthropogenic activities, primarily SO_2-laden pollution. The characteristic trend observed in these two areas was an initial expansion of industrial barrens as primarily closed forests were damaged by airborne concentrations of SO_2, particulate matter, and heavy metals. This was followed by marginal re-vegetation, primarily by tall shrubs more resilient to the pollutants constituting a secondary plant succession process.

The land cover changes evaluated over this 30-year period from the mid-1980s to the 2010s illustrate how anthropogenic influences can exacerbate climate-driven changes to land cover, and provide an important component to consider when discussing future development and sustainability of urban and industrial centers in the Arctic. This is becoming increasingly important in light of recent development to support settlements along the Northern Sea Route along the Arctic coast of Siberia. This work shows how the advanced state of urban-industrial centers in Siberia can provide insights that can lead to improved ecosystem modeling and more environmentally sustainable development practices.

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