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Spatial distribution of pingos in Northern Asia

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Abstract

Pingos are prominent periglacial landforms in vast regions of the Arctic and Subarctic. They are indicators of modern and past conditions of permafrost, surface geology, hydrology and climate. A first version of a detailed spatial geodatabase of more than 6000 pingo locations in a $3.5 \times 10^6 \text{ km}^2$ region of Northern Asia was assembled from topographic maps. A first order analysis was carried out with respect to permafrost, landscape characteristics, surface geology, hydrology, climate, and elevation datasets using a Geographic Information System (GIS). Pingo heights in the dataset vary between 2 and 37 m, with a mean height of 4.8 m. About 64% of the pingos occur in continuous permafrost with high ice content and thick sediments; another 19% in continuous permafrost with moderate ice content and thick sediments. The majority of these pingos likely formed through closed system freezing, typical of those located in drained thermokarst lake basins of northern lowlands with continuous permafrost. About 82% of the pingos are located in the tundra bioclimatic zone. Most pingos in the dataset are located in regions with mean annual ground temperatures between -3 and -11 °C and mean annual air temperatures between -7 and -18 °C. The dataset confirms that surface geology and hydrology are key factors for pingo formation and occurrence. Based on model predictions for near-future permafrost distribution, hundreds of pingos along the southern margins of permafrost will be located in regions with thawing permafrost by 2100, which ultimately may lead to increased occurrence of pingo collapse. Based on our dataset and previously published estimates of pingo numbers from other regions, we conclude that there are more than 11 000 pingos on Earth.

1 Introduction

Periglacial landforms are important climatic and environmental indicators for permafrost-dominated landscapes (French, 1999). Knowledge about the spatial

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distribution, morphometry, and statistical characteristics of a population of such landforms allows for conclusions on geological, geomorphological, hydrological, and cryological conditions during past and present times. Many detailed studies exist on the spatial distribution and spatial statistics of periglacial landforms such as rock glaciers (Matsuoka et al., 2005; Esper-Angillieri, 2009), cryoplanation terraces (Demek, 1968; Nelson, 1998), solifluction features (Gorbunov and Seversky, 1999; Matsuoka, 2001), patterned ground (Hjort and Luoto, 2006; Walker et al., 2008), palsas (Luoto and Seppälä, 2002; Pissart, 2002), pingos (Mackay, 1962; Ferrians et al., 1988), and thermokarst lakes and basins (Coté and Burn, 2002; Hinkel et al., 2005) in various polar regions. Increasingly, more recent studies make intense use of spatial analysis tools within Geographical Information System (GIS) software, allowing for the study of large digital datasets in combination with various environmental data.

Prominent periglacial features in Polar Regions are perennial frost mounds, including the broad categories of pingos, palsas, and lithalsas. A rich literature exists especially on pingos, which are formed by growth of a massive ice-core in the subsurface and associated long-term frost heave of the terrain surface. Pingos are a clear indicator for the presence of permafrost. Many detailed studies exist on the unique hydrologic, geologic, and permafrost conditions required for their formation (Soloviev, 1952; Bobov, 1960; Mackay, 1962; Holmes et al., 1968; French, 1976; Ferrians, 1988), growth and decay rates (Mackay, 1978a, 1986, 1987, 1998; Yoshikawa, 1991; Yoshikawa and Harada, 1995), and age (Craig, 1959; Holmes et al., 1968; Mackay, 1976; Walker et al., 1996). Although the detailed genesis of these perennial frost mounds varies, ground water migration in unfrozen zones (taliks) within the permafrost plays a key role (Mackay, 1978b; review by Gurney, 1998). Subsequent concentrated freezing of water and the formation of a massive ice body are important processes for up-doming of overlying frozen sediments and the terrain surface. Two primary pingo forming processes exist: hydrostatic or closed system pingos, and hydraulic or open system pingos (Mackay, 1966, 1978). The former are typical of regions underlain by continuous permafrost, whereas the latter tend to occur in regions of discontinuous permafrost. Gurney (1998)

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proposed a third distinguishing pingo-form termed “polygenetic pingos” to categorize all remaining pingo types that do not fit the two main classes. The ice-core growth and related frost heave results in usually conical, dome-like mounds of elliptical to circular planar shape with diameters of up to 600 m and up to 50 m in height (Gurney, 1998) (Fig. 1). Various characteristics of pingos and their formation are intensely discussed in the literature mentioned above and will therefore not be repeated here.

The majority of pingos are reported from pan-Arctic lowlands with continuous and discontinuous permafrost, and to a smaller extent from valleys and plateaus in mountain permafrost regions. In North America, pingo research concentrated on Northwest Canada and Alaska. Initial scientific accounts of pingos in this region are from Leffingwell (1919) and Porsild (1938), followed by intense studies of Mackay (1962, and subsequent years) and many others. In Northern Eurasia, detailed scientific research on pingos and their hydrogeology began largely in Siberia in the 1930’s (e.g., Tolstikhin, 1932; Andreev, 1936; Soloviev, 1952; Bobov, 1960; Shumskii and Vtyurin, 1966; Soloviev, 1973). Detailed maps of pingo distribution, often based on aerial imagery, exist for many regions of the Arctic (e.g., Holmes et al., 1966, 1968; Mackay, 1966; Galloway and Carter, 1978). Brown and Pewe (1973) summarized the state of knowledge on pingo distribution in North America and provided generalized maps. Mackay (1998) estimated that there are about 5000 or more pingos on Earth, 1350 of which are found on the Tuktoyaktuk Peninsula in NW Canada alone. For Russia, several generalized maps showing provinces of pingo localities exist (e.g., Ershov et al., 1991; Shumskii and Vtyurin, 1966). Numerous local to regional scale maps of periglacial geomorphology and permafrost hydrology in Siberia were published in the Russian literature, also showing locations of pingos. Beside the main regions of pingo distribution in NW Canada, Alaska, and Siberia, smaller occurrences of pingos are reported from Greenland (Mueller, 1959; Bennike, 1998), Svalbard (e.g., Yoshikawa and Harada, 1995), Scandinavia (Lagerbaeck and Kohde, 1985), China (Wang and French, 1995), and Mongolia (Lamborinchen, 2000).

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permafrost, geologic, hydrologic, and morphometric parameters useful for climate and paleo-environmental modelling (e.g., Harris, 1982; Huijzer and Vandenberghe, 1998), as well as for comparing the distribution of potential submarine and extraterrestrial analogue features. However, although there are many maps showing local and regional pingo distribution and the general occurrence of pingos in the Arctic, detailed GIS-based spatial databases of pingo locations on a large regional or panarctic scale are currently non-existent to our best knowledge.

The primary objective of our study is to introduce an initial GIS dataset on the spatial distribution of pingos for a large region in Northern Asia based on digitized features from medium-resolution topographic maps. Though generalized maps of pingo distribution in this large region already exist they do not have the level of detail necessary for analysis of spatial distribution, morphometry, and the relation of pingos to other environmental parameters. In this study, first-order spatial information from this newly assembled pingo dataset is assessed in relation to various other environmental parameters (geology, hydrology, climate, permafrost, topography, geography, and bioclimatic zone). Possible spatial relations are discussed, and some conclusions are drawn on their use as indicators for climatic, environmental and permafrost conditions. We also discuss the impact of near-future diminished permafrost distribution as projected by numerical permafrost models on the North Asian pingo population. Based on the methods and available base data used, the presented dataset should be understood as a conservative (minimum) estimate of pingo numbers in Northern Asia and an additional effort towards a detailed global map of pingo distribution.

2 Study area

The study area comprises the North Asian lowland regions of North, Northeast, Far East and Central Siberia and adjacent mountain ranges from 60°00' N to 76°40' N latitude and 60° E to 168° W longitude (Fig. 2). The geographic regions covered in this study are the northern part of the West Siberian Lowlands including the

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Yamal and Gydan peninsulas; Taymyr Peninsula; Putorana Plateau; Khatanga-Anabar-Olenek Lowlands; Lena River Delta; Lena River Valley; Central Yakutian Lowlands around Yakutsk; Yana-Indigirka-Kolyma Lowlands; New Siberian Islands; and the Far East Siberian Chukotka region. The total land area included in the study region is $3.48 \times 10^6 \text{ km}^2$. This land area is largely characterized by continuous ($3.30 \times 10^6 \text{ km}^2$; 94.7%) and discontinuous ($0.15 \times 10^6 \text{ km}^2$; 4.4%) permafrost as well as a very small fraction of other ground (<0.9%) (Brown et al., 1998). Climate zones in the study region range from very-cold, arid to moderate-cold, moist climates. Bioclimatic zones, based on Stolbovoi et al. (2002), include polar deserts, tundra, and various forms of taiga. Elevations for the mapped part of the study region range from 0 m a.s.l. in the Arctic coastal lowlands to 2400 m a.s.l. in some of the mountain ranges.

3 Methods

3.1 Pingo mapping

The locations of pingos were manually digitized from 1:200 000 Russian topographic maps (Fig. 2). These medium-scale maps are based on detailed mapping efforts at 1:50 000 and 1:100 000, which in turn are derived from aerial photography acquired in the 1970–1980's (Soviet Military Topographic Survey or Voенно-Topograficheskoe Upravlenie General'nogo Shtaba, VTU GSh). Their unique mound shape makes pingos important relief, survey, and viewpoint features especially in otherwise flat lowlands, warranting their inclusion also in medium-scale maps even if their actual size is of insufficient size for the map scale. According to Russian cartographic standards used in these maps, such mounds are indicated either with a specific symbol (red star), or, if diameter and height warrant, by contour lines, both usually accompanied by a Russian map label for pingo (Fig. 3). Labels used in these maps to indicate pingos include the classical Yakutian term *bulgunnyakh*, the term *ledyanoy bugor* mostly used in West Siberia, and the more widely used term *ledyanoy kholm*. These terms are partially

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based on regional terminology for the same feature and partially based on different hypotheses on their genesis. The term *bulgunnyakh*, e.g., specifically describes pingos that form during freezing of closed or semi-closed taliks. In a few cases, pingo fields consisting of multiple spatially close pingos were specified in the maps, which were mapped by us as single pingo occurrence because of lacking detailed information on the exact pingo numbers in such an area.

With few exceptions, most of the map sheets cover an area of 2 degrees longitude by 40 min latitude. The original maps are projected in Gauss-Krueger with Pulkovo 1942 datum. The entire map dataset was available in digital form (MicroGlobe LLC) and imported in a desktop GIS. Each map tile was then visually searched for pingos and identified features were marked with a point in a point layer. If available, additional map-derived information was added in an attribute table: Pingo height above surrounding terrain; absolute height above mean sea level; and Russian label for the mound. Eventually, the complete point layer was exported and converted to a dataset with geographic latitude-longitude coordinates in datum WGS-84.

3.2 Accuracy assessment

Three main error sources exist for pingo locations derived from the maps. First, errors can be inherited from the original mapping efforts based on stereo aerial imagery, including potential mis-interpretation of features as pingos or missing of true pingos by the image interpreters (particularly in forested regions). Second, errors in our dataset could be related to an intentional decreasing of information content for map clarity in the scaling process during map production going from aerial imagery mapping to generation of fine-scale resolution maps and eventually to the medium-resolution maps used in this study. Last, potential location errors are related to georeferencing of the original aerial imagery and the produced maps. We assume a horizontal geo-localational error of up to 250 m based on individual map quality and georeferencing. Further studies need to be conducted to assess accuracy and completeness of the map-derived pingo locations in the entire study region. Such studies would include field ground

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truthing, high-resolution satellite image analysis, and incorporation of existing local high-resolution pingo maps.

We performed an initial accuracy assessment that consisted of image analysis of six cloud-free scenes of late winter Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images onboard Terra from different subregions in northern lowland tundra (Table 1). ASTER imagery from 2000 and 2007 from the TerraLook Collection was acquired from the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center website. The TerraLook ASTER images were produced as simulated natural color images using the green, red and near infrared bands, and have a pixel size of 15 m and a foot print of about 3600 km². Late winter optical satellite imagery (February to March) of northern high latitude tundra regions has unique properties that aides mapping of relief features such as pingos. Relatively homogeneous snow cover provides a homogeneous surface reflectance over the entire image scene, while a low sun angle and southern sun position results in pronounced shadows and strong contrasts between sun-facing (south) and sun-opposing (north) slopes. Even low to moderate relief features, such as pingos, are visible in the winter imagery, which resemble shaded relief maps produced from digital elevation models. Pronounced circular to elliptic elevation features, such as pingos, in otherwise relatively flat thermokarst basins or fluvial landscapes with homogeneous reflectance stand out in such imagery by having a very bright sun-facing side and a long shadow on the sun-opposing side (Fig. 4).

We manually mapped pingos in the six ASTER scenes and compared the number of identified pingos with that derived from the topographic maps for the same area (Table 1). We clearly found more pingos in all ASTER scenes than were marked in the 1:200 000 scale topographic maps, which is likely related to a reduction in resolution and the intentional loss of some spatial information in a medium-resolution map. Pingos found in ASTER imagery but not identified in topographic maps are considered *false negatives* in our accuracy assessment. Furthermore, some pingos marked in the maps could not be identified in our ASTER scenes, which we considered *false*

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is based on the Global Lake and Wetland Database (GLWD) (Lehner and Döll, 2004), we (1) applied manual corrections to the GLWD by selecting lakes only, (2) removed lagoons and streams misclassified as lakes, and (3) generated a lake area density map for all lakes > 10 ha with 5 km grid cell resolution using ArcGIS. Basic geographic distribution of pingos as well as pingo distribution in relation to these thematic datasets were plotted in map and histogram form and subsequently analyzed. Some regional characteristics of the identified patterns are discussed. Spatial point density of pingo locations was determined using a 10 × 10 km search kernel (100 km²) for a 5 km grid cell raster (for reporting in text) as well as a 20 × 20 km search kernel (400 km²) for a 5 km grid cell raster (for enhanced clarity in maps).

4 Results

A total of 675 map sheets covering an area of 4.00×10^6 km² (87% of it terrestrial) in Northwest, North, Northeast, and Central Siberia were analyzed (Fig. 2). The mapped area covers most of the Siberian lowlands with continuous permafrost. A total of 6059 mounds were identified in 296 map sheets (Fig. 2). The majority were labelled as *bulgunnyakh* (Table 3). Pingos labelled with *ledyanoy bugor* are found only in West Siberia, while those labelled with *ledyanoy kholm* are found broadly across the region (Fig. 2). 1126 mounds were not labelled specifically as pingos in the topographic maps; however, based on map signatures, topographic location, and proximity with other clearly identified pingos occurrences, these were interpreted as pingos and included in this analysis (see also Fig. 3). The number of pingos in the mapped region can be considered a conservative minimum value due to the degree of generalization likely in the 1:200 000 scale maps and our comparison with ASTER mapping results proving that numerous pingos are missing in the maps. Pingo counts per map sheet ranged from 0 to a maximum of 231.

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4.1 Geographic distribution

Pingos in the study region occur between 61.39°–74.65° northern latitude. However, a clustering is observed for the northern latitudes between 69° and 72°, where 2990 pingos or 49% of the mapped population occur (Fig. 5). Pingo numbers decrease with lower latitudes, with an exception being the dense pingo occurrence of the Central Yakutian region. Several important pingo provinces were identified: About 1620 pingos were mapped on the Yamal and Gydan peninsulas in West Siberia (66.9–86.2° E longitude) (Fig. 6), 260 pingos in the lowlands south of the Taymyr Peninsula (87.2–108.9° E) (Fig. 7), 360 pingos in the Khatanga-Anabar-Olenek lowlands (109.2–120.7° E) (Fig. 8), 85 pingos in the Lena River Delta (123.5–129.4° E) (Fig. 8), 600 pingos in Central Yakutia (126.0–133.6° E) (Fig. 9), 1500 pingos in the Yana-Indigirka lowlands (132.4–154.0° E) (Fig. 10), 700 in the Kolyma Lowlands (150.7–162.5° E) (Fig. 10), and 735 pingos in Chukotka (159.5°E–174.3°W) (Fig. 11).

Several geographic regions have a high density of pingos (Fig. 5). Highest densities occur in the Central Yakutian Lowland near Yakutsk with up to 28 pingos per 100 km² and in the Anadyr River Valley with also up to 28 pingos per 100 km² (Table 4). A very high density of up to 26 pingos/100 km² was also detected for some mountain valleys in Chukotka. For most of the northern lowlands moderate point densities of up to 6–14 pingos per 100 km² were identified. Highest pingo point densities in northern lowland plains were encountered on the Gydan Peninsula with 21 pingos per 100 km² (Table 4). Higher local densities can be expected if focusing on particular landscape elements favourable for pingo formation in such a high density region.

Elevation data clearly indicates that a large number of mapped pingos (4166; 68.8%) occur in lowland plains dominated by thermokarst lakes and basins below 50 m a.s.l., mainly found along the Arctic Ocean coasts (Fig. 12). Notable exception are the pingos in the Central Yakutian Lowland around Yakutsk (600 pingos; mean elevation 160 ± 38 m a.s.l., 1σ) and smaller populations of pingos in higher densities identified in mountainous regions of Chukotka (123 pingos; mean elevation 633 ± 112 m a.s.l., 1σ)

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and the Putorana Plateau (49 pingos; mean elevation 699 ± 109 m a.s.l., 1σ). Many pingos were found in river estuary and delta regions (Ob, Yenisey, Khatanga, and Anabar estuaries; Lena, Yana, Indigirka, and Kolyma deltas) and as well as large river valleys (Khatanga, Anabar, Lena, Indigirka, Kolyma, and Anadyr rivers) (Figs. 6 to 11).

5 Finally, the majority of pingos in the study region are located in the tundra zone (4938; 81.5%) (Fig. 13). Lower numbers are located in the pre-tundra/northern taiga zone (452; 7.4%) and the middle taiga zone (670; 11.1%).

4.2 Pingo height

Heights above surrounding terrain were provided in the analyzed topographic maps for 3109 pingos (51.3% of entire dataset) and ranged from 2 m to 37 m with a mean of 4.8 ± 2.8 m (1σ) (Fig. 14). A vast majority of the pingos range in height from 2–8 m (2873 pingos, or 92% of pingos with height data). Only 236 pingos are higher than 8 m (8% of pingos with height data). The 2 highest pingos in the dataset, 36 m and 37 m, were both found in the lowlands south of Pevek, Chukotka. The pingo on the Bykovsky Peninsula shown in Fig. 1 is 28 m high and the 3rd highest in this dataset. Such tall pingos occur only in the northern regions of the study area. Beyond this notion, no specific trend in pingo height was observed over this large region except that taller pingos tend to occur in lowlands as compared to higher elevations. Frequently reported pingo heights in Siberia of up to 50 m could not be confirmed with the present dataset. However, since only for half of the pingos in the dataset direct height values were provided in the maps and the ASTER imagery indicated that numerous pingos remain un-mapped and thus are absent from our map-derived dataset, we cannot rule out the presence of some very large pingos in the study region.

4.3 Distribution in relation to permafrost parameters

25 Based on Brown et al. (1998), the study area is dominated by continuous (94.7%) and discontinuous (4.4%) permafrost (Fig. 15). The large majority of pingos are located

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in the continuous permafrost zone (5948; 98.2%) and only a very small number were found in discontinuous permafrost (111; 1.8%) (Fig. 15). Since no isolated and sporadic permafrost regions were included in the dataset compilation and analysis yet, the presence of pingos in these regions remains unclear. Most pingos are found in continuous permafrost regions with large sediment thickness and high ground ice content (Chf; 3897; 64.3%) or moderate ground ice content (Cmf; 1126; 18.6%). Pingos in these permafrost types are concentrated in the North Yakutian Lowlands and Northeast Siberia, as well as to some extent in Central Yakutia and Northwest Siberia. The remaining pingos (1036; 17.1%) are spread over other permafrost types with lower ice contents, lower sediment thickness, or discontinuity in permafrost extent. Pingos in regions with lower ground ice contents are also found in Central Yakutia (old Lena river terraces), the valleys south of the Taymyr Peninsula (glacio-fluvial terraces), in Chukotka (mountain valleys), and in Northwest Siberia (glacio-fluvial deposits) (Fig. 15). Some localized pingo occurrences are confined to regions with low sediment cover, namely in mountain valleys of Chukotka and the Putorana Plateau.

The distribution of pingos in relation to modern mean annual ground temperature (MAGT) reveals an interesting pattern (Fig. 16). Most pingos are confined to permafrost areas with MAGT between -3 and -11°C (5581; 92.1%). The ground temperature range most populated with pingos is the range from -9 to -11°C (1931; 31.9%). With higher MAGT in the range -3 to -9°C there is a gradual decrease in pingo numbers. There is a sharp decline in pingo numbers for MAGT above -3°C and below -11°C , possibly also due to the lack of suitable land area and subsurface geology for pingos in regions with lower MAGT. Small populations of pingos in permafrost warmer than -3°C are found in the southern part of the NW Siberian Lowlands and in the Lena River Valley.

4.4 Distribution in relation to climate parameters

The histogram of pingo distribution by mean annual air temperature (MAAT) shows a primary distribution of pingos in the study region between -7 and -18°C (5943;

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98.1%) (Fig. 17). There are nearly no pingos in regions with a lower MAAT, which partially might be caused by the lack of land areas suitable for pingo growth in higher latitudes. The pingo-rich regions around Yakutsk as well as in the coastal lowlands of North and Northeast Siberia are dominated by low to very low (-10°C to -18°C) mean annual air temperatures (MAAT) (Fig. 17). Pingo regions with relatively high MAAT above -10°C are found on the Yamal and Gydan peninsulas, and in the Pacific part of Chukotka. Pingo numbers also decrease sharply for MAAT above -7°C (110; 1.8%). Nearly all of these pingos with high MAAT occur in the southern part of the Northwest Siberian Lowlands. However, no regions with MAAT above -5°C were included in the study region and it is thus unclear whether any pingos currently occur in North Asia above this MAAT.

The histogram of pingo distribution by mean annual precipitation (MAP) shows a gradual decline in pingo numbers with increasing precipitation from 100 to 425 mm (Fig. 18). The northern coastal lowlands with very low precipitation rates have the highest numbers of pingos, which is especially pronounced in the Khatanga-Olenek Lowlands, the Yana-Indigirka Lowlands, and the Kolyma Lowlands. The spatial distribution of pingos versus MAAT and mean annual precipitation patterns reflects the occurrence of the majority of pingos in regions with a highly continental, cold and relatively arid climate.

4.5 Distribution in relation to surface geology

Pingo distribution in the study region is closely related to surface geology, i.e. lithology (Fig. 19). Major differences in surface geology in the study region, and thus also the suitability for pingo growth, are linked strongly to mountain vs. lowland landscape character, to past glaciations and permafrost history, and to dynamics of topography and drainage development during the Holocene. Only a very small number of pingos (204; 3.4%) were identified in areas within the extent of the Last Glacial Maximum ice sheet and mountain glaciations in the region after Ehlers and Gibbard (2003) (map not shown). On the contrary, more than 50% of all pingo locations coincide with a region

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identified by Romanovskii (1993) as accumulation zone for Yedoma, a thick ice-rich permafrost deposit typical for non-glaciated regions (Schirrmeister et al., 2010), during the LGM (map not shown). A large number of pingos (2525; 41.7%) are found in lowland coastal plains in North East Siberia with limnic deposits, encompassing sequences of sandy to silty limnic and alluvial sediments. Most pingos in such regions were found in fully or partially drained thermokarst lake basins. These basins likely have refreezing taliks and permeable sandy sediment layers in the subsurface, and the majority of these pingos will be of the closed system type typical for thermokarst lake basins (Mackay, 1978a). Large numbers of pingos (754; 12.4%) are also related to alluvial deposits in large river deltas and fluvial valleys of the Lena, Yana, Indigirka, and Kolyma rivers. The presence of permeable sandy layers in these environmental settings allow for ground water movement towards a freezing front in refreezing taliks under e.g. abandoned river channels or floodplain terraces, allowing the formation of pingos. Finally, morainic and fluvio-glacial sedimentary deposits in Northwest Siberia, the Taymyr Lowland and the Khatanga-Anabar Lowlands provide medium to coarse-grained sandy lithologies allowing water migration and ice core growth in refreezing taliks (Fig. 19). 1558 pingos (25.7%) are located in regions with such lithologies. A small number of pingos, potentially with open system character as described for other mountain regions (e.g., Hamilton and Obi, 1982), were identified in morainic and colluvial deposits of mountain ranges.

4.6 Distribution in relation to lakes and streams

High pingo densities are often found in lake- and basin-rich regions of the northern coastal lowlands. Our lake density map shows the tight coupling of thermokarst lake-rich regions in northern lowlands with the occurrence of pingos (Fig. 20). Intense spatial dynamics of thermokarst lakes including formation, growth, shrinkage, and drainage of thermokarst lakes in these landscapes are indicated by very high lake densities and the occurrence of a vast number of multiple generations of drained thermokarst lake basins. Talik formation and refreezing within these lake dynamics, in addition to sandy

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sediment layers permeable to ground water flow, play a key role for the formation of pingos in these lowlands. Detailed maps of pingo distribution in subregions of the study area (Figs. 6 to 11) also reveal patterns that often align well with river networks, indicating the connection of pingo growth to certain lithological and hydrological settings typical for river and stream corridors in permafrost regions.

4.7 North Asian pingo distribution in a warming Arctic

The current pingo distribution was analyzed in relation to scenarios of near-future, surface-permafrost distribution in Northern Asia. Spatially distributed numerical permafrost models predict strong degradation of permafrost at the present day southern margins of its extent through 2100 (Romanovsky et al., 2008). According to Romanovsky et al. (2008), permafrost degradation will be especially strong in late Holocene permafrost of Northwest, South Central, and Pacific Siberia, with Late Pleistocene permafrost starting to thaw by the end of the century. Over the coming century, surface permafrost thawing is expressed by an increase in the active layer thickness (ALT) and the formation of taliks that could generate new hydrological conditions and enhance ground water runoff in the southern permafrost regions. Though the direct impact of an ALT increase on a pingo is depending also on the insulating sediment and soil overburden above the ice core, long-term substantial ALT increases can be seen as a general indicator for permafrost warming and starting degradation. These processes likely will affect pingos in these regions by (a) increasing MAGT to a level not sustainable for pingo growth and preservation in some regions (Mackay, 1988), (b) exposing the ice core of some pingos to above freezing temperatures followed by ice melting and pingo collapse and (c) by changing hydrological and pressure conditions in the talik necessary for pingo growth and preservation. The majority of pingos today occur in regions with ALTs between 0.5 m and 1.0 m (Fig. 21a). Exceptions are pingos in Central Yakutia and West Siberia with ALTs up to 1.75 m. Today, no pingos in our dataset occur in regions with ALTs more than 2.0 m. However, by 2100, several regions containing a total of 2073 pingos (34.2%) will be affected by deepening of the

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ALT to more than 2.0 m (Fig. 21b). Regions most impacted are NW Siberia, including large parts of Yamal and Gydan peninsulas, parts of Central Siberia around Yakutsk, and the Pacific side of Chukotka. An increase in permafrost temperatures will shift some pingo populations out of their current range of stability, and projected increases in ALT indicate that many regions with pingos will be affected from such a shift (Fig. 21). Pingos there will be increasingly prone to rapid collapse if the surface thawing reaches their ice core. The formation of pingo scars and new thermokarst ponds will likely be a result of this process. In other regions, ALT will also increase, but is less likely to cause pingo collapse in this century.

5 Discussion

In general, our findings are in good agreement with previous research on environmental conditions required for pingo presence. With the majority of pingos in our dataset occurring in regions with permeable, medium to coarse grained sediments that are sometimes covered by finer grained lacustrine sediments we can confirm such unconsolidated sediment deposits as one important precondition for pingo formation (see also Mackay, 1978a; Gurney, 1998). This is in agreement with detailed findings by e.g. Carter and Galloway (1979) for the National Petroleum Reserve Alaska (NPR), where about 97% of the 732 pingos mapped by are underlain by sandy unconsolidated deposits, and by Ferrians (1983) for the Eastern Alaska Arctic Coastal Plain, where all ca. 300 pingos are underlain by sandy gravels and a thin cover of finer grained sediments.

A majority of pingos in our database is located in drained thermokarst basins in lake-rich lowlands massively reshaped by degradation of ice-rich Yedoma permafrost (Romanovskii, 1993; Schirrmeister et al., 2010) since the Late Glacial and Early Holocene (Romanovskii et al., 2004; Grosse et al., 2007). Thermokarst lakes were major agents in reshaping these landscapes and resulted in deep thaw of permafrost beneath lakes in taliks. The dynamic cycling of thermokarst lakes involving formation, growth, and drainage or drying resulted in the presence of a considerably larger area covered by

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lake basins then by present-day thermokarst lakes in North Siberia (Grosse et al., 2006). We can use the pingos in our dataset as a paleoclimatic indicator. In the continuous permafrost zone of the study region, Holocene climatic conditions apparently were severe enough to allow refreezing of lake taliks after lake disappearance, which provided the environment necessary for closed system pingo formation. Pingos have earlier been used to access the age of thermokarst basins and drainage history beyond the remote sensing record (e.g., Marsh et al., 2009). Our dataset of pingo distribution, in combination with a relatively well-founded mechanistic understanding of their growth and collapse (Mackay, 1987, 1998) and the understanding that the age of pingos can be absolute or relatively dated (Holmes et al., 1966; Mackay, 1978a; Walker et al., 1999), might thus be useful to access the temporal dynamics of thermokarst lakes and basins over longer Holocene time-scales. Since these dynamics have an important impact on carbon cycling related to thermokarst lakes and permafrost (Walter et al., 2007), a detailed pingo dataset could help to refine long-term carbon budgets in permafrost regions.

MAAT for pingo locations in our dataset largely (98% of all sites) range from -18 to -7°C , which is in good agreement with previous assessments of pingos in North America: Mackay (1988) identified maximum MAAT for open system pingos at -1 to -3°C and for closed system pingos at -4 to -6°C . Similarly, a MAGT range of -3 to -11°C for 92% of pingos in our dataset agrees with maximum MAGT identified in previous studies (< -2 to -4°C) (Mackay, 1988). Our comparison of pingo locations with projected end-of-century results from spatially distributed permafrost modeling (Romanovsky et al., 2008) has shown that large regions with presence of pingos will be affected by active layer increases by the year 2100. Generally, impacts of large changes in active layer depth on pingo stability are difficult to predict in detail because of heterogeneity of pingo types and structure. However, observed spatial patterns suggest that pingos do not occur below certain climatic and permafrost thresholds and thus are likely to disappear during changes crossing these thresholds in certain regions. A continued shift towards higher MAAT and MAGT in the study region as observed

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over the last decades (Romanovsky et al., 2010) could result in destabilization of permafrost and climate conditions required for pingo persistence and thus increased ice core melting and pingo collapse (Mackay, 1987, 1998). Potentially, a detailed spatial dataset of pingos could be used to trace the progression of projected permafrost degradation along climatic and permafrost gradients using remote sensing-based detection of pingo persistence or collapse.

5.1 Limitations of pingo database

In our initial effort to provide information on the presence and location of pingos over a vast region of the circum-Arctic, we have identified the occurrence of more than 6000 pingos in Northern Asia. However, the presented dataset should be viewed as a minimum estimate of the distribution of pingos in this region, owing to the fact that some pingos remain unmapped in our study region as well as for the reported occurrence of pingos in adjacent areas of Northern Asia. For example, pingo populations in Russia are also reported from the Pre-Baikal region, NW European Russia, and along the Okhotsk Sea coastal lowlands (e.g., Shumskii and Vtyurin, 1966). These other regions are not yet considered here, however, we believe that the main North Asian pingo provinces have been captured in the presented dataset thus far.

The presented data on pingo distribution are only as good as the topographic base maps used to derive the location information. At a topographic map scale of 1:200 000 some information from the original aerial photo mapping is certainly lost due to map generalization. Independent remote sensing-based data for the mapped pingos was assessed only for a very small fraction of the study region (21 600 km² out of 3 500 000 km²; 0.6%). We here largely rely on the judgement of Russian aerial photo interpreters and map producers. Visual verification of small regions with high-resolution satellite data indicated that the general patterns of pingo distribution are well preserved in the 1:200 000 topographic maps.

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data-based assessment for completeness of our dataset showing that many pingos are still missing in our map-derived dataset we safely can assume that this estimate is a minimum value.

Pingo densities reported from other studies are difficult to compare with results from this subcontinental scale study. Densities were frequently reported for small subsets of regions and pingo populations, usually as pingos per km² of a certain landscape unit (Table 4). The highest densities for terrestrial pingos so far were reported by Stager (1956) with up to eight pingos per km² in the Mackenzie region, NW Canada. Commonly reported densities for Alaska sites are smaller than one pingo per km² (e.g. Holmes et al., 1968; Walker et al., 1985). To account for spatial heterogeneity of pingo distribution we calculated pingo densities using a 10 × 10 km kernel (100 km²) moving in 5 km steps. The results showed high variability of pingo densities between subregions and within subregions (Table 4; Fig. 5). However, the pingo densities in our study region are within previously reported ranges from other regions. The possibility of very high pingo densities for some sites in Siberia like the one reported by Stager (1956) cannot be ruled out since the map scale apparently sometimes required combining multiple pingos into a pingo field (as specified in the maps), which we mapped in our dataset as a single pingo location, and because of pingos still missing in the database.

5.3 Database development for periglacial landforms

Through the development of sophisticated GIS platforms the utility of compiling and comparing spatial information on numerous variables is possible. Our pingo database for Northern Asia can be updated to include data derived from higher-resolution imagery as well as inclusion of other regions of Siberia and the circum-Arctic. Not only will detailed GIS pingo databases such as the one presented here prove useful for making comparison between circum-Arctic regions that vary by climate, vegetation, and history but it may also prove useful for characterizing other landscape patterns and phenomenon associated with hydrology in permafrost regions, such as thermokarst lake drainage history or permafrost and talik character. We believe that similar to our

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initial compilation of information on the location of pingos across much of Northern Asia, the development of large regional GIS databases and maps for other terrestrial periglacial landforms such as ice wedge polygonal networks, other frost mound types, water-tracks, thermo-erosional valleys, thaw slumps, etc. would be beneficial for better understanding of broad-scale permafrost distribution and its character. Remote sensing will play a major role in such efforts.

6 Conclusions

We present a high-resolution GIS dataset of pingos for a large region in North Asia that allows first order spatial analysis of environmental parameters critical for characterization of pingo distribution. Confirming previous studies, surface lithology, hydrology, and the surface and subsurface thermal regime were found to be key factors for the presence of pingos. A clear association with limnic and a range of coarse to medium-grained lithologies and a high sediment thickness highlights the need for permeable layers for pingo growth. The majority of pingos are located in thermokarst-dominated lowlands of the continuous permafrost zone and likely formed through closed system talik refreezing, typical for drained/draining thermokarst lake basins in settings with very low mean annual air temperatures. Detailed GIS pingo databases may therefore prove useful for characterizing long-term temporal and spatial thermokarst lake dynamics, i.e., regarding lake area loss due to drainage or drying. We believe that this dataset represents a step towards an integrated pan-Arctic geospatial database of frost mounds useful to analyze past and modern permafrost and climate conditions as related to permafrost formation and stability.

Based on our dataset and data available from other pingo regions, we estimate that there are more than 11 000 pingos on Earth, which roughly doubles previously published counts. Near-future reduction in permafrost extent will likely impact pingo distribution in North Asia, including a reduction in pingo numbers due to thawing and collapse, and formation of pingo scars and thermokarst ponds. The present dataset

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could potentially be used as a base for an extensive monitoring of pingos as indicators of permafrost degradation in discontinuous permafrost regions and along the present southern boundary of continuous permafrost.

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Table 2. Various datasets analysed in relation to identified pingos.

| Parameter | Source and characteristics of main parameter |
|---|--|
| Pingo location | Russian topographic maps 1:200 000; point location |
| Pingo height | Russian topographic maps 1:200 000 |
| Pingo spatial density | This paper; number of pingos per 100 km ² |
| Elevation above sea level | GLOBE digital elevation model (Globe Task Team, 1999); 1 m vertical and 1 km horizontal resolution |
| Limnicity | Derived from Global Lake and Wetland Database (Lehner and Döll, 2004) corrected by excluding lagoons and rivers; scale 1:1 to 1:3 Mio; includes lakes ≥ 0.1 km ² ; lake density ranges from 0–100% with resolution of 1% |
| Maximum ALT in 2000 and 2100 | UAF Geophysical Institute Permafrost Model (GIPL 1) output (Romanovsky et al., 2008; Sazonova and Romanovsky, 2003); 0.5° lat/long resolution; ALT have ca. 1 cm vertical resolution |
| <i>Land Resources of Russia CD-ROM (Stolbovoy and McCallum, 2002)</i> | |
| MAAT | New et al. (1999); 0.5° lat/long resolution; observation period 1961–1990; resolution is 0.1°C |
| MAP | New et al. (1999); 0.5° lat/long resolution; observation period 1961–1990; resolution is 1 mm |
| MAGT | Kotlyakov and Khromova (2002); scale ca. 1:10 Mio; zones of 2°C range are distinguished |
| Lithology | Stolbovoi et al. (2002); scale ca. 1:10 Mio; condensed to 9 classes |
| Bioclimatic zone | Stolbovoi et al. (1998); scale ca. 1:4 Mio; eight vegetation zones, one non-vegetation zone, and one water class are distinguished |
| <i>International Map of Permafrost and Ground Ice Conditions (Brown et al., 1998)</i> | |
| Permafrost extent | Brown et al. (1998); scale 1:10 Mio; four distinguished permafrost classes include: isolated (0–10%), sporadic (10–50%), discontinuous (50–90%), and continuous (90–100%) permafrost |
| Ground ice content | Brown et al. (1998); scale 1:10 Mio; Ground ice contents by volume are distinguished as low (0–10%), moderate (10–20%) and high (>20% in lowlands; >10% in mountains) |
| Sediment thickness | Brown et al. (1998); scale 1:10 Mio; Sediment cover thickness is distinguished as low (<5–10 m) and high (>5–10 m) |

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Table 3. Map labels of 6059 pingos identified in topographic maps 1:200 000.

| Map label | Count |
|----------------|-------|
| Bulgunnyakh | 3513 |
| Ledyanoy kholm | 721 |
| Ledyanoy bugor | 699 |
| Not specified | 1126 |

Table 4. Spatial pingo densities reported from various regions. Depending on study area size and sometimes focus on particular landscape units densities are reported as pingos per km² (detailed assessment of small areas or landscape units) or pingos per 100 km² (averaging over large regions).

| Region | Reported density | Source |
|--------------------------------------|-------------------------|----------------------|
| Alaska | | |
| Interior Alaska | <1/km ² | Holmes et al. (1968) |
| Alaska coastal plain (Beechey Point) | | Walker et al. (1985) |
| Flat thaw lake plains | 0.096/km ² | |
| Gently rolling thaw lake plains | 0.286/km ² | |
| Floodplains | 0.012/km ² | |
| Hills | 0.027/km ² | |
| Siberia | | |
| | | This study |
| Yamal Peninsula (Fig. 6) | <13/100 km ² | |
| Gydan Peninsula (Fig. 6) | <21/100 km ² | |
| Taymyr Lowland (Fig. 7) | <12/100 km ² | |
| Khatanga-Anabar Lowland (Fig. 8) | <13/100 km ² | |
| Lena River Delta (Fig. 8) | <6/100 km ² | |
| Central Yakutian Lowland (Fig. 9) | <28/100 km ² | |
| Yana River Delta (Fig. 10) | <8/100 km ² | |
| Indigirka Lowland (Fig. 10) | <14/100 km ² | |
| Kolyma Lowland (Fig. 10) | <12/100 km ² | |
| Anadyr River Valley (Fig. 11) | <28/100 km ² | |
| NW Canada | | |
| Yukon region | <1/ km ² | Hughes (1969) |
| Mackenzie region | <8/ km ² | Stager (1956) |

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Table 5. Selection of pingo regions and number of detected pingos.

| Region/subregion | Pingos | Source |
|--|----------|---------------------------------------|
| Canada, total | ca. 1500 | Mackay (1966) |
| Richards Island, Tuktoyaktuk Peninsula, Canada | 1350 | Mackay (1966) |
| Central Yukon Territory, Canada | 463 | Hughes (1969) |
| Banks Island, Canada | >100 | French (1976) |
| Alaska, total | >1350 | Ferrians (1988) |
| Alaska, total | 3166 | Yoshikawa (in Jorgenson et al., 2008) |
| National Petroleum Reserve Alaska | 732 | Carter and Galloway (1979) |
| Alaska Arctic coastal plain east of Colville River | >300 | Ferrians (1983) |
| Prudhoe Bay region, Alaska | 102 | Walker et al. (1985) |
| Brooks Range, Alaska | 70 | Hamilton and Obi (1982) |
| Interior Alaska | ca. 300 | Holmes et al. (1966, 1968) |
| Central East Greenland | >70 | Worsley and Gurney (1996) |
| Svalbard | 80 | Yoshikawa and Harada (1995) |
| Usa River Basin, Russia | 42 | Mazhitova and Oberman (2003) |
| Northern Asia, Russia | 6059 | This study |
| Northwest Siberian Lowland (66.9–86.2° E) | ca. 1620 | This study |
| Taymyr Lowland (87.2–108.9° E) | ca. 260 | This study |
| Khatanga-Anabar Lowland (109.2–120.7° E) | ca. 360 | This study |
| Lena River Delta (123.5–129.4° E) | ca. 85 | This study |
| Yana-Indigirka Lowland (132.4–154.0° E) | ca. 1500 | This study |
| Kolyma Lowland (150.7–162.5° E) | ca. 700 | This study |
| Central Yakutia (126.0–133.6° E) | ca. 600 | This study |
| Chukotka (159.5°E–174.3°W) | ca. 735 | This study |

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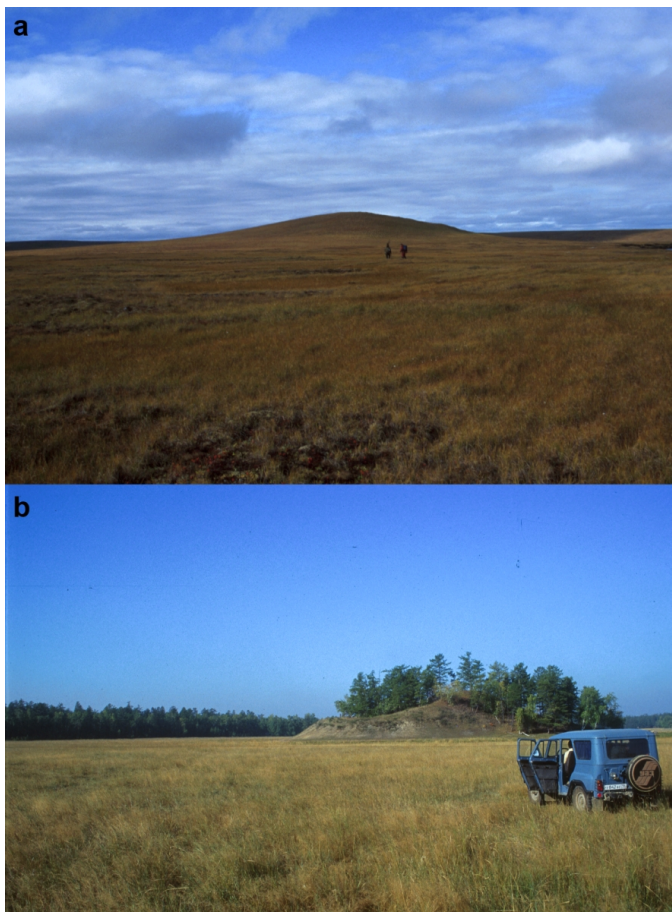


Fig. 1. (a) Ca. 28 m high closed-system pingo in a drained thermokarst lake basins in the tundra of the Bykovsky Peninsula, North Siberia and **(b)** ca. 7 m high partially collapsed closed-system pingo in a dried-up thermokarst lake basin the taiga of Central Yakutia.

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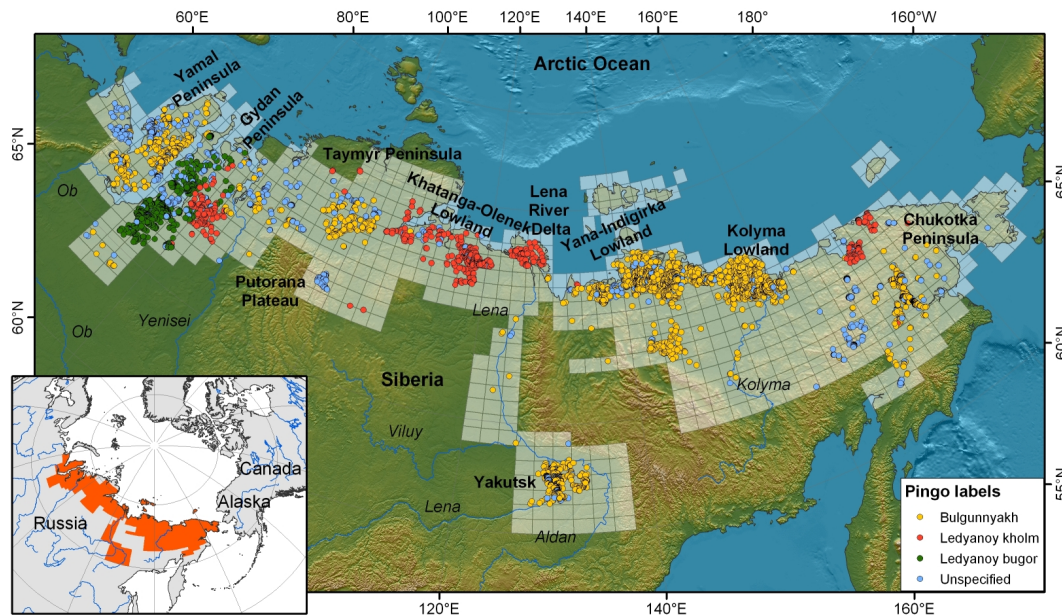


Fig. 2. Location of study region in North Asia (map inset) and distribution of 6059 pingos (large map) digitized from 675 topographic maps 1:200 000 (red area in map inset and light semitransparent frames in large map).

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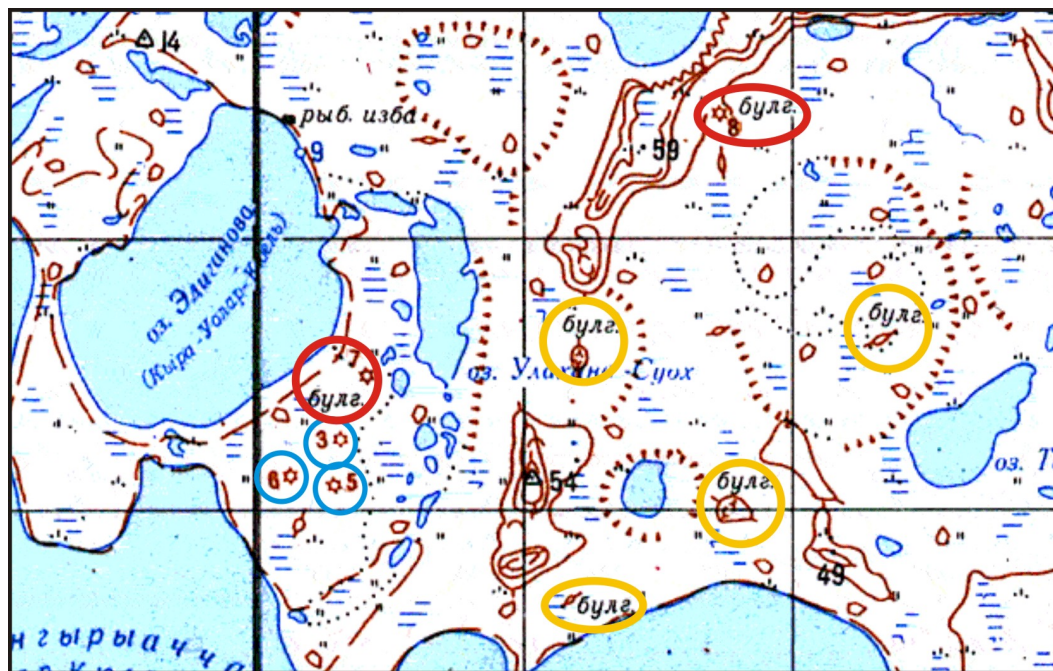


Fig. 3. Subset of topographic map 1:200 000 from the Indigirka lowland with examples of pingos (grid spacing is 4 km). Red circles – pingos are marked with red star and the label *bulg.* for *bulgunnyakh*, height given in m; blue circles – pingos are marked with red star but not specifically labelled, height given in m; yellow circles – pingos are marked with contour lines and the label *bulg.*).

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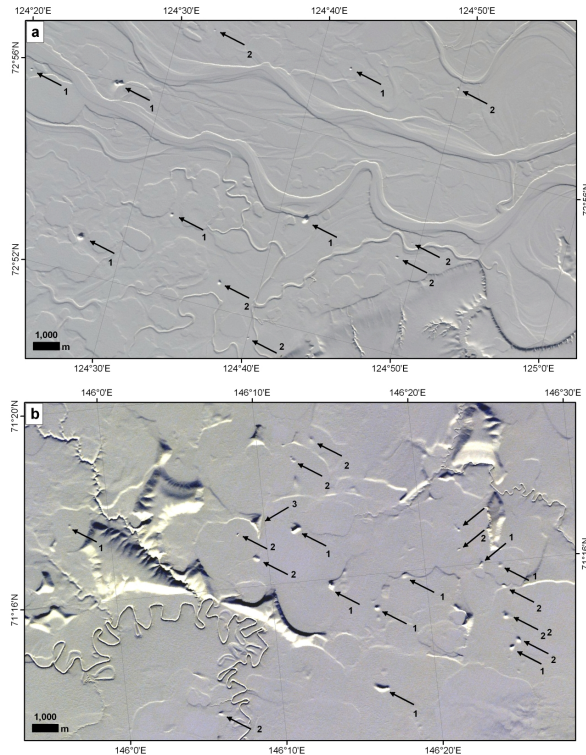


Fig. 4. Mapping of pingos using Terra ASTER late winter imagery for assessment of completeness of pingo locations in 1:200 000 topographic maps. **(a)** Fluvial floodplain of the first terrace of the Lena River Delta with numerous pingos (black arrows); **(b)** – Lowland landscape strongly dissected by thermokarst lakes and basins with numerous pingos; note also large Yedoma remnants. Numbers indicate: 1 – Pingos identified in both topographic map and ASTER data; 2 – Pingos identified only in ASTER data, but not in topographic map; 3 – Pingos identified only in topographic map, but not in ASTER data. Note general variation in shape and size of pingos (sun illumination approximately from south).

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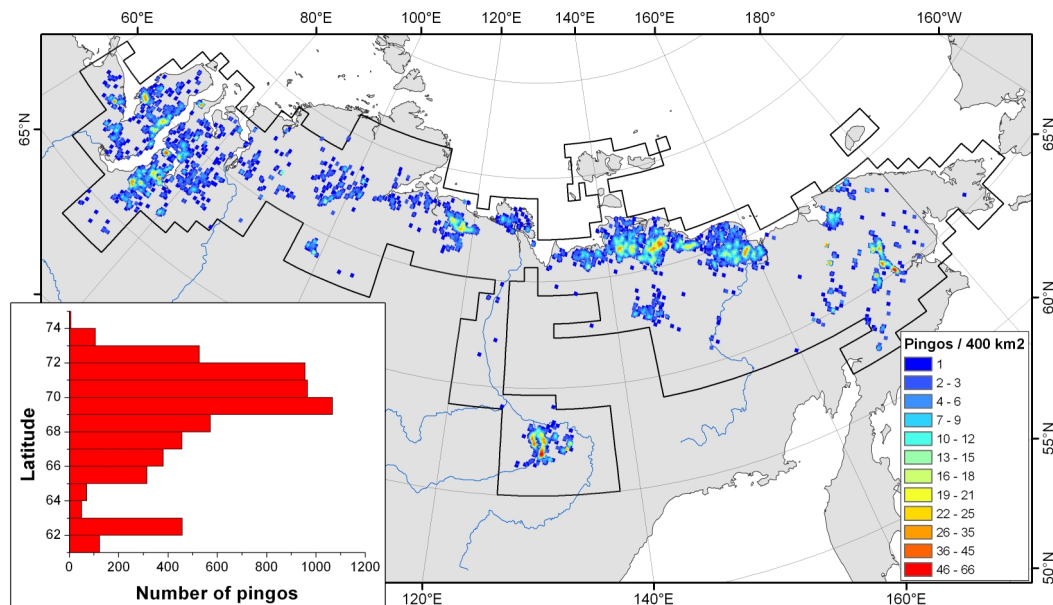


Fig. 5. Spatial point density of pingo locations using a 20×20 km search window (400 km^2) and 5 km grid cell size. Histogram shows pingo distribution by geographical latitude. Black outline in this and subsequent figures indicates the study area boundary.

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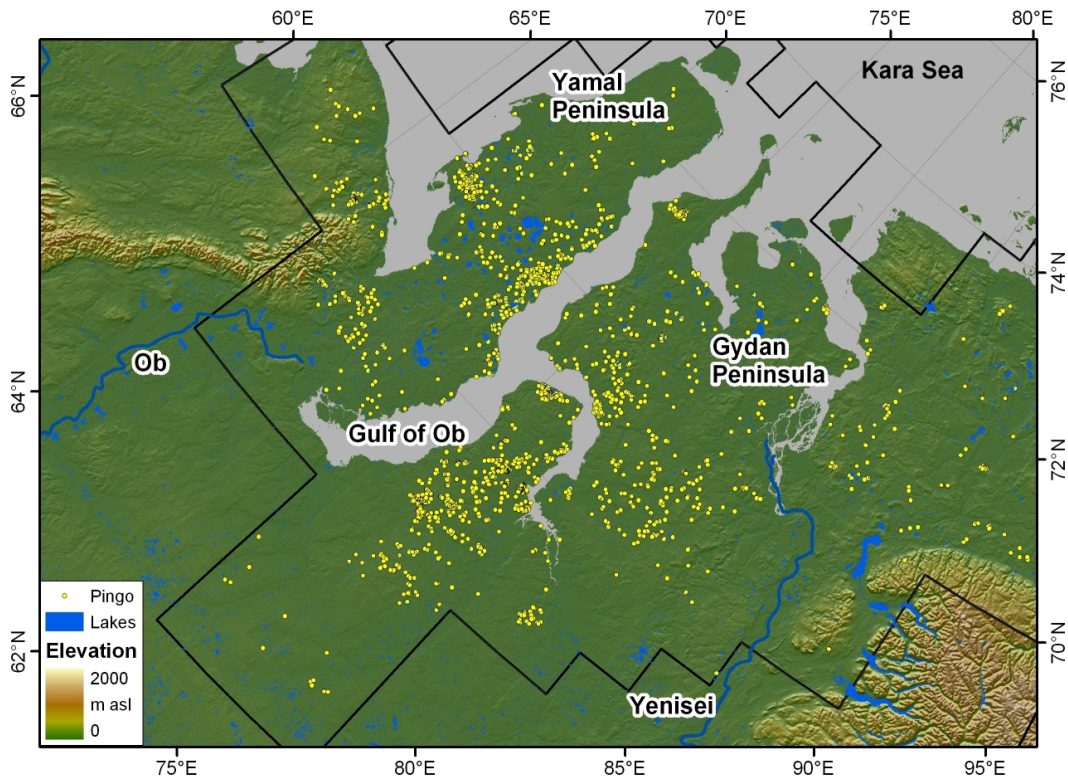


Fig. 6. Distribution of pingos in subregion: Northwest Siberia (Yamal and Gydan peninsulas). Pingos here occur in regions with glacial and glaciofluvial deposits; pingos are less aligned with river networks but many are found in drained thermokarst lake basins.

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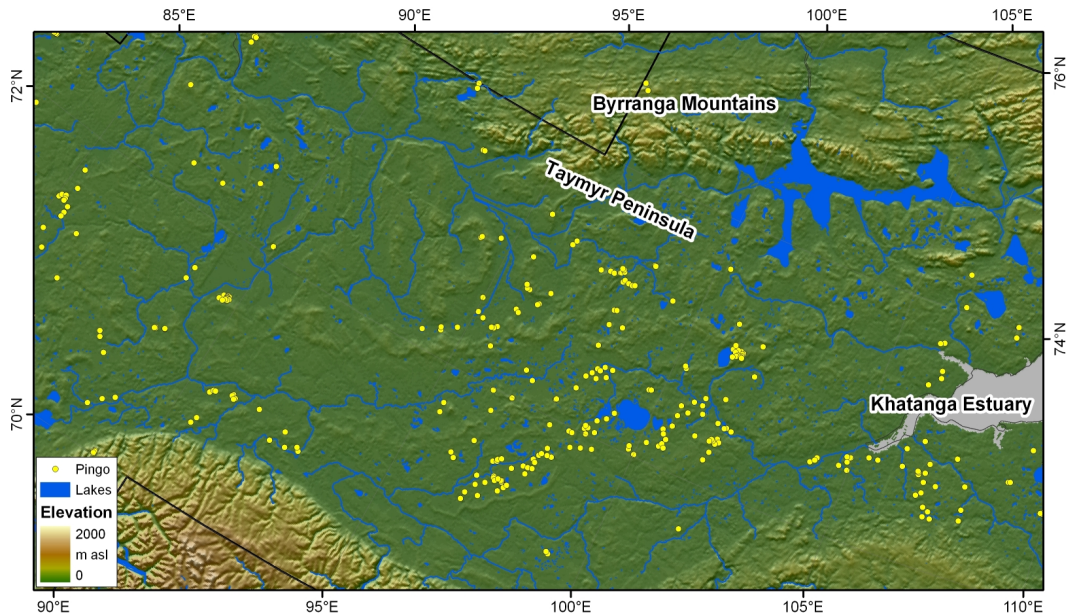


Fig. 7. Distribution of pingos in subregion: Taymyr Lowland. Pingos are found in regions with fluvial and fluvio-glacial deposits. Pingo locations are more broadly scattered and less aligned with river networks.

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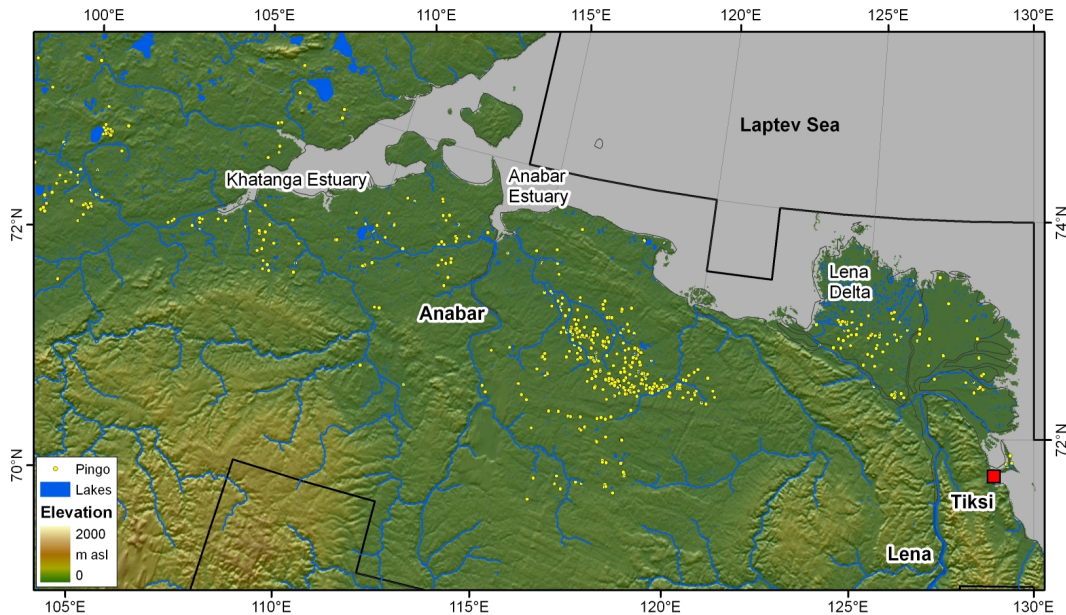


Fig. 8. Distribution of pingos in subregion: Khatanga-Anabar-Lena lowlands. Pingos in the Lena River Delta are mostly confined to 1st terrace floodplains (recent + Holocene sandy fluvial deposition) and 3rd terrace drained thermokarst basins in Yedoma (sandy silt above fluvial sandy units). Interestingly, pingos do not occur in homogeneous fluvial sands of the 2nd terrace. Pingos in Anabar river basin are found in regions with sandy fluvial deposits covered by Yedoma deposits; many of the pingos are located in drained lake basins.

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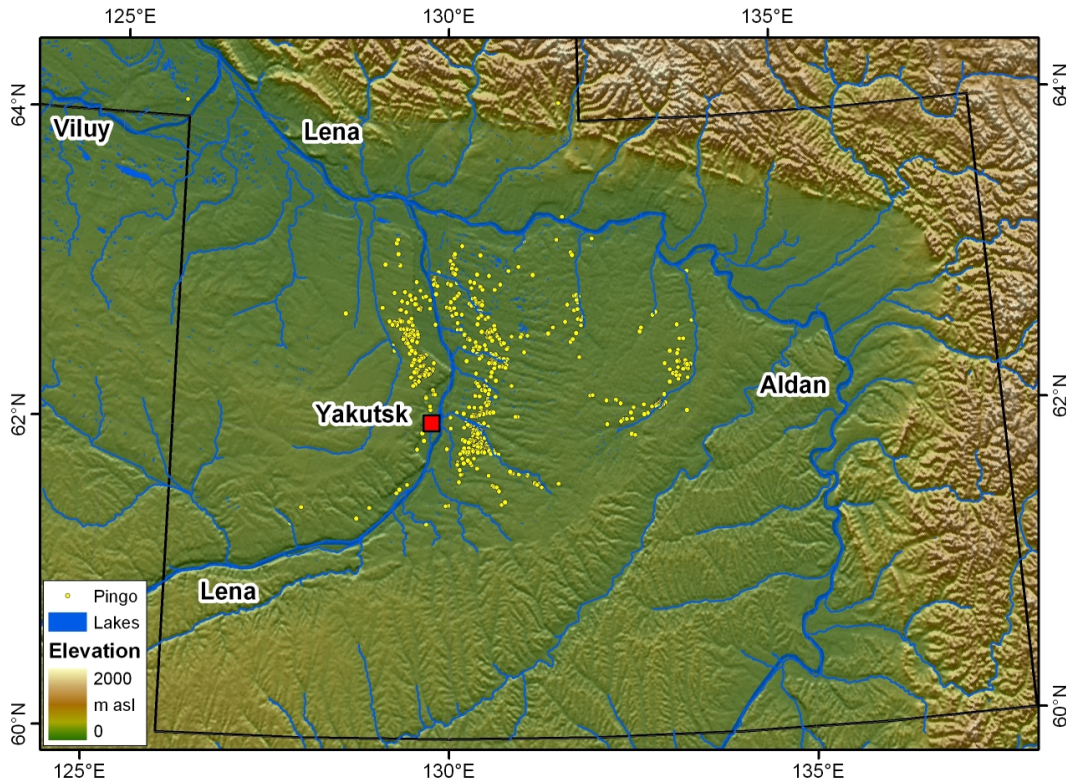


Fig. 9. Distribution of pingos in subregion: Central Yakutia. Subsurface is dominated by sandy fluvial and aeolian sediments deposited on paleo Lena river terraces. Many pingos east of the Lena River are strongly aligned with networks of rivers, streams, and coalesced thermokarst basins (alasy). Pingos west of Lena River largely occur in alasy formed on old Lena river terrace levels.

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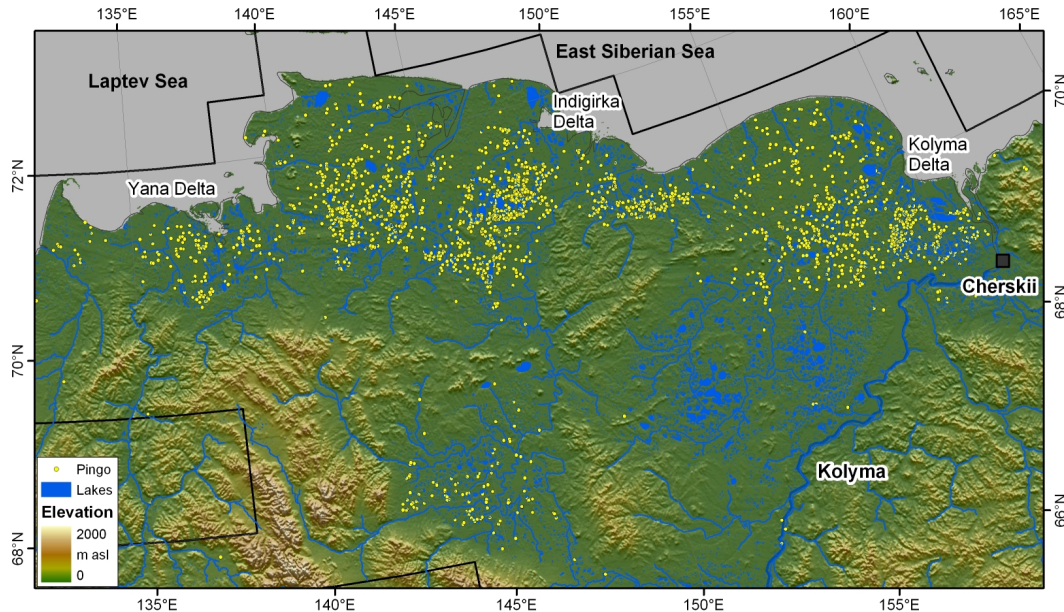


Fig. 10. Distribution of pingos in subregion: Yana-Indigirka-Kolyma lowlands. Most pingos are found in fully or partially drained thermokarst lake basins that formed in ice-rich Yedoma. Pingos in the Yana, Indigirka, and Kolyma river delta regions are strongly aligned to sandy fluvial units in the subsurface.

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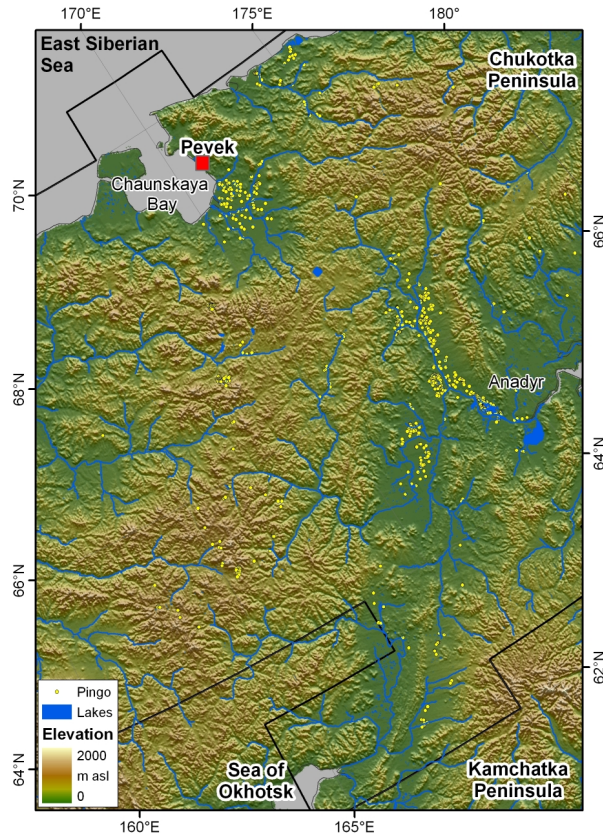


Fig. 11. Distribution of pingos in subregion: Chukotka. Pingos are concentrated in Anadyr river valley with its fluvial sandy deposits. Pingos south of Chaunskaya Bay are likely also related to sandy deposits from fluvial runoff of nearby mountains. High pingo densities occur also in mountain valleys west of the Anadyr river valley. These likely are mostly open system pingos forming in sandy deposits along mountain streams.

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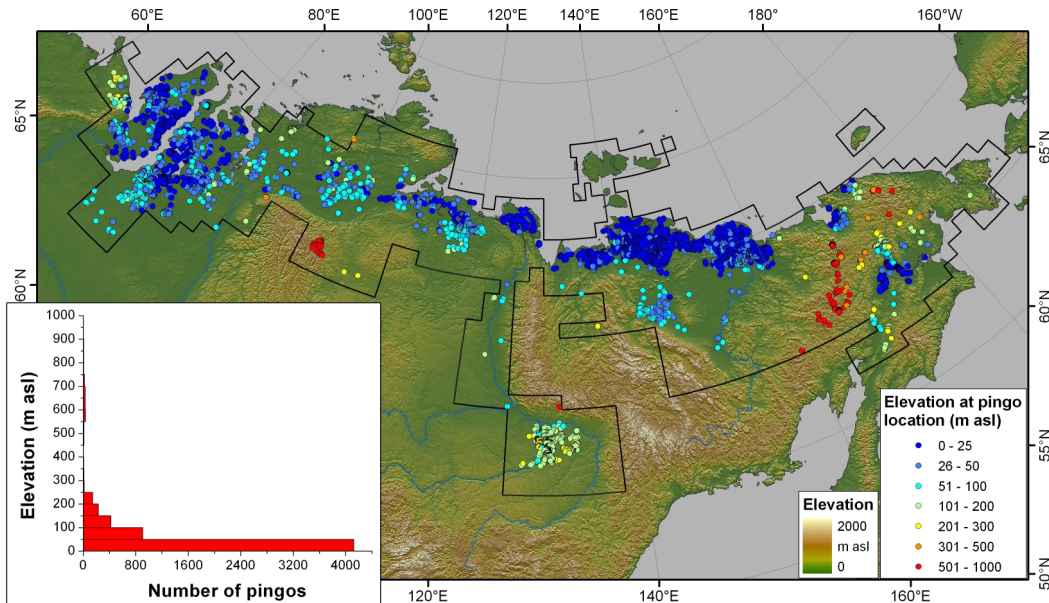


Fig. 12. Elevation of pingo locations above sea level derived from GLOBE global 1 km DEM (Globe Task Team, 1999). Though the vast majority of pingos occurs in lowlands below 50 m, some pingos occur in up to 1000 m elevation in some mountain valleys.

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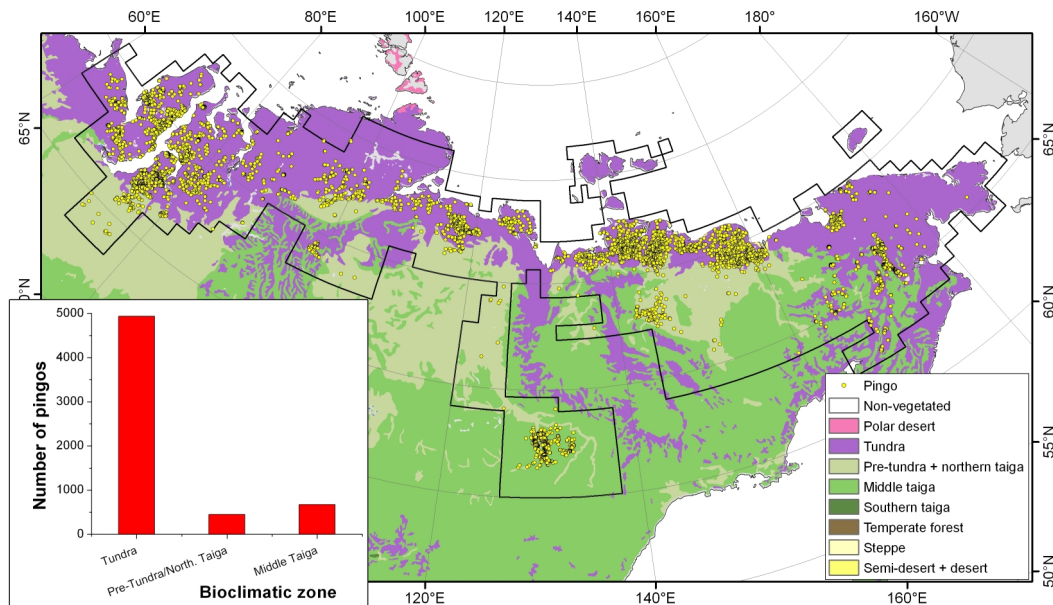


Fig. 13. Pingo distribution by bioclimatic subzone (based on Stolbovoi et al., 1998).

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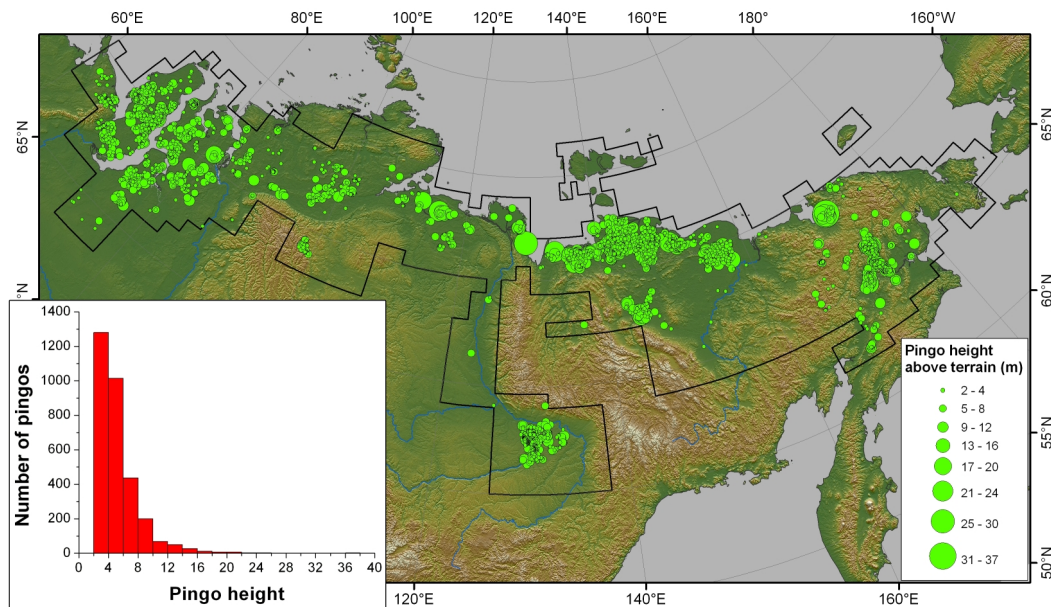


Fig. 14. Height above surrounding terrain for 3109 pingos (51.3% of dataset) as indicated in topographic maps.

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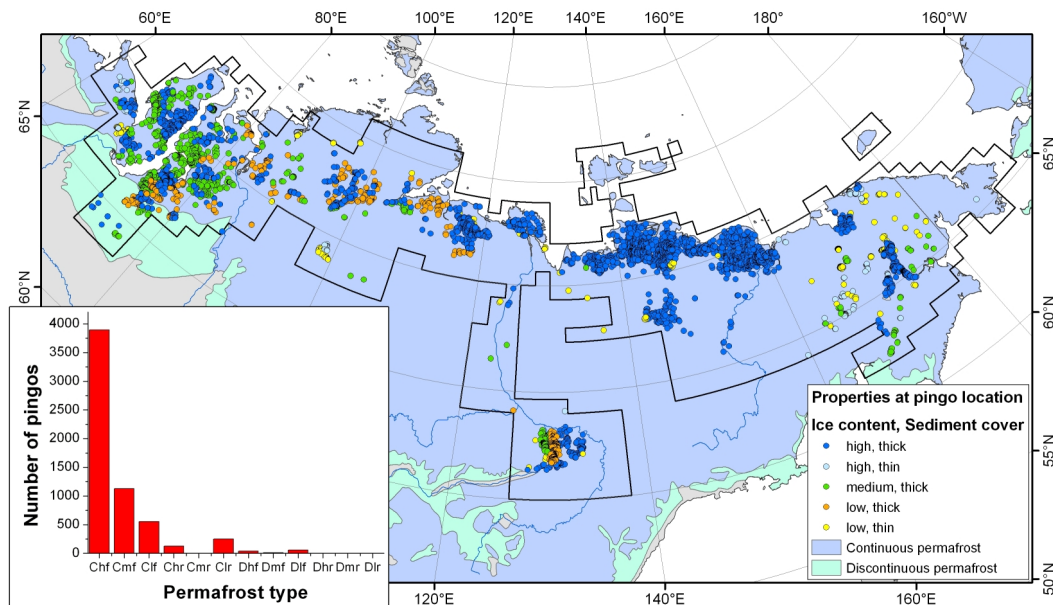


Fig. 15. Pingo distribution by permafrost type, ground ice content, and sediment thickness (based on Brown et al., 1998). (Permafrost type: C – continuous, D – discontinuous; Ground ice content: h – high, m – moderate, l – low; Sediment thickness: f – high, r – low).

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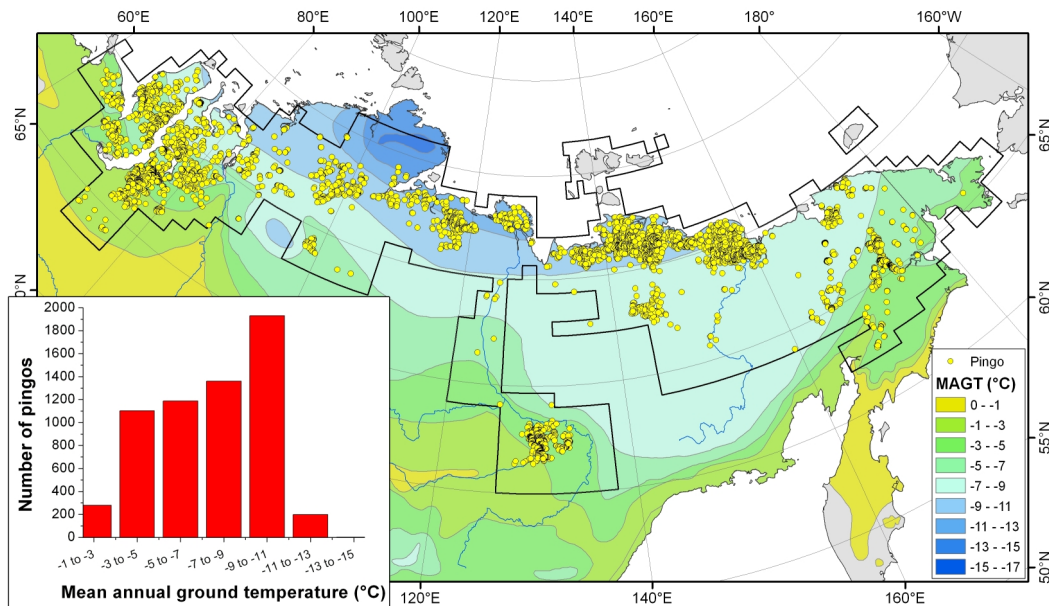


Fig. 16. Pingo distribution by mean annual ground temperature (MAGT) (based on Kotlyakov and Khromova, 2002).

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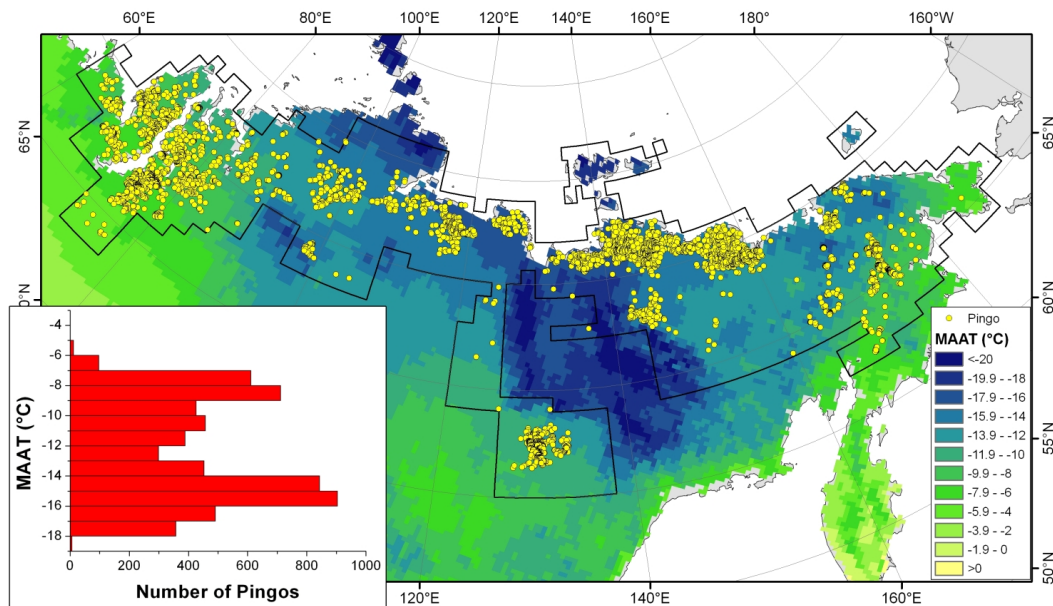


Fig. 17. Distribution of pingos by mean annual air temperature (MAAT) (based on Stolbovov and McCallum, 2002).

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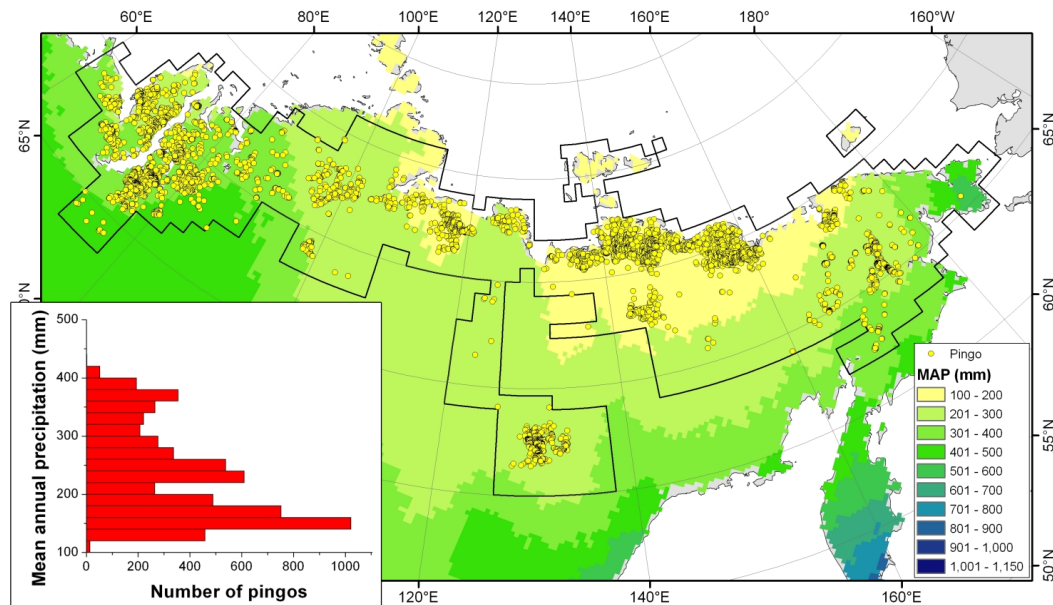


Fig. 18. Distribution of pingos by mean annual precipitation (MAP) (based on Stolbovoy and McCallum, 2002).

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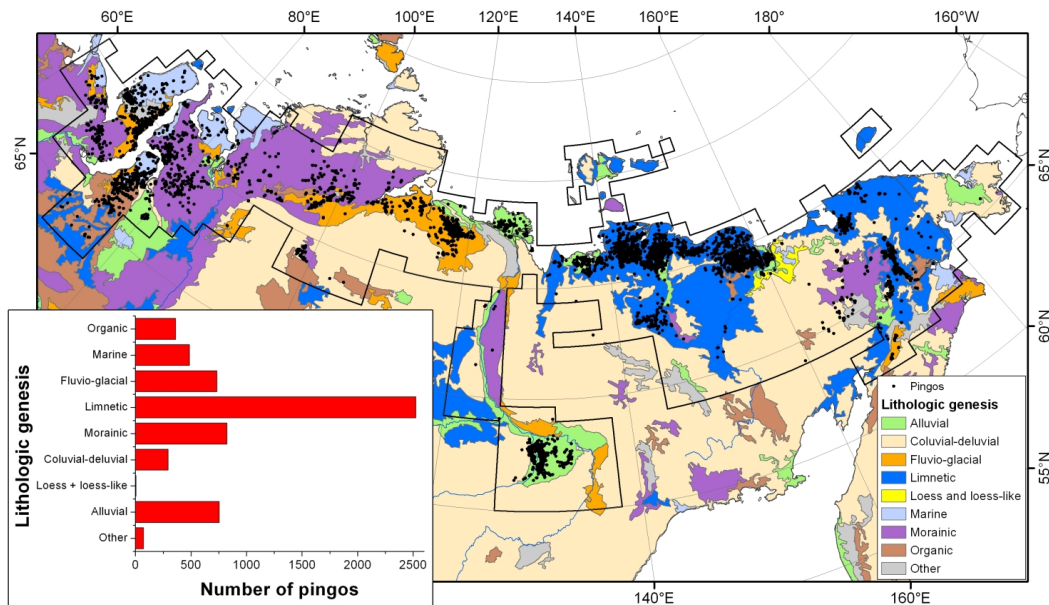


Fig. 19. Distribution of pingos by surface lithology (based on Stolbovoi et al., 2002).

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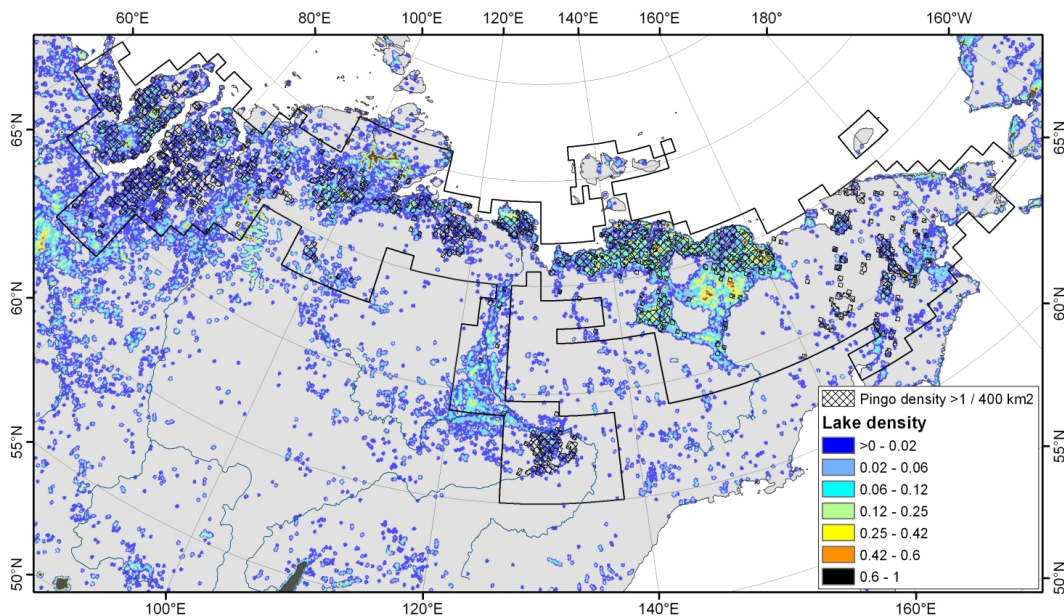


Fig. 20. Distribution of regions with pingos (pingo density $>1/400 \text{ km}^2$) in relation to lake density (derived from Lehner and Döll, 2004).

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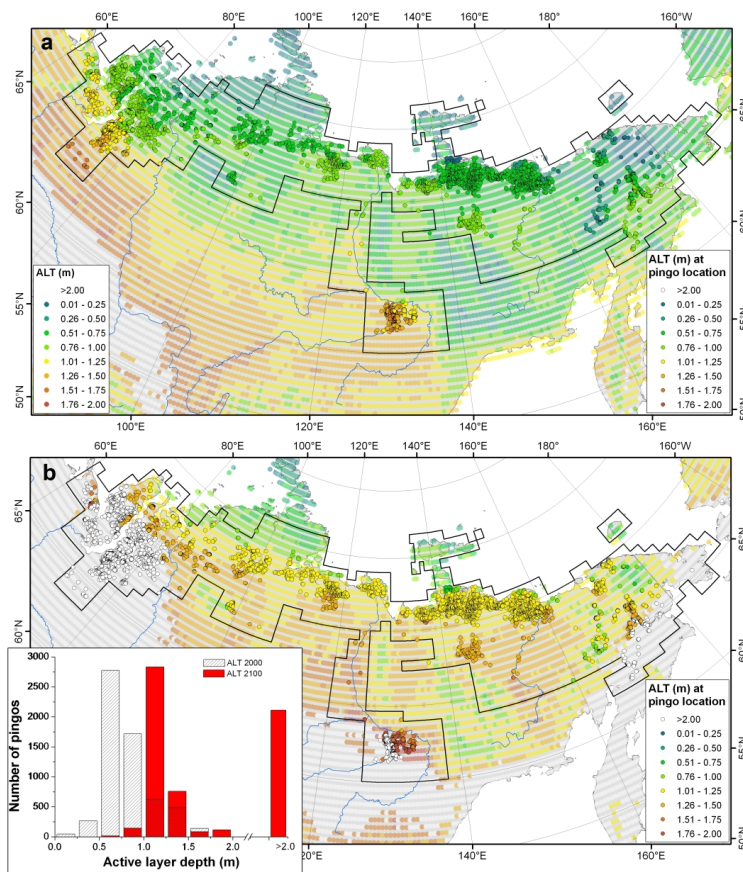


Fig. 21. Distribution of pingos by maximum active layer thickness (ALT) as modeled for the period (a) 1990–2000 and (b) 2090–2100 by Romanovsky et al. (2008). Histogram shows the shift of pingo populations from regions with ALT ranging from 0.25–1.5 m to ALT ranging from 0.75–>2 m by the end of the 21st century.

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