Review

Permafrost livelihoods: A transdisciplinary review and analysis of thermokarst-based systems of indigenous land use

Susan Cratea,1, Mathias Ulrichb,*,1, J. Otto Habeckc,1, Aleksey R. Desyatkinbd,e, Roman V. Desyatkinb, Aleksander N. Fedorovc, Tetsuya Hiymag, Yoshihiro Iijimah, Stanislav Ksenofontovf, Csaba Mészársose, Hiroki Takakurak

a George Mason University, 4400 University Dr. MS 5F2, 22030 Fairfax, VA, United States
b Leipzig University, Institute for Geography, Johannisallee 19a, 04103 Leipzig, Germany
c Hamburg University, Institute for Social Anthropology, Edmund-Siemers-Allee 1, 20146 Hamburg, Germany
d Institute for Biological Problems of Cryolithozone, Russian Academy of Sciences, Lenin ave. 41, 677980 Yakutsk, Russia
e Meltkov Permafrost Institute, Russian Academy of Sciences, Merzlotnaya St. 36, 677010 Yakutsk, Russia
f North-Eastern Federal University, Belinsky St. 58, 677000 Yakutsk, Russia
g Institute for Space-Earth Environmental Research (ISEE), Nagoya University, 464-8601 Nagoya, Japan
h Graduate School of Bioresources, Mie University, Tsu, Japan
i University of Zurich, Dept. of Geography, Winterthurerstrasse 190, 8057 Zurich, Switzerland
j Hungarian Academy of Science, Research Centre for the Humanities, Institute of Ethnology, Országház u. 30, 1014 Budapest, Hungary
k Center for Northeast Asian Studies, Tohoku University, Kawauchi 4-1, 980-8570 Sendai, Aomori, Japan

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In a context of scientific and public debates on permafrost degradation under global climate change, this article provides an integrated review and analysis of environmental and socio-economic trends in a subarctic region. It focuses on Sakha (Yakutia) animal husbandry as an example of indigenous land use. Within Sakha-Yakutia’s boreal forests, animal husbandry takes place in thermokarst depressions containing grassland areas (alas) that formed in the early Holocene in a complex interplay of local geological conditions, climate changes, and permafrost dynamics. The current scale and speed of environmental change, along with shifting socio-economic processes, increasingly challenges Sakha’s adaptive capacity in use of alas areas. The paper synthesizes information on the evolution of permafrost landscapes and on the local inhabitants’ and scientific knowledge. It also probes land-use prospects for the near future. The imminence of challenges for alas ecosystems requires a holistic understanding between researchers and stakeholder communities, which in turn depends on a comprehensive assessment of the dynamic interaction of physical and social drivers of change.

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* Corresponding author.
E-mail addresses: scrate1@gmu.edu (S. Crate), mathias.ulrich@uni-leipzig.de (M. Ulrich), fkm206@uni-hamburg.de (J. O. Habeck), desyatkinar@rambler.ru (A.R. Desyatkin), rvdes@bpc.ysu.ru (R.V. Desyatkin), fedorov@ropi.ysu.ru (A.N. Fedorov), hiyama@nagoya-u.jp (T. Hiyama), yjiyama@bio.me-u.ac.jp (Y. Iijima), stanislav.ksenofontov@geo.unizh.ch (S. Ksenofontov), meszaros@etnologia.mta.hu (C. Mészáros), hrk@m.tohoku.ac.jp (H. Takakura).

1 These authors contributed equally to this work.

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1. Introduction

In this article, social and natural scientists review the evolution and resilience of alaas, a permafrost-based ecosystem, including human land-use practices. The goal is to exemplify how transdisciplinary consideration of climatic, biological, and sociocultural processes provides a more complete understanding of subarctic resource use and resilience in the context of global change. Alaas (in Sakha/Yakut language, known as alas in Russian and English) are highly sensitive to climatic variability, due to their location in arctic and subarctic latitudes (Fig. 1). They are a characteristic permafrost landscape feature of the central and western lowlands of the Sakha Republic (synonymous with Sakha-Yakutia) (Fig. 2). Geomorphologically, alaas are thermokarst depressions or drained thaw lake basins characterized by large areas of subsided ground surface resulting from thawing of ice-rich permafrost (Solov’ev, 1973). Alaas are typically covered by grasslands. The Sakha word ‘alaas’ means “meadow in the forest”. Alaas can vary in size and depth but their specific shape and their geomorphological genesis is what distinguishes them from other grassland areas. For at least the last half millennium, since Sakha’s Turkic ancestors transmigrated from southern Siberia, alaas have provided forage and fodder for Sakha’s horse and cattle subsistence, which maximizes production by manipulating alaas, for example, by draining lakes to increase grasslands and by creating dams to hold water during dry periods and release it in times of water abundance. To this day, many Sakha continue to utilize these unique conditions of alaas landscapes for subsistence and market production.

Recent decades of global climate alterations, however, threaten the relative physical stability of alaas beyond their ability to rebound. Additionally, shifts in resource use and the socioeconomic effects of post-Soviet development and globalization further threaten the physical and socio-cultural alaas complex, making its continued use increasingly challenged and uncertain. Considering the interactions of these rapid physical and sociocultural changes, assessing the degree to which contemporary alaas landscapes have been altered is critical, including the potential effect of widespread permafrost degradation (i.e. thermokarst...

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Fig. 1. View of a typical Central Yakutian alaas landscape during hay making end of July. (Photograph by M. Ulrich).
processes) on the local economy (Fedorov and Konstantinov, 2009).

Today, Sakha are by no means alone in their plight of unprecedented change and increased uncertainty. Anthropogenic climate change challenges the adaptive capacity of human-environment interactions in many parts of the world (Crate and Nuttall, 2009; Crate, 2016; Fiske et al., 2014). In the Arctic and sub-Arctic, local inhabitants possess detailed knowledge of environmental dynamics based on their culture’s centuries-old experience of making a living in a sensitive habitat; however, many report that current processes are of unprecedented speed and magnitude (Krupnik and Jolly, 2002; Holvsrud-Broda and Smit, 2010; Hassol, 2004; Ford et al., 2008, 2016). Similarly, scientists have documented invaluable knowledge about how the physical world is transforming (IPCC (Intergovernmental Panel on Climate Change), 2013). Integration of these two domains of knowledge provides important insights into how change is occurring, perceived, understood and responded to, and can help to clarify novel adaptive and policy strategies (Crate, 2014). In short, to be effective, global-change research requires a comprehensive understanding of human-environment interactions, integrating the natural and social sciences, to assess future options more accurately, to bring together stakeholders’ views on adaptation or mitigation, and to inform policy (Castree et al., 2014).

Earlier research has studied alaas but rarely in a manner integrating the social and physical sciences (e.g., Czudek and Demek, 1970; Solov’ev, 1973). The body of geomorphological, geocryological, and climatological studies needs to be combined with social-sciences and historical research on land use (see Table 1). Gaps also remain within each of these two science domains. In the physical domain, geomorphologists and geocryologists have a long-standing interest in how periglacial processes shape the land surface, hydrological conditions, and vegetation cover in lowland areas with Quaternary sediments (e.g., Czudek and Demek, 1970; Solov’ev, 1973; Ivanov, 1984; Bosikov, 1991 for the region in question). Permafrost thawing, surface subsidence, and sedimentation along with changes in hydrology and vegetation create a particular dynamic of alaas landscape development (e.g., Bosikov, 1998; Desyatkin, 2008; Séjourné et al., 2015; Ulrich et al., 2017a). Thus far, however, insufficient understanding exists of several factors in this process, notably hydrological conditions and short-term climate changes (Kata-mura et al., 2009b; Kravtsova and Tarasenko, 2011; Iijima et al., 2013), along with forest clearings and other changes in land use (Brouchkov et al., 2004; Ulrich et al., 2017b).

While knowledge exists of the consequences of permafrost degradation for engineering and construction work in the Far North (e.g., Mazhitova et al., 2004) and of the effects of climate change on Northern indigenous communities (e.g., Forbes and Stammler, 2009; Pearce et al., 2015), understanding is lacking in the social domain of the dynamics of permafrost as a condition of and basis for indigenous forms of resource use. Given that Sakha have used alaas basins for at least half a millennium, these ecosystems have not only economic but also symbolic and spiritual importance (Crate, 2006a; Mészáros, 2012a; Takakura, 2015). Exactly how the local population are engaged with thermodkarst processes to utilize alaas is not well understood.

Considering the effects of global climate change and also the fact that local inhabitants have been drivers of change in alaas ecosystems, it is necessary to ask: How did alaas ecosystems initially form, what change have they undergone, and what processes are currently at work? Historically, how did humans interact with alaas, how do humans use alaas today, will they be able to continue using alaas into the future and if so, how? To answer these questions, this paper presents a transdisciplinary review and analysis of the alaas ecosystem and the challenges it
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Table 1
Timeline combining current geoscientific and socio-economic knowledge on landscape evolution and climatic changes as well as human development and their implications for environment, infrastructure, and/or society during different time periods since the late Pleistocene in Central Yakutia.

faces. It aims to first provide a more holistic understanding developed by researchers and stakeholder communities, and second, to synthesize the dynamic interaction of physical and social drivers of change.

We begin with reviewing the knowledge of alaas formation from the late Pleistocene through to present. We then complement that synthesis with a historical overview of ecological processes, tracking how human populations have used this thermokarst landscape up to the present day. Next, we outline our approach to integrating diverse knowledge and review the relevant scientific observations and local knowledge on environmental change over the last few decades. The subsequent reflection on integration and communication of knowledge lays the ground for assessing future trends of permafrost degradation and rural livelihoods in this
region. In conclusion, we provide recommendations for future research.

2. The alaas landscape: characterization and development

2.1. Physical evolution and ecological aspects of alaas

Contemporary alaas (Fig. 1) have a long geomorphological history, spanning the last 60,000 years. The central and western lowlands of the Sakha Republic are critical permafrost regions globally because of the depth of the permafrost layer, extending more than 1000 m in some locations and its comparable high ice-content in large areas (Czudek and Demek, 1973). During the late Pleistocene (<126,000 years ago), glaciation occurred repeatedly, with ice shields covering large parts of Northern and Central Eurasia. The central and western regions of the Sakha Republic and large parts of the East-Siberian lowlands, however, did not undergo glaciation. Consequently, the soil surface was exposed to very low air temperatures over a long period, resulting in the freezing of the ground and permafrost build-up extending into depths of several hundred meters (Hubberten et al., 2004). For the Lena-Aldan area (Fig. 2B), one explanatory theory suggests that in the late Pleistocene, the Lena river formed a large lake dammed by Verkhoinans mountain glaciers and expanses of adjacent wetlands came into existence (e.g., Ivanov et al., 2015). The resulting wet soils experienced frost cracking, the formation of a polygonal relief and the active development of ice wedges. Repeated changes in climatic conditions, water levels, erosion and sedimentation led to the formation of terraces (Kataasonov et al., 1979) (see Fig. 2B). Annual cycles of thaw and freeze together with a syngenetic accumulation of polygenetic sediments led to the gradual development of substantial ice wedges (see Fig. 3).

These ice-complex or Yedoma deposits cover large parts of central and western Sakha and are characterized by more than 60% ground-ice content by volume, (Solov'ev, 1959; Kataasonov et al., 1979), in which the ice-wedge volume alone is estimated to be about 50% of the total permafrost volume (Ivanov, 1984). This characteristic is crucial for the development of large alaas, since surface subsidence is related to ice-volume loss (e.g., Ulrich et al., 2014). Fluctuations in climate conditions during the early- and mid-Holocene led to extensive thermokarst formation caused by the degradation (i.e. thawing) of the ice-rich permafrost deposits and subsequent surface subsidence (Bosikov, 1991; Katamura et al., 2006; Kaplina, 2009; Grosse et al., 2013). Table 1 summarizes alaas landscape development.

Today, approximately 16,000 alaas are found in the lowlands of central part of the Sakha Republic (Central Yakutia), covering ~4400 km² or ~17% of the total Central Yakutian lowland area (Bosikov, 1991). Within these areas, the spatial distribution and density of alaas is varied. For example, in the Lena-Aldan-interfluve region, alaas cover up to 30% of the territory’s surface (Bosikov, 1991) (see Fig. 2B). The thermokarst process is initiated by the gradual deepening of the seasonal thaw layer (i.e. active layer) because of soil warming and subsequent thawing of the underlying ice complex, initiated by warmer climatic periods. This process can also begin due to temporally and spatially limited non-climatic factors, such as destruction of vegetative cover, local erosion, forest fire, and land use change. The process occurs over decades, centuries or several thousand years and has four main stages (Fig. 4), each producing a different thermokarst landform (in Sakha bīllaar, ḏūddek, tyympy) and finally, the thermokarst basin named alaas (Solov'ev, 1973; Bosikov, 1991). Timing is highly variable, with the first two stages of initiation and enlargement occurring over several decades or up to a few hundred years (Solov’ev, 1973; Fedorov et al., 2014). Today, we can witness all stages of thermokarst evolution in the central and western lowlands of the Sakha Republic. Thermokarst dynamics, however, are still not fully understood. One unknown aspect is whether alaas development is unidirectional or cyclical (e.g., Pestryakova et al., 2012). The model of unidirectional thermokarst evolution includes initiation, expansion, drainage, and cessation (Morgenstern et al., 2013; Ulrich et al., 2017a).

Alaas form within a taiga (boreal) forest type dominated by Dahurian larch (Larix dahurica), Siberian spruce (Picea obovata) and Siberian pine (Pinus sibirica). The alaas itself is bare of forest and supports three vegetation zones: wetland, moist grassland, and dry grassland, each extending concentrically around the alaas lake (Desyatkin, 2008). The wetland area is dominated by peaty-eutrophic permafrost soils. These soils produce vegetation that is dominated by sedges and sweet grasses, and used by Sakha only as forage reserve, since harvesting on the boggy terrain is difficult. Moderately moist grasslands with relatively high soil salinity

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**Fig. 3.** Ice-complex exposures in Central Yakutia. (A) Large ice wedges on the Tyungulyu (Töŋgüül) terrace, reaching 40 m depth and 8 m width. (B) Large ice wedges on the Abalakh (Aboloukh) terrace, reaching 60 m depth and 10 m width. (Photographs by R.V. Desyatkin and M. Ulrich).
dominate the largest alaas areas. These grasslands are home to the salt resistant alkali or salt grass (Puccinellia tenuiflora). These areas have high biomass productivity and are extensively used for hay-making (see Fig. 1). The most elevated areas, such as the alaas slopes are dominated by dry grassland of low productivity that holds little practical value for cattle breeding (Desyatkin, 2008).

These three areas of biomass production are subject to fluctuations of alaas-lake levels, which are cyclical as proven by both scientific research and Sakha local knowledge. Bosikov (1998) identified a cyclical character of high and low lake-water levels in Central Sakha-Yakutia, in the period from 1891 to 1995. Inhabitants distinguish dry and wet periods that influence alaas-lake level oscillations and hence grassland productivity (Crate, 2011). Wet years cause alaas lakes to expand and reduce the grassland area. Dry years lead to lake shrinking and consequently to an increase of grassland area (i.e. hayland). The productivity of grasslands dramatically decreases during dry years, however, due to low soil moisture in the alaas periphery. Dry years are, in fact, most harmful

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**Fig. 4.** Thermokarst stages in ice-rich permafrost in the boreal zone of Central Yakutia. The graphic above was modified after Bosikov (1991) and Desyatkin et al. (2009). Note, the term alas is shown in its English spelling. Sakha names given in the graphic divert from Sakha orthography. For each stage corresponding pictures are shown below (Photographs by R.V. Desyatkin).
for indigenous horse and cattle breeding. Sakha have, to date, been successful using the alaas due to their ability to manipulate these water extremes, a topic addressed in the next section.

2.2. The socio-cultural evolution of the alaas landscape

The horse and cattle breeding Sakha have been and remain important actors in alaas landscape change. Table 1 indicates hunting and foraging as earlier, though still existing, forms of resource use in this region (Argunov and Pestyereva, 2014; Crate, 2003a; Waters et al., 1997), whereas animal husbandry and the pertinent intensification of land use emerged more recently. Between the 12th and 15th centuries, Sakha’s Turkic ancestors migrated north in several waves from the Lake Baikal region of southern Siberia to the alaas areas of the middle Lena and Viliiui Rivers (e.g., Okladnikov, 1970; Ksenofontov, 1992). Sakha maintained a steppe type of pastoralist society. Based on a sociocultural system of military aristocracy, this society adapted to the northern climate by foddering their herds during winter using the natural pasture and forage resources of the long river terraces and numerous alaas areas (Takakura, 2015). Sakha’s subsistence activities flourished due to their manipulation of the alaas landscape. They controlled water to maximize hay production by draining lakes and/or water-logged areas, creating khoruu (canals) (Fig. 5) and holding water in times of drought via the use of various styles of dams, a practice carried over from their ancestral southern habitat (Ermolaev, 1991).

Sakha cosmology played an important role in adaptive practices. According to Sakha’s ancestral belief system in which all of nature is sentient or spirit-filled, alaas are living beings and considered members of the local community, with whom human beings regularly communicate and give sacrificial foodstuffs, rituals, blessings, and dreamings (Mészáros, 2012b; Takakura, 2015). One example that demonstrates this belief is the shaman’s ritual performed before draining an alaas lake to create more hayland. To these ends, a shaman is called to appease a potentially angry spirit of the lake who may drown or harm those involved in the draining process (Nikolaev, 1968). Rituals of this type also occur at present (Aytal Yakovlev, personal communication, October 2015). Also in line with Sakha cosmology, grasslands are sacred and not to be unnecessarily disturbed, which explains why Sakha usually traveled in the forests adjacent to alaas and not upon them.

Historically, several pivotal events affected Sakha’s initial adaptation to the Far North and establishment of an alaas land tenure strategy. With the 17th century advent of Russia’s land-tenure taxation system and increased importance of cattle over horses, Sakha began changing pasture to hayfields to produce fodder resources for cows (e.g., Seroshevs’kii, 1993; Takakura, 2015), a trend that continued into the 19th century. During this period, various methods of alaas management – draining, ground leveling, and deforestation – became widespread in the central and western lowlands of the Sakha Republic (Petrov, 2002). By the early 20th century half of Sakha agricultural territories were hayfields (Matveev, 1989).

A second major land tenure change came during the Soviet period (Table 1). Before collectivization, extended clan households were situated on alaas and householders utilized many small and disperse hayfields (Gabyshev, 1929). Loosely cooperating neighbors, many of whom were kin, formed residential groups of 5 to 15 households called тыйлан meaning both a cohesive group of people and a round-shaped meadow (Rastsvetaev, 1932; Mészáros, 2012a). Households moved semi-annually between a winter and summer camp, maintaining a distance between them approximating 10 km. Beginning in the late 1920s and lasting several decades, the Soviet government invited and later forced Sakha to give over their herds and land holdings to collective farms. Households were moved into increasingly compact village settlements. Alaaas continued to be used but now for expanding Soviet-style agricultural production. After World War II, the Soviet government began the gradual establishment of the state farm system, with collective farms amalgamated into large agricultural enterprises by the late 1950s and early 1960s (Crate, 2006a; Mészáros, 2012b; Takakura, 2015). With this final step of centralization, the majority of alaas were used for large-scale crop production, pasture or fodder and as summer camps for farm brigades.

Among the many changes of the time, the change from aboriginal Sakha cattle to European breeds was particularly relevant, first to Khomgory cattle in the in the 1950s and then to Simmental cattle from the 1960s onwards, for their higher milk production (cf. Stammer-Gossmann, 2010a). Unlike native cattle, however, Simmental required protection from the extreme northern climate for up to 9 months of the year, requiring substantial fodder. To meet these needs, state farms intensified hay-making and conducted alaas drainage on a grand scale. The total territory of drained fields grew between 1975 and 1985 by nearly 50% (Matveev, 1989; Gavr’iev, 1991), with some state farms (especially in Viliiui district) having more than 25% of their agricultural areas drained (Fig. 5).

Another important change to alaas was the introduction of plough technology. In 1966, the Communist Party of the Yakutian ASSR (present-day Sakha Yakutia) dictated that grain production

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**Fig. 5.** Artificial canals (khoruu) for draining lakes and/or water-logged areas. (A) Pre-Soviet khoruu (Photograph by S. Crate) and (B) Soviet State Farm khoruu illustrating the change in scale of drained areas before and during Soviet period (Photograph by Akimov, 2006).
expansion into alaa fields in central, southern and western state farms (Vinokurova, 1999). Previously untilled meadows were turned into plough lands, resulting in approximately 9% of the Republic’s agricultural territories intensively drained and tilled as crop fields (Matveev, 1989). Different and more efficient methods of irrigation were also introduced at that time and total irrigated land nearly doubled between 1970 and 1985 (Matveev, 1989). Sprinkler irrigation was used in crop fields, whereas flood irrigation typically upgraded pastures. The spread of tractors and other agricultural machinery from the mid-1950s onwards made it gradually easier to drain meadows and wetlands and to introduce irrigation systems (Gavriliyev, 1991). However, the heavy machinery compacted the soil structure of the delicate sub-arctic soils.

The post-Soviet period, beginning in the early 1990s, brought more changes in alaa use. The state farms were disbanded and because large-scale cattle breeding was no longer profitable (Darbasov et al., 2000), the number of cattle decreased by 40% from 396,500 in 1990 to 233,300 in 2012, plummeting rapidly in the 1990s and less so in the 2000s (Vinokurova and Prokhorova, 2013). Similarly the state-farm summer camps and their facilities were abandoned (Ivanov et al., 2000). Despite the precipitous drop in cattle overall, most households adapted to the almost overnight loss of state-farm salaries and food stuffs by developing small-scale food production; holding cows on a household level and interdependency with kin households to realize hay needs (Crate, 2006a). Official land tenure regimes also changed. Hayfields went from being state-owned to usufruct on local household levels (Crate, 2003b). Many hayfields that had been transformed into grain production during the socialist period were reverted back to haylands. Since tractor and other intensive agricultural practices compacted and disrupted the delicate northern soil structure, however, hay fields were less productive than in pre-Soviet times.

The ethnic revival of the post-Soviet period also brought a renewal of inhabitants’ understanding and reverence for the sacred aspects of alaas. When contemporary elders mapped their birth land alaas in an oral history project, they spoke of how, to this day, they and their extended families return to those homesteads to feed their ancestral spirits (Crate, 2006b). To date, many Sakha continue to perceive alaa landscapes as sentient beings. Symbolically, it is the relationship among people, land, and spirits that enables exclusive and continuous ownership by particular families (Takakura, 2010, 2015). Although people identify ancestral lands (sir-uot) as their own, it does not mean that a descendant has free license to these areas until the proper rites are performed. Alaas possess an immanent power of a highly complex character. It is a power known as alaa’s benevolent power. This power must be respected, and therefore a number of taboos protect alaas.

Contemporary Sakha healers describe how alaas are not only exposed to climatic change and permafrost soil degradation, but they also respond to it. Furthermore, alaas and lakes, also considered sentient beings, are said to communicate with each other by a complex “vascular” system, and may react in concert to human harms in an unfriendly or even hostile way (Protopopova, 2002, p. 60; Sleptsov-Slyk, 2013).

3. Knowledge on environmental change and landscape dynamics in the era of climate change

3.1. Integrating social and geoscientific methods and knowledge

In addition to the historical changes that have affected the overall ecosystem state of alaas and the pertinent land use and livelihood, synthesizing environmental changes as observed over the last 20–30 years by natural scientists, on the one hand, and social scientists collaborating with local Sakha inhabitants, on the other, is important. Because the two domains of knowledge – one based on predominantly qualitative findings and the other mainly quantitative – are validated differently, we first present them separately and then integrate them in discussion. We review, compile, and discuss relevant published research with focus on human-environment interaction in permafrost landscape dynamics and also alaas and thermokarst processes.

This article demonstrates how diverse disciplinary findings can be exchanged and integrated to produce a more holistic understanding, in the context of Sakha-Yakutia. Without outlining the methodological details of the different disciplines we draw upon, we present an approach for integrating different domains of knowledge, along with the difficulties. In terms of the latter, divergent timescales are particularly challenging (Table 1). The time span of observations of social and environmental scientists varies, for the former spanning anywhere from ten years (data on flooding, rural residents’ perceptions of change) to over several decades and for the latter from ~150 years (climate records, lake-level changes) to up to several thousands of years, as with paleoenvironmental and geomorphological records of alaas evolution. Additionally, the contrast between the two domains’ methods and rigor, with scientific observation employing procedures and protocols to produce scientifically valid quantitative data, and local knowledge, which can be elicited through social scientific inquiry using largely qualitative methods whose rigor depends on saturation and the development of patterns. Methods and problems of integrating scientific and local environmental knowledge have been debated over the last twenty years (Nadasdy, 1999; Karjalainen and Habeck, 2004; Ford et al., 2016).

The primary vehicle for integrating scientific knowledge and research results from many disciplines were several forums that

Fig. 6. Air and soil temperature variability for the Yakutsk region (1930–2014). Data of mean annual air temperatures (MAAT) were obtained from the Yakutsk weather stations (NOAA National Climatic Data Center; http://www.ncdc.noaa.gov). The mean annual ground temperatures (MAGT) at 3.2 m depth were averaged from four meteorological stations (Yakutsk, Pokrovsk, Churapcha, Okhotsk-Perevoz) in the region. Data means are illustrated by the solid lines and data trends by the dashed line.
included community knowledge exchanges, academic workshops, and field visits engaging multiple stakeholders. In 2010, two of the authors (S. Crate and A. Fedorov) facilitated knowledge exchanges, aimed to forefront inhabitants’ local knowledge and to share regional scientific findings using familiar images and explanations, in eight communities of the Vilui region (Crate and Fedorov, 2013, see Section 3.3.1). A majority of the authors collaborated in a scientific workshop during the 2014 Arctic Science Summit Week in Helsinki (see acknowledgements) in order to contextualize local knowledge about mid-term and short-term changes in terrestrial and cryospheric conditions using geological, geomorphological, geocryological, historical, and archaeological data on the physical and social evolution of alas systems. In 2015, a workshop in Yakutsk (see acknowledgements) brought together many of the authors with Sakha historians, sociologists, anthropologists, biologists, geocryologists and other scholars from outside Russia. Interdisciplinary break-out groups assessed and summarized the scope and limits of current knowledge about (i) land-use history; (ii) socio-economic development and prospects; and (iii) permafrost formation and degradation, all with regional focus on the Lena–Aldan interfluve. During the workshop, an interdisciplinary team spent two days conducting field visits to Yukechi (Úkechi) and Tyrungulyu Tungulu thermokarst/alaa areas, allowing all participants to observe and discuss landscape development and use with local private farmers and collective farm managers. Below, we draw from the findings of these three main forums.

3.2. Geoscientific studies

3.2.1. Air and ground temperatures

Proxy data, specifically contemporary dendro-climatic reconstructions of 11th–13th century June temperatures in eastern Siberia show a warming of 1.5 °C (Sidorova and Naurzbaev, 2005). This warming reflects the global trend of the Medieval Warm Period, which was then followed by a marked decrease of air temperature through the 19th century, corresponding to global models of the Little Ice Age. Since that time to today, average air temperatures have steadily increased (e.g., Jones et al., 2001). During the period of reliable direct records (1930 to present) the mean annual air temperature measured at the Yakutsk meteorological station increased by ~0.03 °C per year (Fig. 6). Concomitantly, the permafrost temperatures in the central and western lowlands of the Sakha Republic have increased by ~0.02 °C per year (in 320 cm depth) (see also Romanovsky et al., 2007). The activation of thermokarst is due to the steady increase of mean annual air and ground temperatures.

Critical to our synthesis are two sharp shifts of ground temperature, one occurring between 1950 and 1970 and another, more pronounced, in the early 1980s (Fedorov et al., 2014; Ulrich et al., 2017b). Both shifts contributed to an increase in the seasonal thawing depth (i.e., the active layer is usually up to 200 cm deep in forest-free areas) and subsequent melting of the upper parts of ice wedges on landscapes with ice-rich deposits. The thawing is the very characteristic of the region’s permafrost, which makes the alas ecosystems particularly sensitive and reactive to relatively small amounts of warming.

3.2.2. Hydrological processes

Field studies clearly indicate that thermokarst lakes are expanding and the permafrost underneath is thawing, a process due to both the warming detailed above but also to shifting hydrological processes. The exact extent of change is highly dependent on the specific context of each alas’s physical characteristics. We illustrate with a few examples. Data from Yukechi – a field site of Central Sakha-Yakutia located c. 55 km ENE of Yakutsk, on the Abalakh (Abalakhi) terrace (see Fig. 2) – illustrates the scope and speed of change (Fedorov et al., 2014; Ulrich et al., 2017b). From 1980 to 2012, the area of thermokarst lakes on the Yukechi site increased four times with the bottom of these lakes deepening 2–2.5 m from 1992 to present and terrains with ice-wedge polygons turned into ponds (Fig. 7).

Additionally, from 2005 to 2007, sudden warming on landscapes with above-average amounts of snow cover in combination with increased summer precipitation, led to both a significant expansion of thermokarst lakes and to the extensive development of primary thermokarst landforms – badarakh or thermokarst mounds in treeless areas (the latter represented by Stage I in Fig. 4). Such data clarify the complexity of the hydrological processes involved, with increased lake area and depth a result of both permafrost ice meltwater and increased above-ground precipitation. Beside climatic influences, also small-scale, local interactions of thermal and hydrological changes and specific permafrost conditions can cause thermokarst-lake-level changes (Smith et al., 2005). One study estimated the water balance from 1993 to 2008 for a thermokarst lake at the Yukechi study site and showed how the lake area increased rapidly by a factor of 16 and the lake volume by 114, with melting ground ice making up one third of the total water increase (Fedorov et al., 2014).

Fig. 7. Landscape change at Yukechi (Úkechi) study site during recent years. Several thermokarst lakes around the Yukechi (Úkechi) alas have developed rapidly in areas ploughed until the 1950s. The blue ellipse in the upper satellite image time series marks the view of the photographs below. (Photographs, satellite and airborne imagery provided by A.N. Fedorov and M. Ulrich).
Studies by Iijima et al. (2010) and Ulrich et al. (2017b) demonstrated how hydrological processes of larger lakes within alaas basins are linked to climatic conditions. Data from the Tyungyulyu field site also shows that water-level changes are highly correlated with air temperature (Fig. 8). Before the 1980s, the Tyungyulyu water level was higher than today, explained by the lower average summer temperatures and resulting lower evaporation. In the context of warmer drier summers since that time, the lake’s water level continues to decrease. However, the years from 2005 to 2007, consecutive years of abnormally high precipitation, resulted in an abrupt increase in the water level (Iijima et al., 2010).

Another important aspect of alaas ecosystem hydrology is their annual flood regime, which has seen significant changes in recent years. Typically only occurring during the spring season with the melt of snow and ice, recent years show a new trend of summer floods. Cyclones have appeared frequently in summer in the region, bringing more precipitation to eastern Siberia in particular. Such changes in the atmospheric water cycle have caused river flooding in summer, not only at Lena River (Takakura, 2016), affecting Yakutsk, but also at numerous tributaries. Alaaas basins have also become water-logged (Hiyama et al., 2013). Generally, spring floods bring nutrient-rich water to the river islands on which the farmers cultivate pastures for cattle and horses, thus they are considered beneficial (unless they destroy buildings or infrastructure). In the case of summer floods inundating river islands, however, hay production becomes impossible.

3.2.3. Land cover changes

The changes in temperature and hydrology are evidenced by direct and cascading ecosystem change. With the large increase in precipitation in the research region since 2004, in combination with near-surface permafrost thawing, soil moisture has increased substantially (Iijima et al., 2010; Hiyama et al., 2013). These perennially waterlogged conditions increase soil subsidence and affect the boreal forest habitat, specifically by changing soil conditions that no longer support the historical floral species. Increasingly, boreal forest trees are withering and dying throughout the region. According to multi-year sap flow measurements from 2006 to 2009, transpiration from larch trees was significantly reduced in conjunction with the deepening and moistening of the active layer (Iijima et al., 2014). At a different research site, the number of living larch decreased by 15% from 1998 to 2011 due to unusual waterlogged conditions and the composition of floor vegetation changed from dense cowberry to grasses and shrubs with high water tolerance (Ohta et al., 2014). These same processes are evident at the aforementioned Yukechi site (see Fig. 7), with the increased moisture and deepening of the active layer in side slopes of young (only decades old) thermokarst lakes resulting in lake expansion, topographic instability and adjacent forest erosion. Generally, an increasing total lake area in Central Sakha-Yakutia was also reported by e.g. Kravtsova and Tarasenko (2011), Boike et al. (2016) over the last decades. The exact causes of lake area changes are complex, however, and depend on regional and local factors including the specific alaas’s permafrost zonation (continuous vs. discontinuous), ground-ice content, size and its geomorphological composition (e.g., Ulrich et al., 2017b).

In addition to the cascading ecosystem effects due to increased soil moisture, extreme fire seasons now occur with more frequency and are characterized by dry periods with high air temperature and low relative humidity. Recent studies showed that the period of high fire danger under current climate conditions in the central and western lowlands of the Sakha Republic is as long as 50–60 days. According to future climate scenarios, it will increase on average by 20–30 days by the end of the century (Tchebakova et al., 2009). The overall trend of an increase in forest fires further exacerbates the unprecedented thermal and hydrological conditions of the active layer described above and the related changes in vegetation.

To summarize this geoscientific section, observations of climate, water and land cover show an overall increase in both precipitation and in air and ground temperatures, which has translated to an acceleration of thermokarst activity in the central and western lowlands of the Sakha Republic. These findings are further substantiated by social science investigations documenting local inhabitants’ observations of environmental change affecting the alaas ecosystem economy.

3.3. Social science studies

3.3.1. Longitudinal research with Villui Sakha

Long-term ethnographic research with Villui region communities shows multiple aspects of environmental change, many of which can be ultimately related to climate change (Crate, 2008, 2011, 2015). Based on focus groups, interviews and surveys in four Villui Sakha communities, inhabitants identified nine main changes that were before unknown to them and challenging their livelihood. They were: 1) winters are warm; 2) too much water on the land; 3) too much rain; 4) summers are cold; 5) more floods; 6) seasons arrive late; 7) too much snow; 8) temperatures change suddenly; 9) less birds and animals. These changes affect rural inhabitants' livelihoods, most significantly their cattle and horse breeding activities, but also their foraging (hunting, fishing, gathering) and gardening activities with which they supplement their diet.

Among these, analysis of findings showed that inhabitants are most concerned about the increase of water on the land, which not
only impacts hay production but also affects many aspects of Sakha livelihood. The increased water on the land limits access to forest and other needed resources. Furthermore, because many settlements are located around lakes for water access, households closest to the village lake find themselves needing to relocate their house farther back as the damp conditions undermine the house structure and rot the foundation. Many complain that they can no longer use their bulus (underground cold storage) because water has permeated the frozen layer and flooded the storage cavity. Inhabitants and regional representatives report more floods, wetter ground, and higher amounts of rain and snow (Crane, 2011). These conditions not only affect hay production for fodder but also work to decrease available forage when animals go to pasture during the temperate months. Lastly, the increased water on the land floods into adjacent forests and tree roots suffocate, leading to gradual decline of the forest.

As shown by Fedorov et al. (2014), the increase of water on the land is a combination of the increase in precipitation, especially in the winter months (which, when it thaws in spring, produces large volumes of water), and water from thawing permafrost, rising up from below. In addition, hay production is also affected by precipitation patterns, which are tending towards less rain in the spring and more in the summer, especially during the critical hay cutting time.

The difficulty of harvesting sufficient hay and being able to access usable pasture has led some to stop keeping cattle. When author S. Crane asked longtime herding households in 2012 why they decided to stop horse and cattle breeding, however, their reasons were not just about forage and fodder (Crane, 2014, 2016).

Many spoke about how their youth had gone to the city for work or higher education and decided not to return, leaving them with less of a need to produce meat and milk in the amounts they used to and also without the work force needed for hay-making in the summers. In addition, many said that now they can buy all they need since the village stores are fully stocked. Explanations like this were common: ‘We used to get most of our household food from our animals, garden and nature. Now we get most of it from the store. Back then everything was deficit in the store—I remember getting in line the night before for some deficit item—a women’s dress or other—now the stores are full and we are having a deficit of cow products! That’s a big change, if you ask me.’ (Viliui Sakha householder, summer 2012). Although many are ‘freeing themselves of the cow barn,’ in each village there are several households who are not only maintaining their herds but expanding, taking advantage of the newfound market, since their neighbors prefer the local meat and milk over store bought. Overall, this research clarifies the importance of long-term social science work and collaboration with affected communities in order to not only document communities’ rich local knowledge of change but also to ascertain how other drivers interact in climate processes.

3.3.2. Preliminary findings in the Central Yakutian regions

While all these observations have been documented for the Viliui region (Crane, 2011, 2015; Crane et al., 2013) they are not limited to that part of Sakha. Nascent social science research with residents of Central Sakha-Yakutia (in and around Tyungyulyu and Maja, Fig. 2B) show similar trends, despite the fact that hydrographic and climatic conditions are locally diverse (Y. Zhegusov, personal communication, July 2015). For instance at Tyungyulyu residents observe multi–annual oscillations of alaas lake size with direct impact on pastures and hay-making areas.

Local perceptions of less predictable seasonal air temperatures and precipitation, along with occasional reports about invasive species, imply a general change in regional climate conditions in the Lena–Aldan interflueve.

In summary, local inhabitants have expertise that contributes richly to a more nuanced understanding of alaas degradation and change. Given the highly specific nature of alaas change depending of the properties of the alaas in question, inhabitants’ expert knowledge reveals how change is occurring in very place-specific ways. Additionally, given inhabitants’ long-term residence and use in these locales, they also offer a potentially viable agency for on-the-ground alaas observation and effective adaptive response.

4. Integration and communication of knowledge as a basis for adaptation strategies

While findings based on local inhabitants’ perceptions and observations described above are in general agreement with scientific observations on environmental change, they also show some dissonance. This does not mean that either is less credible, however, but rather that other factors need to be taken into consideration when corroborating these two knowledge domains. Consider this example: while corroborating the nine main changes of Viliui Sakha with scientific data, there was dissonance when considering inhabitants’ observation of ‘too much rain’ and precipitation data of the last 20 years. The data showed no significant increase. Although the tendency may have been to discount inhabitants’ claim of ‘too much rain,’ with an anthropological appreciation for why people may make such a claim, namely that the seasonal precipitation patterns had changed to bring more rain during the hay season and less in spring, it became clear that both domains were correct. This kind of consideration is critical to understand the cultural implications of global change research.

Furthermore, identifying the gaps between the two domains, shows their complementarity. In consultations in the Viliui regions and in Tyungyulyu, inhabitants possess detailed knowledge of seasonal weather, lake-surface and vegetation changes; but they are less knowledgeable about ground temperatures and the causal connections of thermokarst processes with landscape changes. Scientific observations, in turn, do not sufficiently acknowledge the cultural and spiritual significance of alaas landscapes. Moreover, agricultural policies and engineering activities, despite their scientific basis, often lead to negative consequences, as exemplified by soil compaction or construction activities in thermokarst-sensitive areas. The integration of the two domains of knowledge allows local inhabitants to better assess the causal interconnections of landscape change and the speed and scale of it. Reversely, empirical studies can incorporate surface–change observations and better comprehend the importance of land–use activities over past decades and centuries and current socio-economic processes when assessing and forecasting environmental change (Table 1).

For local inhabitants and external observers alike, the consequences of climate change are topical, but the complexity of environmental processes is sometimes hard to assess and may lead to misinterpretations. Considering that human land–use strategies of alaas actively utilize processes of thawing, including permafrost degradation, soil subsidence, and thermokarst formation, it may appear that this type of land use would benefit from higher annual air and soil temperatures. If land use is based on thermokarst, why then be concerned about the prospect for a warmer climate? At least two reasons are possible. First, pastoral land use depends on “mature” forms of thermokarst, those which have developed over thousands of years, whereas the initial forms of thermokarst – boggy, inundated areas – are detrimental to this economy. Second, the speed and scope of contemporary thawing challenges users’ adaptive capacity.

Furthermore, in the Sakha Republic as elsewhere in the Russian North (Karjalainen and Habeck, 2004), local inhabitants perceive environmental change as one of a wider array of processes,
including social and economic change (c.f. Crate, 2014). As detailed in the Viliiu Sakha case above, the decision of whether or not to continue pastoralism in alaas ecosystems hinges not only on regional aspects of climate change but also on work conditions and technological innovations, other sources of monetary and non-monetary income, opportunities for youth out-migration to the city, the next generation’s intent to and economic opportunity to continue pastoralism, and the symbolic importance alaas pastoralism has for inhabitants. All these factors determine present and future alaas use and contribute to the other factors, geomorphological and ecosystemic, that have repercussions on the alaas as an object of study.

Considering the central role alaas play in local economies and the unprecedented physical and sociocultural changes affecting them, the next questions concern how communities, scientists and other stakeholders can best integrate their knowledge systems towards holistic understanding, thereby envisioning more realistic future scenarios, and making more evidence-based policy recommendations that accommodate, as best they can, unprecedented change.

Historically, scientists have considered the natural environment as relatively stable and human activity as introducing change and degradation into that stability. This view takes humans out of “the Environment” (Ingold, 2000). Ethnographic studies showing that inhabitants of Siberia, and most world locations, tend toward a common set of subsistence and land use practices in their respective environment, developed over centuries and with an ability to adapt and respond to ecological and economic fluctuations. Ecosystem stability is more often a consequence of resilience or “the ability of these systems to absorb changes and still persist” (Berkes, 2008). However, contemporary climate change introduces unprecedented conditions, challenging and tending to outpace resilience, wherein “nature [is] on the move” (Takakura, 2012; Takakura, 2015). In some contexts, the pace of change renders local adaptive practices ineffective.

One way to bolster local adaptive capacity in these contexts is for researchers to communicate their findings and global change information to affected populations (Alexandrov et al., 2010). Within the region under study, there are not only some incongruences between local inhabitants’ and scientific perceptions of environmental change, but also a wide gulf between these groups’ perceptions of societal action and stakeholder involvement (Forbes and Stammler, 2009; Stammler-Gossmann, 2010b).

The knowledge exchanges initiated by authors Crate and Fedorov in the Viliiu region (Section 3.3.1) directly addressed this gap: their objective was both to communicate scientific knowledge of regional change in the local vernacular for inhabitants but also to validate and corroborate inhabitants’ local knowledge of how global climate change was affecting local conditions. Following the exchanges, the team published a succinct, easily accessible handbook, emulating the knowledge exchange process and communicating critical information, all in the Sakha language, which was distributed throughout Viliiu-Sakha communities (Crate et al., 2013).

Scientists and local stakeholders have started to jointly develop practical recommendations to: identify areas unsuitable for construction work because of thermokarst risk; design temperature insulation of houses in rural communities (Crate et al., 2013); provide adequate machinery for hay-making in sensitive areas; and consult on fodder distribution networks that help cattle and horse breeders. Today, the Ministry of Agriculture already distributes hay and artificial feed (Press-sluzhba, 2013) and helps brigades of hayworkers find hayfields in other administrative units. Hay production networks among river islands and alaas have been established to secure the continuation of cattle and horse breeding in cases of summer floods (Takakura, 2015).

5. Future prospects for the alaas ecosystems in the Republic of Sakha (Yakutia)

5.1. Predictions of environmental change

The IPCC’s (Intergovernmental Panel on Climate Change) fifth assessment clearly links increasing air temperatures with permafrost decrease (IPCC (Intergovernmental Panel on Climate Change), 2013). The smallest-change scenario (RCP2.6) predicts that by the end of the 21st century the near-surface permafrost area will shrink by 37%, whereas the scenario with highest confidence (RCP8.5) predicts a shrinkage of 81%. Scientists also predict a significant thawing of near-surface permafrost by the end of the 21st century for large parts of Russia, Alaska, and Canada (Slater and Lawrence, 2013). This thawing will increase the active layer thickness, expand taliks (i.e. bodies of unfrozen ground within the permafrost) and thermokarst processes. Melting ground ice and an increase of the mean active-layer thickness will release vast amounts of water (e.g., Fedorov et al., 2014). Such release of water will greatly expand lakes and the adjacent water-logged territories within the alaas and cause catastrophic flooding of small rivers in summer. Increasing the depth of seasonal thawing transforms the water balance of permafrost areas which will cascade multiple effects on biodiversity, ecosystem productivity and human use of large areas (Iijima et al., 2014).

However, prediction of permafrost landscape change is not straightforward. It involves much uncertainty, considering the cascading ecosystem effects, the sociocultural interactions and incomplete understanding of alaas processes to date. Consider that the IPCC value of global temperature increase using its conservative scenario PTC2.6 amounts to +1 °C by the end of this century (IPCC (Intergovernmental Panel on Climate Change), 2013), close to the warming during the Holocene climate optimum, when most alaas of Central Sakha-Yakutia were formed. The alaas density map compiled by Bosikov and Ivanov (1978) suggests that the consequences of such temperature change today may be less drastic than expected, as it shows that with a +1 °C change during the Holocene climate optimum only 10–20% of the ice complex in Central Siberia did undergo degradation. This strongly indicates that the resilience of alaas permafrost landscapes might be sufficient to save 80–90% of permafrost areas of the ice-complex type, i.e. areas with underlying large ice wedges and high ground-ice contents.

To illustrate the dynamism of this system further, this resilience can be offset by vulnerability specific to local/regional context, including vegetative land-cover conditions and geomorphology (Jorgenson et al., 2010). In forested areas, permafrost stability is usually buffered by the shielding layer (i.e. transient layer), preventing the underlying icy deposits from thaw even under severe climate change (Shur et al., 2011). Research suggests that in the late Pleistocene and early Holocene, the shielding layer below forested permafrost landscapes preserved the ice complex from thaw (Ronishev, 2011). The presence of a sufficiently strong shielding ground layer (up to 1 m) in contemporary boreal forests of the Sakha Republic testifies to the stability of permafrost in forest landscapes. Katamura et al. (2009a,b), however, show that forest fires were one of the multiple causes that induced thermokarst processes and, finally, over several hundreds to thousands of years the formation of alaas, as evidenced by the remains of charcoal in alaas sediments. The risk of permafrost degradation is thus generally higher in disturbed landscapes (e.g., those affected by forest fires) and open, treeless areas underlaid by ice-rich deposits in which the shielding layer decreases or is absent. If in such areas the depth of seasonal thawing reaches the horizon of the ice complex, rapid degradation is very likely to...
ensue. Such areas must frequently be abandoned, if they were used as croplands (Ulrich et al., 2017b; see also Fig. 7).

Geomorphological characteristics also factor into vulnerability. According to Bosikov and Ivanov (1978), in the previous eras of climate warming the better-drained surface of the Abalakh ice complex in the Lena- Aldan interfluve region (Fig. 2B) was less affected by degradation than the less drained surface of the Tyunguluyu terrace, which accumulated considerable amounts of surface and supra-permafrost water.

Moreover, future predictions must accommodate a multitude of nascent factors relevant to our contemporary world, perhaps most importantly being the alteration of carbon (C) fluxes and greenhouse gas (GHG) emissions. Three aspects relevant to alas ecosystems are: first, the reduction of the soil C stock from utilization of thermokarst basins as pastures and hay-making areas (Desyatkin et al., 2007); second, the increased emission of GHGs from medium–moist and wet grasslands in hot summers (Takakai et al., 2008); and third, the significant emissions of methane due to decomposition of carbon stored in flooded grasslands and during thaw processes below thermokarst lakes (e.g., Desyatkin et al., 2009; see also Schuur et al., 2015 and references therein).

5.2. Changes in the conditions of rural livelihoods dependent upon alas

Future predictions of alas-landscape development must factor in socio-economic and cultural change. The post-Soviet transition continues to evolve and, as detailed in section 3.3.1, recent research documents how inhabitants are challenged by a complexity of change (Crate, 2014). Within this paradigm the development of rural economies that create local jobs and household incomes is to date lacking. While virtually all rural districts of the Sakha Republic have seen significant youth out-migration to the city of Yakutsk (Argounova-Low, 2007), trends vary widely. In the central part of the Republic where villages are adjacent to the urban area, many extended families maintain households in both the city and countryside (G. Belolyubskaya, personal communication, July 2015). Such changes in residency patterns will potentially create higher demand for alas areas closer to the city, but also new options for milk and meat producers farther away.

Simultaneously, rural livelihoods can offer a fallback option in times of economic crises. Viliiu Sakha research suggests that although household-level cow keeping may be in decline, entrepreneurial initiatives of extended kin households keeping larger herds to supply local markets is on the rise (Crate, 2014). These entrepreneurs are taking advantage of the market created when their neighbors discontinue cow keeping and are rendered clients because they continue to prefer the taste and quality of local products. In fact, the development of several such entrepreneurial efforts in each of author Crate’s research villages suggests this may be the gradual evolution to an efficient local economy wherein instead of all households maintaining the cows-and-kin food production system (Crate, 2006a), several extended households engage in meat and milk production for their communities (Crate, 2016). Thus, in turn, may work in favor of these small-scale entrepreneurial efforts and thus sustain alas-based pastoralism in the future, despite that it will not regain the spatial extent it had in previous centuries due to environmental constraints.

Furthermore, the intensity and spatial pattern of alas use today is often determined by two other factors: access to technological rather than manual methods of both hay harvesting and drainage techniques, and property and institutional land-use arrangements. Finally, for the herders who continue their craft, the last decade has seen a trend away from the work-intensive responsibilities of cattle breeding, involving daily milking, feeding, watering, barn cleaning, etc. in an economic environment where sale of products is less and less profitable. Instead, many are opting for horse breeding which involves no daily work since horses roam freely in harems and can produce meat in a year from birth. Both the cow and the horse stand in a complementary economic and also symbolic relationship. Currently, the horse has higher significance as a prestige animal and symbol of Sakha identity, with horse meat being praised as a Sakha delicacy (Maj 2009; Stammler 2010; Stammler-Gossmann, 2010a). All these factors interact with and are complicated by the physical conditions of the alas, such as soil temperature, moisture, rising and shrinking water levels and forage quality.

6. Conclusion

To effectively study how climate change may influence northern livelihoods in the context of the many interactions of diverse agents – humans, other sentient beings and the dynamics of the natural world – this article presents an interdisciplinary approach surpassing language barriers between the international scientific community, regional scholars and local residents. Scientific observations of climate, water and land cover show an overall increase in precipitation and in air and ground temperatures, which has translated to an acceleration of thermokarst activity in the central and western lowlands of the Sakha Republic. These findings generally concur with social science investigations documenting local inhabitants’ reports on environmental change affecting the alas ecosystem and economy. Covering the physical and socio-cultural development of alas shows that in the last three decades significant changes of permafrost landscapes and associated alas land-use practices have occurred. Combining these domains of knowledge through novel forms of communication between scientists, regional scholars and local inhabitants, this article has reviewed, portrayed, and analyzed the changes documented during the last three decades, and identified the range of factors that need to be considered when forecasting permafrost dynamics and their consequences in the near future.

Several areas demand further research. First, it is key to study the spatial and temporal hydrological and ground-thermal conditions in order to understand the ecological system of thermokarst regions in their full complexity. As of now, hydrology is one of the least understood domains of alas and thermokarst development. Second, there is a need for more detailed information of settlement and land use history, including the effects of artificial drainage and irrigation, at specific alas sites to understand human-induced landscape changes. Third, the exact function of the shielding layer is insufficiently understood, as is the impact of forest fires and changes in the vegetation cover more generally. Fourth, in rural communities in the Viliiu Regions and Central Sakha there needs to be investigation examining the decisions of members of different generations whether to leave or stay (along with the economic and legal aspects that stand behind these). Who will work in the alas in the future? Fifth, in the light of old policies and subsidies having waned and with a view to new patterns and predictions of food consumption, the question of cattle breed should be subjected to a new assessment. The traditional Sakha breed of cattle has less milk output but is also less demanding in forage quantity. Is the reintroduction of Sakha local breed a viable option in the likely context of pasture deterioration? Sixth, and academically particularly challenging, is the demand for closer integration of different types of data and different time scales. The timespan of biographical memory, rarely extending beyond the 1940s, and the historical record of Sakha residence in the alas regions, which comprises up to 800 years, may at first glance seem incompatible with the temporal scope of soil profiles or palaeoclimatic pollen analysis.
The exceptionally rapid character of thermokarst development allows and requires juxtaposition with local residents’ observations and memories. The alaas therefore lends itself as an ideal opportunity for transdisciplinary studies of environmental change. Moreover, it presents an exemplary case of indigenous land use in a context of rapid, anticipated and in some occasions consciously triggered modifications of the landscape. These dynamics make the local Sakha communities particularly apt observers of environmental change. By the same token, the recently accelerating speed and magnitude of change appears to call for new strategies of adaptation.

Finally, a central conclusion is the insight that the future of the alaas ecosystem and type of land use – and more generally, of land use in subarctic and arctic regions – depends not only on the speed and scale of environmental change, but also, and to no lesser degree, on global, national, and regional socio-economic factors, such as demographic development, technological change, political dynamics, and cultural significance of food and rural livelihoods. In the alaas context, ecosystem change driven by human activity at the regional and local levels, including indigenous ways of engaging with the land and socio-economic factors, either induces or reduces the intensity of land use. This changing intensity especially occurs in the remoter alaas regions, while physical and ecological factors define the limits of human use for pasturing and hunting/marking. Artificial draining and other modifications of alaas landscapes can shift these limits, as the historical record has shown, but only to some extent, and sometimes with unintended consequences, deteriorating the preconditions for future land use.

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