Local land use associated with socio-economic development in six arctic regions

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Abstract

The socioeconomic causes of land use change are complex. They are highly context dependent, but most often studied through case studies. Here we use a a quasi-experimental paired block design to investigate whether better access to wage income leads to more visible land use around 28 settlements in six regions of the circumpolar Arctic. We mapped visible land use on high-resolution satellite images taken both close to the settlements, and in a more remote area of extensive land use, and payed special attention to tracks of off-road vehicles (ORV). Despite considerable differences among regions, there was an overall positive relationship between better access to wage income and land use. Reindeer herding was also associated with more visible use, in particular ORV tracks. These results suggest that access to wage income in the mixed subsistence-cash communities of the Arctic could lead to more local use related to harvesting and reindeer herding.

Keywords: arctic tundra, motorized vehicles, remote sensing, resource use**,** socio-ecological systems, subsistence

Introduction

Human use of land has transformed ecosystems and landscapes all over the world (Foley et al. 2005). The underlying environmental and socioeconomic causes of land use change processes are complex and often depend on broad-scale transitions in market demands, urbanization and globalization that interact with local land use systems (Rounsevell et al. 2012; Meyfroidt et al. 2013). To date most studies have investigated local land use change using a place-based, case study approach. Many of the empirical case studies provide a rich understanding about the constellations of drivers and the historical legacies that explain land use change at specific localities, but their transferability to other regions remain questionable (Vaclavik et al. 2016; van Vliet et al. 2016). Thinking in terms of counterfactuals through multiple case studies comparisons or natural experiments may address some of these scientific challenges of linking land use to socio-economic processes acting at a broader scale (Young et al. 2006; Meyfroidt 2015).

Deforestation, agricultural frontiers or urban expansion have been the main focus in land use studies, but small-scale land uses are also affected by similar socioeconomic changes (Sonter et al. 2015). Land use on the arctic tundra has rarely been researched, with the exception of a few mega-projects related to oil drilling in Alaska (Walker et al. 1987), or mining and gas extraction in northern Russia (Kumpula et al. 2011). Most of the arctic tundra is sparsely populated, difficult to access, and characterised by small indigenous communities that engage in harvesting renewable natural resources for local subsistence use (Larsen and Fondahl 2015; Fauchald et al. 2017). While in North America traditional harvesting activities consist mainly of hunting and fishing, in Eurasia reindeer herding is also important (Huntington et al. 2013). The land use legacies of small arctic settlements range from communities established by the government to settle nomadic populations in the 1930-60's, to older settlements forming as a result of trade and industrialization of furs or whale exploitation (Avango et al. 2014; Bennett 2016). Mineral extraction, geopolitics and military activities have also traditionally been used to encourage people to settle in the Arctic (Luzin et al. 1994). At present the melting sea ice allows for increased access through seaways (Buixadé Farré et al. 2014) opening new frontiers for resource exploitation and trade, and access to markets for these remote areas.

Economic development and increased market access to remote communities that depend on wild food harvest could substantially affect local land use (Kramer et al. 2009; Cimon-Morin et al. 2016). In the Arctic, the use of harvest technologies and motorized transport for subsistence hunting and fishing is limited by the financial costs of investing, maintaining and operating such equipment (Natcher et al. 2016). For example, fuel costs have been shown to affect the frequency, geographic area, or time spent on subsistence activities in Inuit communities (Behe 2011; Brinkman et al. 2014). But a transition to cash economy may also lead to increasing reliance on store-bought food (Loring and Gerlach 2009), decreasing the need for harvesting activities. Moreover, the opportunity to sell wild food may affect the patterns of resource and land use (Fauchald et al. 2017). Reindeer herding is central to Eurasian indigenous cultures such as that of the Sami and Nenets people (Jernsletten and Klokov 2002). Herding practices and lifestyles of herders are also changing depending on cash income, marked access and technology (Riseth and Vatn 2009; Hausner et al. 2011; Stammler 2013), although possibly in a different way than for other forms of wild food harvesting. Furthermore, in-migration resulting from employment opportunities may also alter remote communities by changing lifestyles, resource use and the traditional resource management (Kramer et al. 2009).

Our purpose is to empirically investigate how contrasts in socioeconomic conditions have influenced arctic land use. We include six regions from arctic Russia, Canada and Alaska encompassing different cultures, land use legacies, governance systems and landscapes, and investigate the relationship between socio-economic conditions and visible land use associated with 28 settlements based on remote sensing. We asked whether economic development and better access to wage income in the settlement was related to higher land use, or whether on the contrary most visible use occurred around settlements relying mostly on wild food harvest. As human use of land in the Arctic largely depends on motorized access, we specifically analysed tracks of off-road vehicles (ORV).

Since most settlements in the Arctic are mixed subsistence-cash communities (Larsen and Fondahl 2015), we expected that better access to wage income would be among the main causes of differences in land use. Higher level of wage income will most likely lead to more permanent transformation of land in and around settlements such as buildings and roads (Maurer 1992; Forbes et al. 2004), but the effects on local land use associated with wild food harvest, reindeer herding and recreation is less clear in the literature. On the one hand, it has been suggested that increased wage income could increase the dependence on store-bought food and reduce the investment in subsistence activities (Loring and Gerlach 2009; Fauchald et al. 2017). This would reduce the extensive land use related to hunting and fishing, and consequently the amount of traces from e.g. ORV tracks and camp sites. However, it has also been suggested that subsistence activities are constrained by the high expenses associated with off-road vehicles, fuel, hunting equipment and other supplies (Brinkman et al. 2014; BurnSilver et al. 2016). In this case, increased wage income could increase the opportunities for extensive harvesting, and consequently the amount of visible signs of land use. Reindeer herding requires a high level of activity in the tundra, and is associated with a nomadic lifestyle in the Russian Arctic (Jernsletten and Klokov 2002). Wage income and market access may encourage people to adopt a sedentary lifestyle in the settlements, or, on the contrary, allow the adoption of new technologies in the traditional nomadic way of life

(Stammler 2013). Therefore the relationship between socio-economic conditions and visible land use may be different in areas where reindeer herding is important.

The use of a quasi-experimental design consisting of pairs of contrasted settlements within the same kind of landscapes (blocks), allowed to control for the large-scale differences across regions, and thereby disentangle the effects of wage income on the intensive and extensive land use in the subsistence-oriented arctic communities from their historical legacies. We hypothesized that the relationship of wage income to ORV tracks could differ between the immediate surroundings of the settlement and the more remote areas, which are used less often and only in relationship with specific harvest or recreational activities. If increased access to wage income increased the opportunities for harvest and other extensive nature-based activities, we would expected an increase in ORV tracks in these more remote areas. Alternatively, if increased access to wage income reduced the investment in subsistence activities, we would expected a reduction in ORV tracks. As reindeer herding results in more intensive land use than hunting, gathering or fishing, we predicted that it would increase the amount of visible land use on extensive use images. We also investigated a possible interaction between reindeer herding and income, asking whether better access to wage income would affect this specific type of land use differently than other activities.

Material and Methods

Study area and choice of settlements

Our study encompassed six administrative regions (Fig. 1A): Alaska (USA); Nunavut and Labrador (Canada); and Murmansk, Yamal and Taimyr (Russia; Fig. 1). The regions represent different governance systems, histories, cultures and ethnicities, as well as different biophysical landscapes. To control for the regional differences, we employed a block-design where pairs of neighbouring settlements (200-5000 people) were treated as a random block factor. Within each region we chose 2-3 pairs of settlements located in the low Arctic or sub-arctic climatic zones (Fig. 1A). Within each pair we contrasted settlements with better opportunities for wage income (high income - H) to settlements with less opportunities for employment where subsistence harvest is more important in supporting people's livelihood (low income - L) by using data on i) household income; ii) employment rate; iii) poverty rate; presence of iv) industry; v) administrative centres; and vi) transportation hub (Table 1). In Alaska, data were collected from the community database provided by the State of Alaska, Department of Commerce, Community and Economic Development (https//www.commerce.alaska.gov/dvra/DCRAExternal/Community) and official web-sites. In Canada, data were collected from Statistics Canada, National household Survey, 2011 (https://www12.statcan.gc.ca/nhs-enm/2011/dp-pd/prof/index.cfm?Lang=E) and official web-sites. No data on poverty rate was available from Canada. Due to lack of data at the settlement level, the Russian settlements were classified based on the presence of industry, administrative centres or transportation hubs based on the official web-sites of the regional administrations and the municipalities. This information was confirmed by visits to most of the settlements in 2012 (Appendix S1). Some H-settlements were related to oil and gas extraction or mining sites. Other H-settlements were regional hubs, where the local administration, hospital, commercial companies or transportation facilities (airport) etc. offered employment opportunities. In L-settlements most of these elements were absent, and wild food harvest, including reindeer herding, together with services (e.g., school, shop) constituted the main activities of residents. In Alaska and Canada, the settlements were rather similar with respect to these characteristics, and the classification was based mainly on socioeconomic data.

In addition to access to wage income, we expected visible land use to depend on population size, settlement age, reindeer herding, and landform. Data on population size, settlement age and reindeer herding were obtained from the sources given above (Table 1). With respect to landforms, plains with soft ground (e.g. bogs) are likely to be more prone to visible ORV tracks than harder substrate such as stony hills. The main landforms for the area covered by each satellite image was determined based on a worldwide layer of landform types according to Hammond's classification (ESRI™). This classification was simplified as *Plain* or *Relief* (hills, mountains or tableland with moderate or strong relief) and summarized as the proportion of plain in each image (Table 1).

Satellite image analysis

Visible land use around settlements was mapped on high-resolution satellite images (Quickbird™, GeoEye™ and World View II™). For each settlement, two ca. 10x10 km^2 images were obtained. One image included the settlement and revealed *intensive use* in its immediate vicinity. The other image was placed at a random location 30 km from the settlement, and was used to map *extensive use* far from the settlement (Fig. 1B; Appendix S1). Images were taken mostly in July and August between 2006 and 2012 (Table S1).

All visible land use was mapped. We recorded settlement areas, cultivated land, areas of intense grazing, ORV-tracks, landfills, garbage deposits, fences, camps, mining activity, electrical power lines, pipelines, drilling sites, quarries, other man-made structures and undefined traces of human activity. Traces were detected visually in the satellite images using methods similar to those used by Kumpula et al. (2010) and Tømmervik et al (2012). Visual detection and interpretation was based on both panchromatic and pan-sharpened multiband images (4 channels). Detection was facilitated by enhancement techniques like edge-detection, contrast stretch, histogram-equalization and different filtering methods (Gonzalez and Woods 1992). All detected objects and traces were manually delineated in each image at a 1:2000 resolution using ArcGis 10 software (ESRI^{TM} ArcMap 10.0).

Statistical analysis

To estimate the area occupied by visible land use, objects mapped as lines or points were transformed to polygon features. We created three response variables for the statistical analysis: i) the total proportion of the area of with visible land use; ii) the proportion with permanent structures including buildings, roads and airfields; and iii) the proportion with ORV tracks. These proportions were calculated relative to the visible land area of the images after subtracting the surface of lakes, rivers, sea and clouds.

We used generalized additive models with a logit link and a beta distribution as implemented in the package GAMLSS (Rigby and Stasinopoulos 2005) in R version 3.3.2 (R Core Team 2017) to analyse these area proportions. Intensive and extensive use areas were analysed separately. For *intensive use areas*, we analysed the total proportion of area with visible land use, the proportion with permanent structures, and the proportion with ORV tracks as a function of wage income (H or L). Settlement pair was included as a random factor in all models to reflect the block design. Candidate models with different covariables were assembled for each response variable (Appendix S1, Table S2). The most parsimonious model was chosen based on GAIC (Rigby and Stasinopoulos 2005) following a forward model selection approach. The results of the selected models were reported as parameter estimates for fixed effects with 95% confidence intervals (CI).

For *extensive use areas*, we analysed the total proportion of area with visible land use and the proportion of area with ORV tracks as a function of wage income and the presence of reindeer herding. Candidate models for each response variable included the focal fixed factors wage income and reindeer herding either as additive effects or with an interaction (Appendix S1, Table S3). Model choice and assessment of model fit were carried out as for intensive use areas.

Results

Settlements classified as H (higher opportunity for wage income) were in general larger (mean population size = 1385, SD = 855) than L-settlements (mean = 945, SD = 872), but the difference was not significant (pairwise t-test: $t = -1.35$, $p = 0.19$). Settlement age differed little between the two groups and was on average 118 years (SD = 66) for L and 140 years (SD = 144) for H settlements.

Regions: There were large contrasts in amount and type of visible land use on the different images and among the six regions (Fig. 2). Between 0.84% (Novaya) and 36.3% (Seyakha) of the total area of the intensive use images consisted of visible traces of land use (mean = 8.8 %, SD = 9.5). As expected based on the definition of the areas, there were considerably less traces on the extensive use images. No visible land use was identified on four extensive use images from North America (Chesterfield Inlet, Nain, Rigolet, and Noorvik). The images with the largest proportion of land use (ca 3%; Fig. 2) were from Russia (Mys Kamennyi and Tumannyi). On the remaining extensive use images, 1.5% or less of the area consisted of visible land use. ORV tracks represented the main proportion of land use in Russia (Fig. 3A). Only on the intensive use area image from Zapolyarnyi, permanent structures occupied more space than ORV tracks (Fig. 2, Fig. 3B). In Canada, on the contrary, permanent structures were more important than ORV tracks (Fig. 3C), but the proportion of area affected by visible land use was in general lower, in particular in Labrador (Fig 3D). In Alaska very little visible land use was recorded on extensive use images.

Intensive use area: When controlling for the large regional differences (through the use of settlement pair as random effect) and focussing on contrasts within the block design, the total proportion of area visibly affected by land use in intensive use areas was best explained by a model including landform in addition to wage income. All other candidate models obtained ΔGAIC values > 2, and GAIC did thus not support the inclusion of the covariates population size, settlement age or reindeer herding (Table S2). The model showed that there was on average 1.7 times more visible use around H-settlements than around L-settlements (effect on the logit scale 0.58, 95% CI: 0.22 – 0.94, n = 28; Table 2). Local land use occupied thus a larger area around settlements with better opportunities for wage income, independent of population size and settlement age. There was also a positive relationship with the proportion of plain on the images (landform). The predicted difference between an image with 0% plains and 100% plains was in the same order of magnitude as the effect of wage income (effect on the logit scale 0.56, 95% CI: 0.10 – 1.02; Table 2).

When analysing only ORV tracks, the results were nearly identical. For permanent structures, the most parsimonious model included landform and log age in addition to wage income. A model including also reindeer herding obtained nearly the same GAIC value, but included more parameters. All other candidate models obtained ΔGAIC values > 2 (Table S2). The selected model revealed a positive relationship of wage income to the area occupied by permanent structures, which was slightly larger than for the two other response variables. The confidence intervals for the estimates of the effect of landform and age did not exclude 0, indicating that these variables had only a small effect (Table 2).

Extensive use area: Most of the visible land use recorded in extensive use areas consisted of ORV tracks. For both response variables, GAIC did not support an interaction between wage income and reindeer herding (ΔGAIC = 0.63 and 1.92 for total and tracks respectively; Table

S3). The best models included landform and log of the age of the settlement in addition to additive effects of wage income and reindeer herding. All other candidate models obtained ΔGAIC values of 1.99 or more. The results indicated that there was more visible land use in areas related to H-settlements, and this effect was slightly larger than for the intensive use areas (effect on the logit scale 1.02, 95% CI: 0.61 – 1.43 for total; Table 2). As predicted, the amount of visible land use was also clearly higher in areas with reindeer herding. For total proportion, the confidence intervals for the estimates of the additional factors landform and age of the settlement did not exclude 0, indicating that these factors had only a small effect. For tracks, however, there was a slightly negative effect of age, indicating that there were more tracks in extensive areas related to newer settlements.

Discussion

There is a large heterogeneity in land use among the different circumpolar regions, which need to be accounted for to identify general relationships between socioeconomic conditions and local land use. Land use has often been studied through local case studies and generalizations have mainly been based on qualitative meta-studies (van Vliet et al. 2016). Here, on the contrary, by using pairwise contrasts between neighbouring communities, we were able to detect broad scale patterns of land use in relation to economic development despite the regional differences in biophysical conditions and historical legacies of land use. We found more visible land use where people had better access to wage income in settlements from six regions from the circumpolar North. This was true both for intensively used areas within 10 km of the settlement, and for more distance areas (ca 30 km) reflecting the extensive landscape use of local people. As predicted, permanent structures such as buildings and roads were more important where there was better access to wage income in settlements. But this was also true for ORV tracks in intensive as well as extensive use areas. Moreover, reindeer herding, a more intensive land use activity than subsistence harvesting, was also associated with more visible land use in extensive use areas. Our results are thus compatible with a hypothesis suggesting that wage income leads to increased use of ORV related for instance to harvest activities, reindeer herding or recreational use in mixed subsistence-cash communities.

If ORV tracks reflect an increase in harvest activities, our findings are in agreement with previous reports documenting that wage income can support wild food harvesting by covering some of the high expenses associated with off-road vehicles, fuel, and other supplies (Ready and Power 2018). The importance of high expenses in limiting the extent of land use by local people has been documented in previous case studies from Alaska (Brinkman et al. 2014; BurnSilver et al. 2016), Canada (Pearce et al. 2015) and for reindeer pastoralism in Norway (Riseth 2006). Brinkman et al. (2014) found that higher fuel prices were associated with reduced number of hunting trips and distance travelled. The access to wage income may allow a larger spatial extent of local land use (Wenzel 2009). The costs of travelling thus seem more important than the time available to hunt, fish or collect berries and mushrooms for explaining local land use in the Arctic. These findings must also be seen in relation to the sharing networks in the communities, where costs of local land use and wild food harvest may be shared among the members of the community (Wenzel 2009; BurnSilver et al. 2016) and considered as investment in social relationships (Ready and Power 2018).

Nenets reindeer herders in Yamal and western Taimyr live as nomadic families and migrate with their herds resulting in permanent human presence and activity on the tundra (Forbes et al. 2009). They also live for various periods of time in camps, where they pursue traditional harvest activities, mainly fishing. It is possible that with increased access to income, tundra inhabiting Nenets may afford to use motorized transportation more often and increase the number of trips for instance to the village to buy fresh supplies. Our data did not, however, support an interaction between income and reindeer herding, indicating that the positive effect of access to wage income on the amount of recorded tracks was similar to the rest of the Arctic, despite overall higher levels of visible land use associated with reindeer herding in extensive use areas.

Our results indicate that the mixed subsistence – cash economies of the Arctic may differ from more remote indigenous communities that rely on harvest for subsistence elsewhere in the world. For example, in Ecuadorian Amazonia households with better income from employment harvested smaller amounts of wild meat (Vasco and Siren 2015). Elsewhere, Iwamura et al. (2014) found that the increase in size and age of a village is among the most important factors explaining land cover change and hunting. Village size and age were little influential in our analyses of local contrasts in land use. Other recent studies have also underscored the importance of studying wage income, market access and socioeconomic development to understand changing use of subsistence hunters and fishermen (Cinner et al. 2012; Fauchald et al. 2017).

Local land use recorded in our case is, however, not purely related to subsistence activity. Activity tracks detected on satellite images cannot be clearly assigned to one type of activity, therefore the observed patterns need to be interpreted with caution. Our observations when visiting the communities showed that in some of the settlements visible industrial use has also been recorded, increasing the total area used. This was the case for Gaz Sale and Zapolyarnyi on Yamal (Fig 3B), and to some extent for Tukhard and Baker Lake (Table 1). All of these settlements were classified as H because of the ongoing industrial activity, which may have contributed to the positive effect of wage income on visible traces in intensive use areas. This industrial use may also be related to the negative correlation observed between settlement age and ORV tracks in extensive use areas, as the industrial settlements are often quite recent (Table 1). Moreover, recreational driving may have been important in Murmansk and is also likely to increase with increased access to wage income.

Differences between regions

In general, there was more visible land use in Russia than in North America, but the proportion of used land occupied by permanent structures was larger in Canada than in the other studied regions. There were also considerable differences among the three Russian regions. Overall, there was little visible land use in Alaska. Several historical and contemporary factors may explain these differences.

The main type of local land use is likely to explain some of the observed regional differences. Yamal is a prosperous reindeer herding area (Forbes et al. 2009; Klokov 2011). Although Nenets still use reindeer sledges as their main means of transportation year round, the use of motorized vehicles is increasing. The presence of a tundra population is also likely to lead to more traffic between the settlements and the nomadic camps. Nenets in western Taimyr (Nosok) are poorer, and do not use motorized transport to the same extent. In eastern Taimyr, on the contrary, wild reindeer, which are hunted in fall/winter, constitute the major harvested resource together with fish. Wild reindeer are often hunted in more or less stationary camps close to rivers, or using snowmobiles after the rivers freeze up and the ground becomes snow covered. Most fishing is river fishing, where transportation occurs by boat (Fig. 4D). These harvesting methods can be intensive without leaving visible traces. In Labrador, where the least visible land use was recorded, marine fisheries constitutes the most important natural resource. Also for fresh water fishing and hunting, the main means of transportation are boats and snowmobiles (MacDonald et al. 2013), which do not leave any visible tracks on the vegetation (Fig 3D). In Nunavut, where caribou hunting is more important, visible land use is a bit more widespread, although still low compared to levels observed in Russia. Alaska was characterised by very little visible activity in extensive use areas, possibly because most travelling occurs with boats or snowmobiles. An important source of potential bias when analysing local land use from high resolution satellite images results thus from the different means of transportation used (Fig. 4).

The chosen regions differ also in their legacy of industrial development. Thus, considerable oil and gas exploration and exploitation is taking place in the Yamal region since the Soviet period. A first wave of development in the 1970s and 1980s (Kumpula et al. 2010) was followed by a relative stagnation after the end of the Soviet period in 1991. At present, development is in a boom phase again. Because of the heavy vehicles used in Russia, in particular in the past (Fig. 4A), some old traces, for instance in the extensive use image of Mys Kamennyi or Seyakha, may still be visible today (Forbes et al. 2004), although there is little industrial activity at present. Visible land use related to past and present industrial development may have been recorded in the extensive use areas of both H and L settlements on Yamal, and are thus less likely to have affected our result compared to the intensive use areas. There are also large oil exploitation projects, both past and present, in Alaska, but this activity was not reflected in visible land use to the same extent as in Russia – possible because of the use of different vehicles (Slaughter et al. 1990).

Our study focused on remote settlements in the Arctic, an area with very low population density. The Murmansk region is the most populated region included. Moreover, there is road access to three of the four settlements studied in this region (Teriberka, Tumannyi and Lovozero), which are all accessible within a couple of hours driving from the city of Murmansk (population 300 000). Teriberka is the only place in Russia where the coast of the Arctic Ocean can be visited without special permits. Recreational use by urban citizens and tourism is thus important in this region. This is likely to explain some of the ORV tracks recorded, notably in the extensive use area of Tumannyi, which is an area where residents of Murmansk may go for fishing, hunting or berry picking trips. At the same time the presence of roads may have relieved some of the ORV traffic around settlements, as people can drive cars along the road to some harvesting or recreational destinations.

The dominance of permanent structures in Canada could be explained by housing (Fig. 2). In Canada, houses are usually built for each family separately resulting in more space for roads or squares between them. Most Canadian and Alaskan settlements have a permanent air field (Fig. 3C), whereas many smaller Russian settlements are only accessible by boat or helicopter. Russian arctic settlements are more compact. Larger settlements often have several story houses with apartments (Khatanga, Tumannyi, Teriberka), in addition to older small houses, reducing permanent structures in the settlement. Also small settlements such as Novaya consist of houses with several apartments (2-4) in each.

Conclusions

By using counterfactuals to focus on socioeconomic contrasts between pairs of otherwise comparable settlements, we were able to statistically show the generality of a positive relationship between wage income and local land-use despite the large differences among the six arctic region. But, our result is only a rough indication of this pattern and further research should include market integration and socioeconomic development more explicitly and quantitatively (Verburg et al. 2011). Moreover, the context dependency of local land use and wild food harvest underlines the importance of combining large scale counterfactual designs with knowledge of the local situation to avoid misinterpretations. Indeed, despite the fact that less visible land use surrounded the poorer communities, other research documented that subsistence food is very important in these settlements and may be used in larger amount per person than in communities with higher degree of wage income, where store-bought food is more accessible and affordable.

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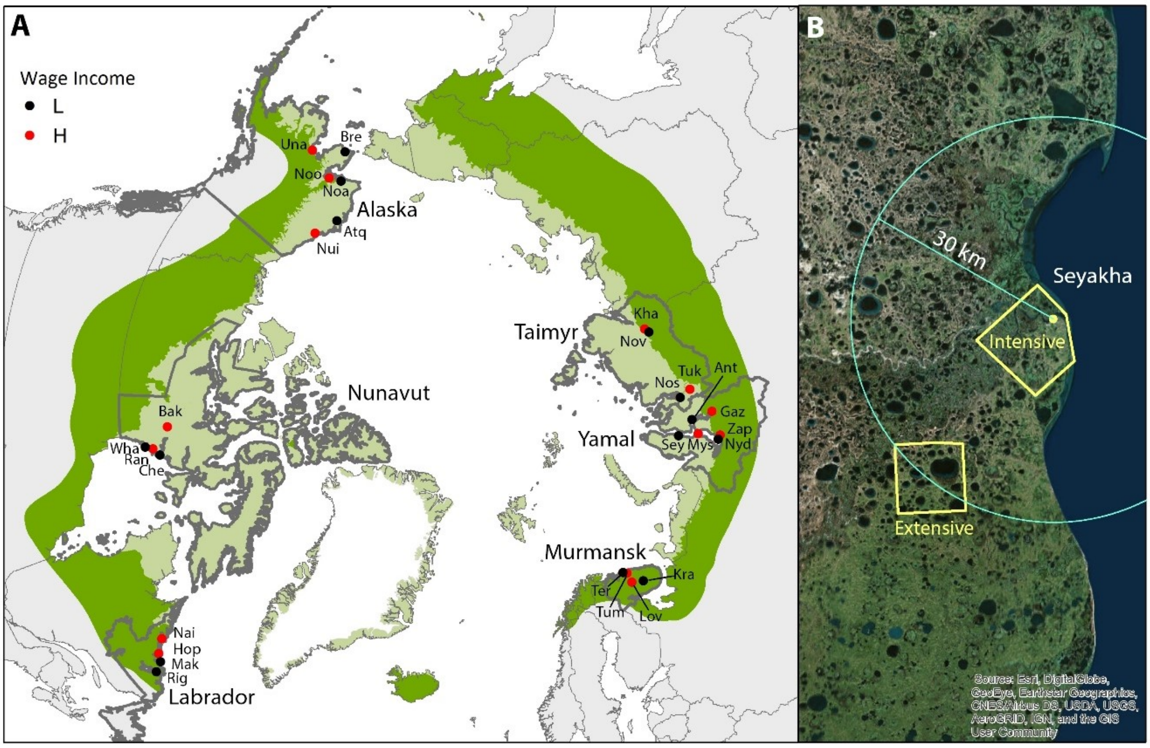

Figure 1. Study design. A) Regions and selected settlements. Study regions, Murmanskaya Oblast' (Murmansk), Yamalo-Nenetsky Autonomous Okrug (Yamal) and the northernmost part of Krasnoyarskiy Kray (Taimyr) are surrounded by thick grey lines. Three letter code indicates settlement name (see Table 1). Wage income: L = settlements with low access to wage income, H = settlements with high access to wage income. Pale green shows the Arctic according to the Circumpolar Arctic Vegetation Map (Walker et al. 2005) and darker green shows the subarctic. B) Example of the selection of areas for satellite pictures of an intensive use area and an extensive use area.

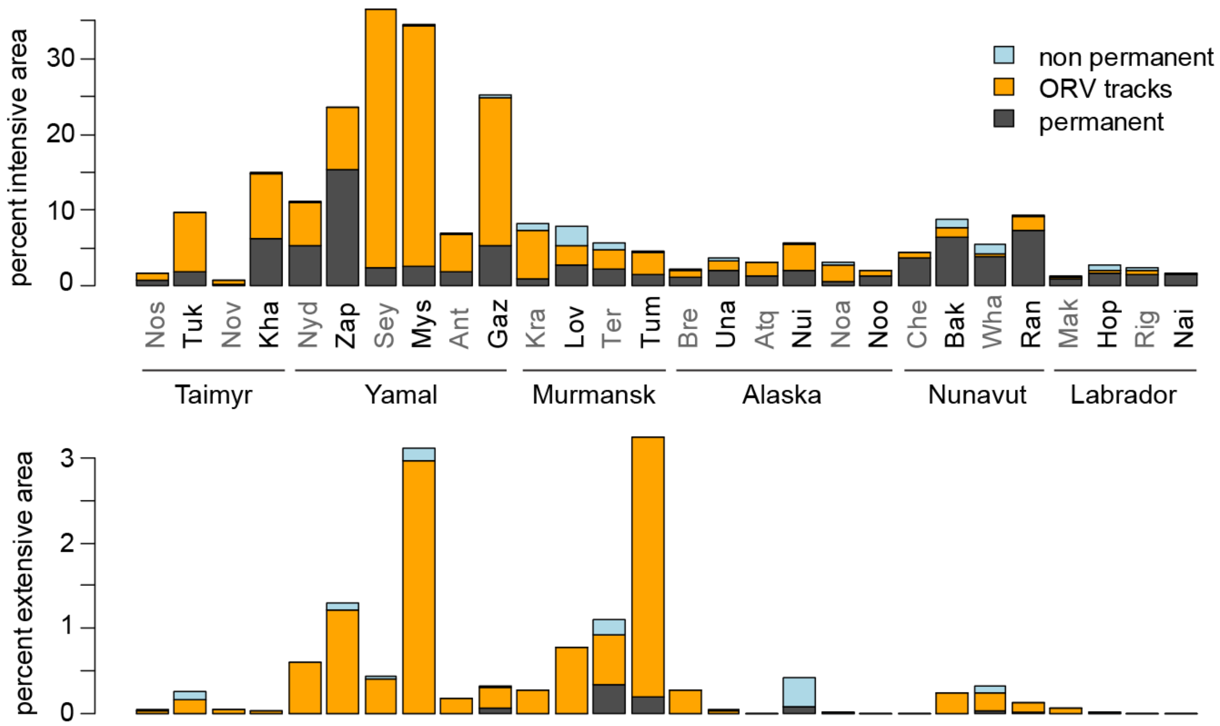

Figure 2 Percent land area occupied by visible land use on each image. The upper panel shows intensive use area images, which included the settlement itself. The lower panel shows extensive use area images situated 30 km from the settlement. Note the different scales. Visible traces are shown according to the categories permanently transformed habitat, ORV tracks, and other non-permanent land cover transformation. Full names of the settlements are given in Table 1.

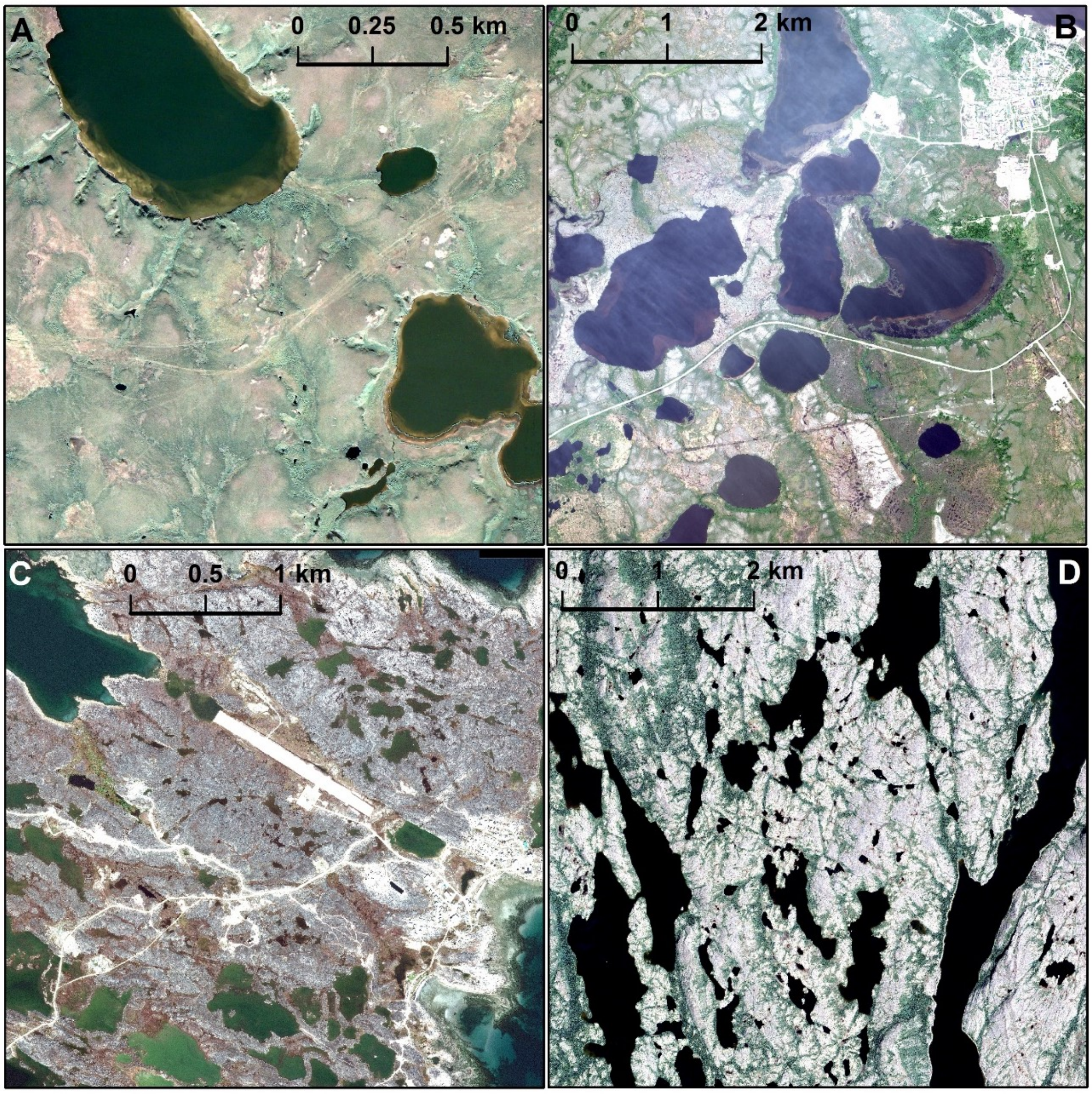

Figure 3 Examples of satellite pictures. A) The extensive use area of Mys Kamennyi was characterized by a high amount of ORV tracks. The high amount of tracks observed in extensive areas on Yamal Peninsula can be related both to reindeer herding and to the fact that the areas is at present experiencing the second wave of development related to oil-and gas exploitations. B) Intensive use area image from Zapolyarnyi, the only area in Russia where permanent structures were more extensive than ORV tracks. Many of the structures on the present image are likely to be related to the gaz industry. C) Settlement area of Chesterfield Inlet, a settlement with a population of 313 in Nunavut, Canada, classified as low access to wage income. Permanent structures such as buildings and roads were more important than ORV tracks in Canada. D) No visible traces of human use were recorded in the extensive use area of Hopedale in Labrador (Canada). In this area boats and snow scooter are main means of transportation, and the stony ground is less prone to show visible traces of use.

Figure 4 Large size Russian off-road cars leave easily visible and persistent tracks, sometimes already after a single passage over a stretch of tundra, whereas intense land use based on boat or snow scooter traffic, which are cheaper means of transportation used a lot in the poorer Russian settlements and in North America, do not leave visible tracks at all. A) heavy chain vehicles were used in the Russian Arctic in the past, which left deep and long-lasting traces in tundra areas on soft ground, here wet areas (Photo V. Belov). B) Also many modern Russian ORV, such as this off-road car in Yamal, are of considerable size and thus prone to leave tracks which can be identified on satellite imagery pictures (Photo I. Fufachev). C) In Alaska and Canada people typically use smaller and lighter ORVs (Photo J. Schmidt). D) Intense fishing based on boat traffic does not leave visible land use traces in Novaya, Taimyr (Photo A. Khrushev).

Table 1. Characteristics of the studied settlements and criteria used to classify each settlement as H (high opportunity for wage income) or L (low opportunity for wage income; WI). Hub includes the presence of administrative centres and/or the presence of a transportation hub. Income is the median household income in USD for Alaska and in CAD for Canada. Employment is the employment rate of residents above 15 years and Poverty is the percentage below poverty level. Reindeer herding refers to the presence of reindeer herding in the area (1). Landform is the proportion of the area classified as plain in the intensive and extensive use areas respectively.

Country	Region	Settlement	Population	Founded	WI	Industry	Hub	Income	Employment	Poverty	Reindeer herding	Landform (I – E)
Russia	Taimyr	Khatanga	2960	1626	H	0	1	_	_	_	0	27 - 100
Russia	Taimyr	Novaya	313	1940	L	0	0	_	_	_	0	100 - 100
Russia	Taimyr	Tuchard	814	1970	H	Gas extraction	0	_	_	_	1	100 - 74
Russia	Taimyr	Nosok	1692	1850	L	0	0	_	_	_	1	100 – 91
Russia	Yamal	Zapoliarnyi	1035	1986	H	Gaz pipeline hub	0	_	_	_	1	100 - 100
Russia	Yamal	Nyda	1763	1896	L	0	0	_	_	_	1	100 - 100
Russia	Yamal	Mys Kamennyi	1639	1950	H	Post-industrial[2]	0	_	_	_	1	100 - 100
Russia	Yamal	Seyakha	2612	1936	L	0	0	_	_	_	1	100 - 100
Russia	Yamal	Gaz Sale	1917	1966	H	Gas extraction	0	_	_	_	1	100 - 100
Russia	Yamal	Antipayuta	2591	1930	L	0	0	_	_	_	1	100 - 100
Russia	Murmansk	Lovozero	2871	1516	H	0	1	_	_	_	1	75 - 2
Russia	Murmansk	Krasnoshelie	423	1920	L	0	0	_	_	_	1	66 - 91
Russia	Murmansk	Tumannyi	685	1971	H	Hydroelectric plant	0	_	_	_	0	0 - 1
Russia	Murmansk	Teriberka	957	1870	L	0	0	_	_	_	0	0 - 0

Canada	Labrador	Nain	1185	1771	H	0	1	62663	74	_	0	0 - 0
Canada	Labrador	Hopedale	555	1782	L	0	0	58485	68	_	0	0 - 0
Canada	Labrador	Makkovik	365	1860	H	0	0	63959	64	_	0	0 - 0
Canada	Labrador	Rigolet	310	1735	L	0	0	46173	53	_	0	0 - 0
Canada	Nunavut	Baker Lake	1865	1924	H	Mining	0	73959	81	_	0	13 - 96
Canada	Nunavut	Chesterfield Inlet	313	1911	L	0	0	*	*	*	0	94 - 82
Canada	Nunavut	Rankin Inlet	2245	1955	H	0	1	111560	85	_	0	100 - 69
Canada	Nunavut	Whale Cove	410	1950	L	0	0	54181	79	_	0	100 - 100
USA	Alaska	Nuiqsut	470	1973	H	Oil and gaz extraction	0	85833	77	3	0	100 - 100
USA	Alaska	Atqasuk	221	1977	L	0	0	51500	69	21.5	0	100 - 100
USA	Alaska	Noatak	583	1910	H	0	0	56250	65	19.9	0	91 - 0
USA	Alaska	Noorvik	644	1920	L	0	0	52500	59	29.3	0	83 - 49
USA	Alaska	Unalakleet	758	1830	H	0	0	57188	70	16.6	0	32 - 14
USA	Alaska	Brevig Misson	418	1900	L	0	0	32143	66	61	0	2 - 21

* Data for this area has been suppressed by statistics Canada for data quality or confidentiality reasons.

[1] Mys Kamennyi was established in the frame of gas exploration and transportation, but at present there is not much industrial activity left in the settlement. For sources see main text.

Table 2 Parameter estimates for the selected generalized additive models (logit link and a beta distribution) describing the relationship of visible traces of human use to wage income. Parameter estimates are given on the logit scale with 95% confidence intervals. For factors, they are presented as contrasts to the reference level as indicated in parenthesis. a) Intensive use areas. Fixed effects are wage income (WI: H – higher opportunity versus L – lower opportunity for wage income), landform (L) and A (settlement age). Response variables are total use area, area occupied by permanent structures and area occupied by ORV tracks. b) extensive use areas. Fixed effects are T, L and A as above, and presence of reindeer herding (R). Response variables are total use and ORV tracks.

A)

Fixed effects	Total use	Permanent	Tracks
WI (H – L)	0.58 [0.22 – 0.94]	0.66 [0.33 – 0.99]	0.52 [0.13 – 0.92]
L	0.56 [0.10 – 1.02]	0.11 [-0.32 – 0.53]	0.67 [0.11 – 1.24]
A		-0.02 [-0.27 – 0.22]	

B)

Fixed effects	Total use	Tracks
WI (H – L)	1.02 [0.61 – 1.43]	1.01 [0.62 – 1.41]
R	1.33 [0.83 – 1.83]	1.61 [1.12 – 2.10]
A	-0.18 [-0.43 – 0.07]	-0.30 [-0.55 – -0.05]
L	-0.16 [-0.72 – 0.40]	-0.45 [-1.01 – 0.11]

Ambio

Electronic Supplementary Material
This supplementary material has not been peer reviewed.

Title: **Local land use associated with socio-economic development in six arctic regions**

Authors: Dorothee Ehrich, Alma E. Thuestad, Hans Tømmervik, Per Fauchald, Vera H. Hausner

Appendix S1: Supplementary Material and Methods

On the ground confirmation of settlement classification

Most settlements included in this study have been visited by the authors or associated researchers in the frame of a large scale interview project in 2012. Originally, it was planned to visit all the settlements, and use the same design and approach for the selection of the settlements as in the present study. However, because of logistic constraints the following settlements could not be visited: Tukhard (Taimyr), Krasnoshelie (Murmansk), Nain, Hopedale, Makkovik and Rigolet (Labrador), Rankin Inlet (Nunavut), Unalakleet and Nuiqsut (Alaska). During the visits one or two researchers/assistants stayed in the settlement for about a week. Interviews about harvesting and other use of renewable natural resources were carried out with selected residents, usually including members of the local administration. Through this work, the structural characteristics of the settlements used to classify them into L or H-settlements were verified on the ground.

Criteria to choose the placement of intensive and extensive use areas

For each settlement, two ca. 10x10 km^2 images were obtained. One image included the settlement (intensive use) and the other image was placed at a random location 30 km from the settlement (extensive use). The distance of 30 km was chosen based on our knowledge of how far people in different parts of the Arctic usually go (obtained among others during the interviews described above), and how far the daily use of the surroundings of the settlement goes compared to distances, which people usually travel to pursue specific activities such as hunting, fishing and recreation. Most of the selected settlements were located along a major water body, such as a river or the sea shore. To standardize the configuration of the images, the settlement was placed at the mid-point of one of the sides of the image with the edge of the water body placed along the same side. The extensive use image was chosen at a random location along a circle with a 30 km radius around the settlement. To secure a remote location reflecting the extensive land use of the focal settlement, additional criteria were that the image should be at least 5 km away from the seashore, not contain any major buildings such as industrial infrastructure visible on Google Earth™, and not be situated closer to another settlement than to the focal settlement.

Statistical modelling

Candidate models with different covariables were assembled for each response variable (Table S2). For *intensive use* areas, we included each of the logarithm (log) of population size, log settlement age, the presence of reindeer herding and landform as additive fixed effects in addition to the focal variable wage income. The most parsimonious model was chosen based on a generalized Akaike's Information Criterion as implemented in GAMLSS (GAIC). Models with a difference in GAIC (ΔGAIC) < 2 were considered equally adequate, and the simpler model was preferred. When several models with one covariate were equally adequate, we additionally considered a model combining these covariates, following a forward model selection approach. The results of the selected models were reported as parameter estimates for fixed effects with 95% confidence intervals (CI) on the logit scale. Model fit was assessed graphically looking at the distribution of normalized residuals.

For *extensive use* areas, a similar modelling approach was taken. Here the focal fixed effects were wage income and reindeer herding either as additive effects or with an interaction. As above, following a forward model selection approach, we considered additive fixed effects of log population size, log age and landform (Table S3) and included settlement pair as random effect in all models.

Table S1 Information about the satellite images used. Type refers to the satellite taking the image, and Area indicates the total area analysed after subtracting areas covered with water (sea, lakes, large rivers) or clouds.

Country	Region	Settlement	Intensive use area			Extensive use area		
			Type	Date	Area (km^2)	Type	Date	Area (km^2)
Russia	Taimyr	Khatanga	WorldView-2	31.07.2011	95.1	WorldView-2	10.07.2011	78.3
Russia	Taimyr	Novaya	WorldView-2	31.07.2011	94.3	Quickbird-2	11.08.2011	74.4
Russia	Taimyr	Tuchard	Quickbird-2	16.07.2012	91.7	Quickbird-2	18.09.2012	74.3
Russia	Taimyr	Nosok	Quickbird-2	23.08.2009	108.2	Quickbird-2	23.08.2009	78.0
Russia	Yamal	Zapoliarnyi	WorldView-2	13.07.2012	90.8	Quickbird-2	18.07.2012	69.2
Russia	Yamal	Nyda	Quickbird-2	20.07.2012	92.5	WorldView-2	13.07.2012	76.6
Russia	Yamal	Mys Kamennyi	Quickbird-2	03.07.2012	112.5	Quickbird-2	27.08.2009	68.2
Russia	Yamal	Seyakha	Quickbird-2	03.08.2012	84.0	GeoEye	27.08.2009	59.0
Russia	Yamal	Gaz Sale	WorldView-2	30.06.2012 01.07.2012	79.4	Quickbird-2	04.07.2012	75.5
Russia	Yamal	Antipayuta	Quickbird-2	01.09.2012	86.7	Quickbird-2	21.07.2012	75.1
Russia	Murmansk	Lovozero	WorldView-2	15.08.2011	98.8	WorldView-2	21.08.2011	79.1
Russia	Murmansk	Krasnoshelie	WorldView-2	20.08.2011	98.7	GeoEye	23.07.2010	83.9
Russia	Murmansk	Tumannyi	WorldView-2	15.08.2011	88.0	Quickbird-2	23.08.2011	69.2

Russia	Murmansk	Teriberka	WorldView-2	26.08.2012	73.3	GeoEye	20.08.2009	73.3
Canada	Labrador	Hopedale	Quickbird-2	24.07.2008	51.3	Quickbird-2	24.07.2008	74.4
Canada	Labrador	Makkovik	WorldView-2	26.07.2011	83.8	GeoEye	28.07.2011	71.3
Canada	Labrador	Rigolet	WorldView-2	25.08.2011	82.5	GeoEye	13.07.2010	81.1
Canada	Labrador	Nain	Quickbird-2	24.07.2011	76.7	WorldView-2	31.07.2011	82.8
Canada	Nunavut	Baker Lake	Quickbird-2	17.07.2006	43.3	WV-02	09.08.2010	62.9
Canada	Nunavut	Chesterfield Inlet	GeoEye	07.09.2010	81.5	Quickbird-2	24.07.2011	71.2
Canada	Nunavut	Rankin Inlet	Quickbird-2	31.07.2007	77.3	WV-02	07.08.2010	59.0
Canada	Nunavut	Whale Cove	Quickbird-2	02.08.2006	51.2	Quickbird-2	16.07.2011	56.6
USA	Alaska	Nuiqsut	Quickbird-2	03.06.2007	74.1	WV-02	28.07.2011	54.3
USA	Alaska	Atqasuk	Quickbird-2	02.07.2007	86.3	GeoEye	18.07.2009	68.2
USA	Alaska	Noatak	Quickbird-2	07.07.2007	83.9	Quickbird-2	25.07.2011	77.6
USA	Alaska	Noorvik	Quickbird-2	02.07.2007	78.3	WV-02	26.08.2010	77.6
USA	Alaska	Unalakleet	GeoEye	16.08.2009	93.1	GeoEye	03.07.2009	77.2
USA	Alaska	Brevig Misson	Quickbird-2	21.07.2011	90.2	Quickbird-2	18.07.2011	75.7

Table S2 Model choice table for the proportion of *intensive use area* with visible traces of human use. Three response variables were considered, the total proportion of area with visible traces of human use (Total use), the proportion of area with permanent structures (Permanent), and the proportion of area with tracks of vehicles (Tracks). Explanatory variables included in the models were abbreviated as follows: WI – wage income, P – logarithm (log) population size, A – log age of the settlement, R – presence of reindeer herding, and L – landform (proportion of plain on the image). Settlement pair was included as a random effect in all models. The selected models are highlighted in bold.

Model	Total use		Permanent		Tracks	
	GAIC	ΔGAIC	GAIC	ΔGAIC	GAIC	ΔGAIC
WI	-98.64	5.66	-156.04	5.09	-131.30	4.86
WI + R	-99.13	6.15	-154.32	3.37	-132.55	6.11
WI + A	-95.93	2.94	-153.55	2.61	-129.48	3.04
WI + P	-95.74	2.76	-155.53	4.59	-129.15	2.71
WI + L	**-92.98**	**0.00**	-153.19	2.24	**-126.44**	**0.00**
WI + L + A			**-150.94**	**0.00**		
WI + L + R			-153.13	2.18		
WI + L + A + R			-150.98	0.04		

Table S3 Model choice table for the proportion of *extensive use area* with visible traces of human use. Three response variables were considered, the total proportion of area with visible traces of human use (Total use), the proportion of area with permanent structures (Permanent), and the proportion of area with tracks of vehicles (Tracks). Explanatory variables included in the models were abbreviated as follows: WI – wage income, P – logarithm (log) population size, A – log age of the settlement, R – presence of reindeer herding, and L – landform (proportion of plain on the image). Settlement pair was included as a random effect in all models. + indicates additive effects and x an interaction. The selected models are highlighted in bold.

Model	Total use		Tracks	
	GAIC	ΔGAIC	GAIC	ΔGAIC
WI + R	-202.12	4.59	-216.50	3.91
WI x R	-201.49	3.96	-214.59	1.99
WI + R+ A	-199.92	2.39	-215.29	2.70
WI + R + P	-202.48	4.95	-219.42	6.82
WI + R + L	-200.54	3.01	-214.96	2.37
WI + R + A + L	**-197.52**	**0.00**	**-212.59**	**0.00**