Potential Effects of Permafrost Melt on Plant Health in the Northeast Siberian Tundra: A Review

By William Jiang

Author Bio

William Jiang is currently a junior in high school with a great interest in environmental science. He has recently been involved with the Sunrise Movement and has experience teaching biology to younger children. He has a wide understanding of plants and nature, as well as a passion for ecological sciences and wildlife. He has participated in a wide variety of activities related to the outdoors, including fishing and gardening. William is also a competitive runner, being involved in both the track and cross-country teams at his school, and he also enjoys astronomy, video games, and cooking in his free time.

Abstract

The Northeast Siberian Tundra is a complex ecosystem home to many species of plants that have adapted over time to survive in the Arctic's cold environment. In recent years, global warming caused by anthropogenic actions has resulted in the melting of the permafrost layer underground in locations throughout the polar regions. As permafrost begins to melt due to global warming, the effects caused by the thawing of the ground disrupts the plant cover and changes the biodiversity of the region. Many plant and animal species that inhabit the grasslands of the Northeast Siberian Tundra have been affected detrimentally by permafrost melt. Much of the permafrost in the soil has thawed, resulting in the permafrost layer receding into the ground. Without the hardened permafrost layer to keep water near the surface, water is allowed to drain through the ground with ease. Visual inspection of satellite image products from NASA's Soil Moisture Active Passive satellite from 2015-2021 revealed a clear decrease in moisture contained in the soil. The surface soil has become drier and less suitable for the grasses and other plants growing in the soil, which are adapted to thrive in moist, cooler soil. As a result, other plant species that are adapted to drier soil begin to replace the original grasses, causing a large shift in the ecosystem's balance.

Keywords: Northeast Siberian Tundra, Permafrost, Active Layer, Qinghai-Tibetan plateau, Degradation, Soil moisture, Soil composition, Biodiversity

Introduction

Over the past few decades, permafrost has been melting in various Arctic regions at an increasing rate, due to rising global temperatures and climate change. Recent investigations indicate that this degradation of permafrost has caused a domino effect that results in changes in various other factors of the ecosystem. Decreases in the amount of water stored in the ground is a direct consequence of permafrost melt. In the Northeast Siberian Tundra, soil moisture observed from space gradually decreased by about 0.270 m^3 of water per m^3 of soil from 2015 to 2021 in certain Siberian tundra regions. Consistent increases in the depth of the layer of yearly ice thaw, also known as the active layer, is caused by global warming resulting in faster heating of the earth, resulting in the degradation of permafrost (Serban et al., 2021). Permafrost melt in the Arctic regions has caused the permafrost layer in the ground to recede each year, resulting in a deeper permafrost limit. The permafrost limit is defined as the upper extent of the permafrost layer, the depth at which permafrost is first found. In addition, the larger active layer allows water to drain out of the ground at higher rates than frozen soil, causing dryer soil near the surface as permafrost melts (Xue et al., 2009). Each year, the soil moisture in the Northeast Siberian Tundra gradually decreases through drainage as the active layer continues to grow due to permafrost melt.

Siberia's northern coastal tundras are diverse ecosystems which support various plant species that are very well suited to survival in the harsh environment. Several species of grasses, sedges, and dwarf bushes, including *Salix polaris*, are some of the few types of plants that are able to grow on the tundra, having small roots intended to grow within the limited active layer, many of which requiring moist soil to grow in as well. These species are able to handle cold winters and large amounts of snow. Due to their adaptation to the extreme tundra environment, many of the different species of plants require these very specific conditions in order to grow. Even small changes in the climate of the northeastern Siberian tundra can put these plant species at increased risk (Liu et al., 2017, Yang et al., 2010). The changing soil regime in these regions will potentially cause changes in the tundra ecosystem's plant biodiversity. With the active layer becoming deeper and the soil moisture decreasing across the region, many of the native plants struggle to gain enough water. These species, especially trees, are better suited to larger active layers and are able to survive with less water in the soil, especially trees and other larger plants which normally cannot be found in the tundra. If these species are able to survive and expand into the tundra, animal species relying on certain plants for food will be affected as well, affecting the entire tundra ecosystem.

Based on our review of recent literature, we have found that melting permafrost in Northeast Siberian Tundra has resulted in decreased soil moisture, which has consequently increased the size of the active layer. In this article, we will discuss the effect of the changing surface layer on plant biodiversity, comparing the situation with many similar changes occurring on the Qinghai-Tibetan plateau, and we will discuss how these changes further influence the populations of large mammal species, namely reindeer and moose, and other animal species that inhabit the tundra. Currently, the primary large herbivorous mammal in the tundra is the reindeer. *Rangifer Tarandus Sibiricus* is the main subspecies of the reindeer population found in tundras across northern Siberia. During the summer, these reindeer generally travel in massive, well-documented herds whose population can number in the hundreds of thousands. This subspecies of reindeer relies primarily on plants common to the tundra, which include grasses and dwarf shrubs. Due to the gradual decline in these species caused by permafrost melt, reindeer populations and behavior will potentially be impacted. By contrast, moose populations could spread into the tundra due to the increased abundance of several tree species, including dwarf birches, willow, juniper, and alder (van der Kolk et al., 2016), some of which are species that moose feed on.

Methodology

The Northeast Siberian Tundra is a region found in northeast Russia, and is divided into several ecoregions, the Northeast Siberian Coastal Tundra and the Taimyr-Central Siberian Tundra. These ecosystems are characterized by their cold temperatures, wide grasslands, lack of large plants, and also by the permafrost located underneath the soil. Permafrost found in these regions is generally continuous and widespread, found in about 90% of the soil across the Arctic. Due to various factors, including climate change, global warming, and anthropogenic activities, permafrost in these areas have been melting at a steady rate.

The temperature and moisture contained within the soil was measured in 5 different locations found within the Northeast Siberian Tundra (Fig. 1). These locations were selected due to a noticeably large increase in soil temperature and decrease in soil moisture from 2015-2021.

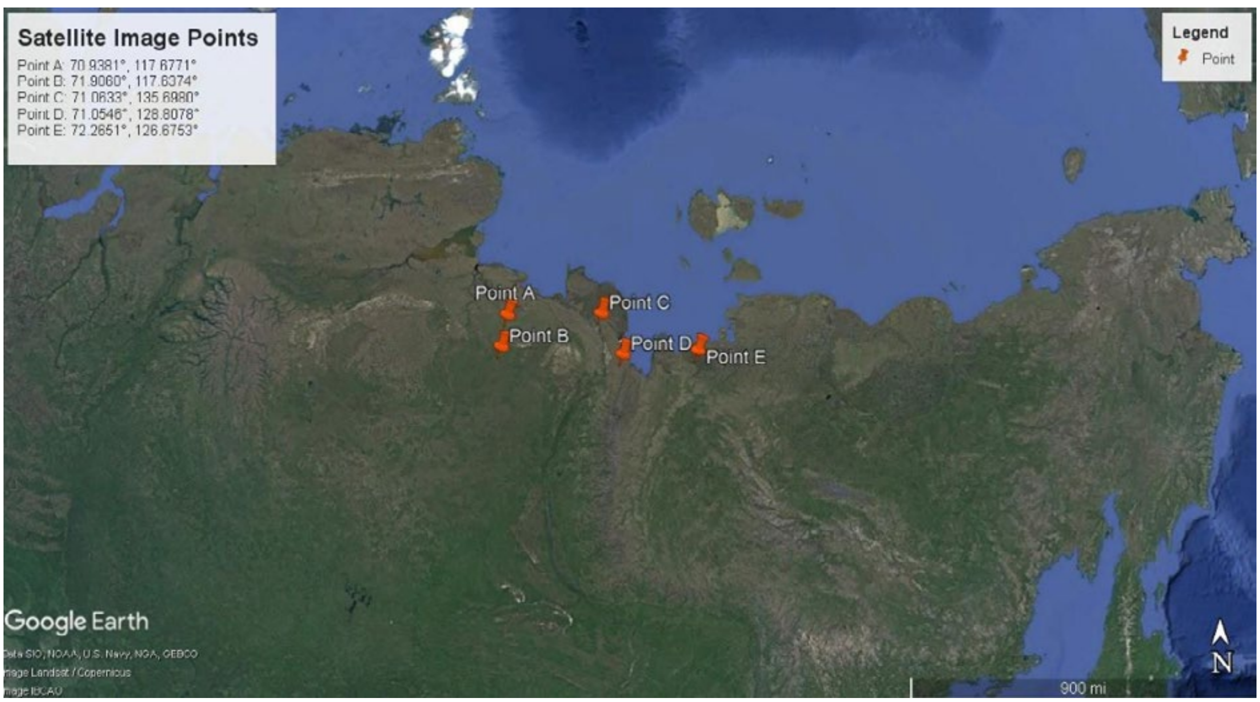


Fig. 1. The location within the northeastern Siberian tundra and the coordinates of the 5 locations measured for soil temperature and moisture. (Google Earth).

For the past few decades, the temperature of the soil throughout Siberia has increased significantly (Chen et al., 2020). Satellite observed temperature data gathered using Atmospheric Infrared Sounder (AIRS) equipment on NASA's Aqua satellite shows slight increases in the average soil temperature from 2015-2021 throughout the northeastern Siberian tundra (Fig. 2.) in the 5 locations where soil temperature was measured. From 2015-2021, the average temperature at point B during the summer months increased by 4.2 K, from 284.3 K (11.3°C) to 288.5 K (15.5°C). At point C, the temperature increased by 4.2 K as well, from 279.5 K (6.5°C) to 283.7 K (10.7°C)(Table 1). Other studies have shown similar increases in soil temperature in the northeastern Siberian tundra (Pollack et al., 2003).

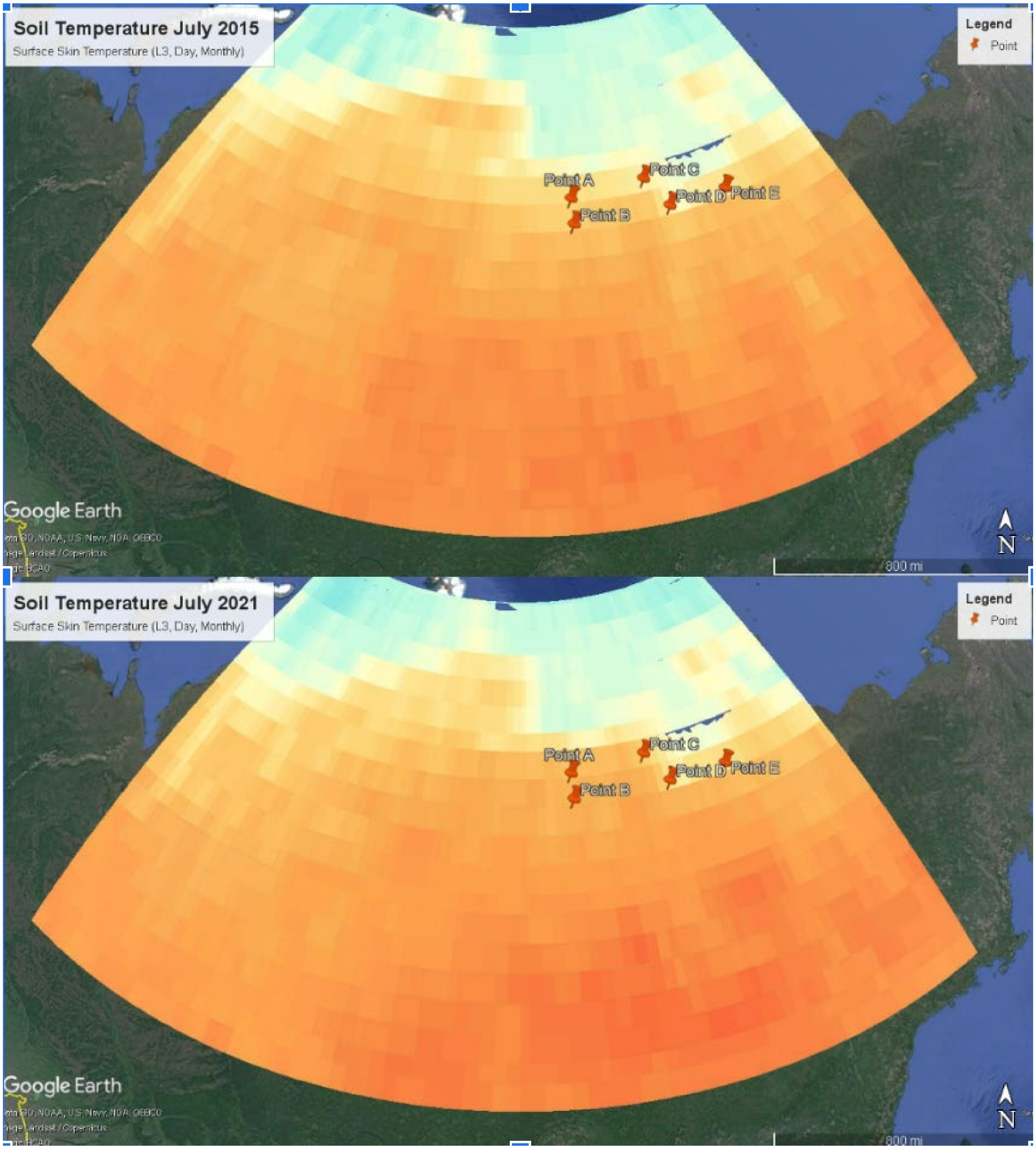


Fig. 2. Observed soil temperature (K) in the Siberian tundra and taiga from 2015-2020. Soil temperature was measured using the Surface Skin Temperature (L3, Day, Monthly) layer. Soil temperature is scaled from purple (very cold), to yellow (moderate temperatures), to red (warm temperatures). From 2015 to 2020, the soil temperature appears to increase, due to a shift in color from a yellow/orange to a deeper orange color. (NASA Worldview).

Point A		Avg. Soil Temp.	Δ Temp.	Net Δ Temp.	Avg. Soil Moisture	Δ Moisture	Net Δ Moisture
	June 2015	289.1			0.1734		
	July 2015	290.9	1.8	1.8	0.1785	0.0051	0.0051
	August 2015	286.7	-4.2	-2.4	0.1654	-0.0131	-0.008
	June 2017	290.3	3.6	1.2	0.1922	0.0268	0.0188
	July 2017	289.7	-0.6	0.6	0.1845	-0.0077	0.0111
	August 2017	287.9	-1.8	-1.2	0.1648	-0.0197	-0.0086
	June 2019	296.3	8.4	7.2	0.1666	0.0018	-0.0068
	July 2019	293.3	-3	4.2	0.14875	-0.01785	-0.02465
	August 2019	291.1	-2.2	2	0.1268	-0.02195	-0.0466
	June 2021	293.9	2.8	4.8	0.1792	0.0524	0.0058
	July 2021	293.3	-0.6	4.2	0.13725	-0.04195	-0.03615
	August 2021	289.1	-4.2	0	0.1022	-0.03505	-0.0712

Point B		Avg. Soil Temp.	Δ Temp.	Net Δ Temp.	Avg. Soil Moisture	Δ Moisture	Net Δ Moisture
	June 2015	284.3			0.3896		
	July 2015	287.3	3	3	0.3905	0.0009	0.0009
	August 2015	286.7	-0.6	2.4	0.3796	-0.0109	-0.01
	June 2017	286.7	0	2.4	0.3974	0.0178	0.0078
	July 2017	290.9	4.2	6.6	0.388	-0.0094	-0.0016
	August 2017	286.4	-4.5	2.1	0.353	-0.035	-0.0366
	June 2019	293.3	6.9	9	0.3582	0.0052	-0.0314
	July 2019	292.1	-1.2	7.8	0.32425	-0.03395	-0.06535
	August 2019	292.1	0	7.8	0.2982	-0.02605	-0.0914
	June 2021	293.3	1.2	9	0.3738	0.0756	-0.0158
	July 2021	292.1	-1.2	7.8	0.32025	-0.05355	-0.06935
	August 2021	288.5	-3.6	4.2	0.2954	-0.02485	-0.0942

Point C		Avg. Soil Temp.	Δ Temp.	Net Δ Temp.	Avg. Soil Moisture	Δ Moisture	Net Δ Moisture
	June 2015	279.5			0.1804		
	July 2015	281.9	2.4	2.4	0.15975	-0.02065	-0.02065
	August 2015	283.1	1.2	3.6	0.1598	0.00005	-0.0206
	June 2017	281.3	-1.8	1.8	0.2044	0.0446	0.024
	July 2017	284.3	3	4.8	0.18125	-0.02315	0.00085
	August 2017	280.7	-3.6	1.2	0.1674	-0.01385	-0.013
	June 2019	286.4	5.7	6.9	0.146	-0.0214	-0.0344
	July 2019	284.9	-1.5	5.4	0.12125	-0.02475	-0.05915
	August 2019	284.3	-0.6	4.8	0.1082	-0.01305	-0.0722
	June 2021	287.3	3	7.8	0.1642	0.056	-0.0162
	July 2021	289.7	2.4	10.2	0.133	-0.0312	-0.0474
	August 2021	283.7	-6	4.2	0.1152	-0.0178	-0.0652

Point D		Avg. Soil Temp.	Δ Temp.	Net Δ Temp.	Avg. Soil Moisture	Δ Moisture	Net Δ Moisture
	June 2015	281.9			0.2726		
	July 2015	284.9	3	3	0.25375	-0.01885	-0.01885
	August 2015	284.3	-0.6	2.4	0.259	0.00525	-0.0136
	June 2017	281.9	-2.4	0	0.2762	0.0172	0.0036
	July 2017	286.1	4.2	4.2	0.257	-0.0192	-0.0156
	August 2017	283.7	-2.4	1.8	0.2416	-0.0154	-0.031
	June 2019	288.5	4.8	6.6	0.26	0.0184	-0.0126
	July 2019	286.1	-2.4	4.2	0.23425	-0.02575	-0.03835
	August 2019	284.9	-1.2	3	0.2174	-0.01685	-0.0552
	June 2021	289.7	4.8	7.8	0.2684	0.051	-0.0042
	July 2021	289.1	-0.6	7.2	0.2405	-0.0279	-0.0321
	August 2021	287.3	-1.8	5.4	0.226	-0.0145	-0.0466

Point E		Avg. Soil Temp.	Δ Temp.	Net Δ Temp.	Avg. Soil Moisture	Δ Moisture	Net Δ Moisture
	June 2015	278.3			0.2136		
	July 2015	283.7	5.4	5.4	0.19075	-0.02285	-0.02285
	August 2015	281.9	-1.8	3.6	0.2042	0.01345	-0.0094
	June 2017	277.1	-4.8	-1.2	0.2662	0.062	0.0526
	July 2017	281.9	4.8	3.6	0.23825	-0.02795	0.02465
	August 2017	281.9	0	3.6	0.2158	-0.02245	0.0022
	June 2019	283.1	1.2	4.8	0.1802	-0.0356	-0.0334
	July 2019	281.3	-1.8	3	0.15025	-0.02995	-0.06335
	August 2019	284.9	3.6	6.6	0.1356	-0.01465	-0.078
	June 2021	284.3	-0.6	6	0.1758	0.0402	-0.0378
	July 2021	284.9	0.6	6.6	0.18025	0.00445	-0.03335
	August 2021	283.7	-1.2	5.4	0.1792	-0.00105	-0.0344

Table 1. Observed soil temperature (K) and soil moisture (m3 water/m3) at 5 different locations in the Taimyr-Central Siberian Tundra ecoregion. Data was used from NASA Worldview, from NASA's Aqua and Soil Moisture Active Passive (SMAP) satellites. Data was recorded every 7 days over 3 months each year during the summer, from 2015-2021. A clear increase in the soil temperature and decrease in the average soil moisture was observed from 2015-2021.

As soil temperature increases, the maximum depth of ice thaw, also known as the active layer, increases accordingly. In many cases, increasing soil temperature allows the active layer to reach the permafrost layer underneath (Fig. 3.), leading to higher rates of permafrost melt (Callaghan et al., 2021). Permafrost melt results in the permafrost layer being pushed deeper into the ground, as it is replaced by the active layer. Unlike the permafrost layer, the active layer is not permanently frozen, but regularly freezes in from late fall to early spring. During the summer months, any ice in the active layer thaws due to rising temperatures, reverting the active layer to normal soil.

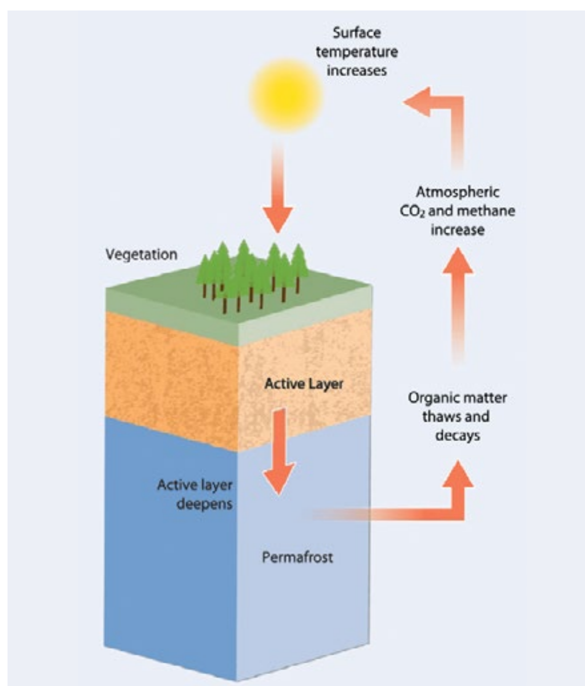
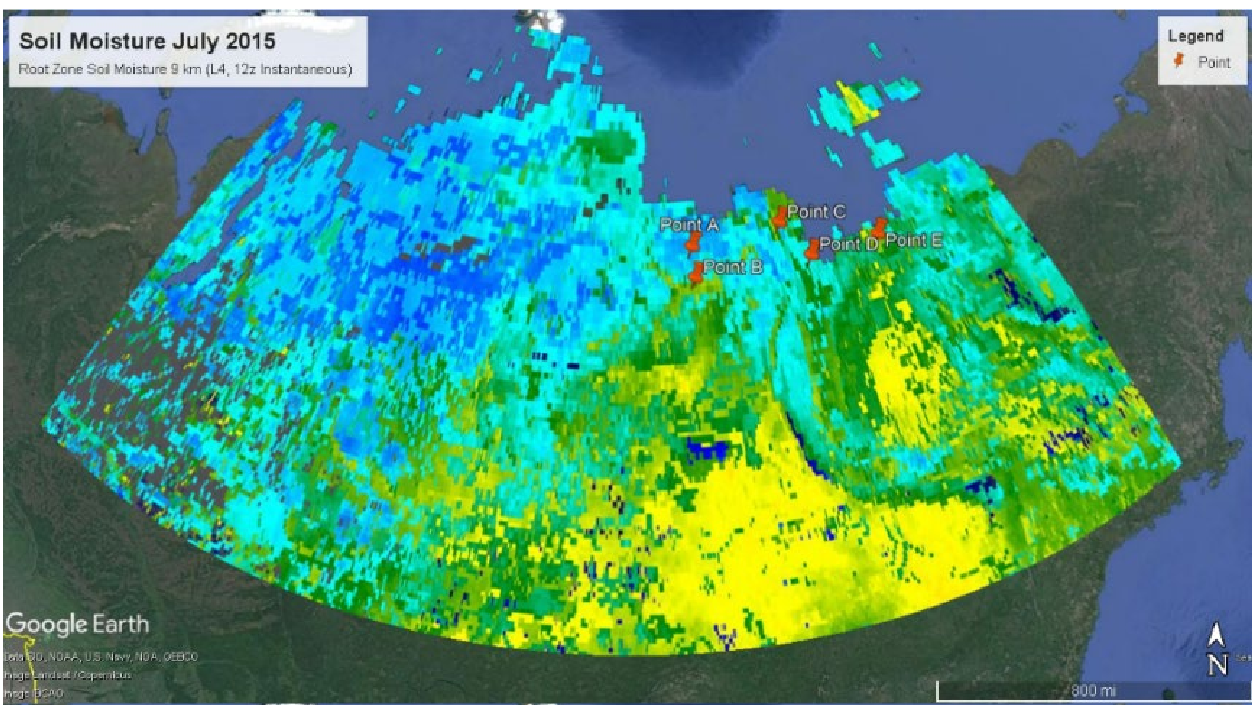


Fig. 3. Diagram of the cycle of permafrost degradation. Rising surface temperatures due to global warming result in an increase in the active layer, and thus an increase in the permafrost thaw depth, causing more permafrost to melt each year. This results in a lower permafrost limit (Schaefer et al. 2014).

As a result of the permafrost melting and regressing, the soil humidity in the region has also decreased. When the permafrost layer is intact, moisture is retained near the surface. Permafrost hardens the soil below and prevents any water from draining, locking the water near the surface and keeping the soil wet and soft. When permafrost melts, the ice present in the soil melts away, causing the permafrost soil to lose its rigidity and the structure formed from the ice.

This leaves the soil softer and more porous due to the absence of ice in between the gaps of soil that binds the soil together. Once the soil becomes porous, water gathered near the surface is able to drain at higher rates through the soil into deeper sections of the ground, causing the soil to dry at faster rates and decreasing the average amount of moisture in the soil, as observed in permafrost located in northeastern China (Serban et al., 2021). At the 5 locations in the northeastern Siberian tundra, we used soil moisture data gathered by NASA's Soil Moisture Active Passive (SMAP) satellite (Fig. 4).

Over the course of the time period from 2015-2021, the soil moisture decreased noticeably. From 2015-2021, the average soil moisture at point B decreased from 0.3896 m^3 water/m^3 to 0.2954 m^3 water/m^3, a decrease of about 0.0942 m^3 water/m^3. At point C, the average soil moisture decreased from 0.1804 m^3 water/m^3 to about 0.1152 m^3 water/m^3, a decrease of about 0.0652 m^3 water/m^3. Among all 5 locations where data was measured, soil moisture generally decreased by 0.03 m^3 water/m^3 or greater (Table 1). Soil in the Northeast Siberian Tundra is showing to be significantly drier than 5 years ago, owing to permafrost melt.



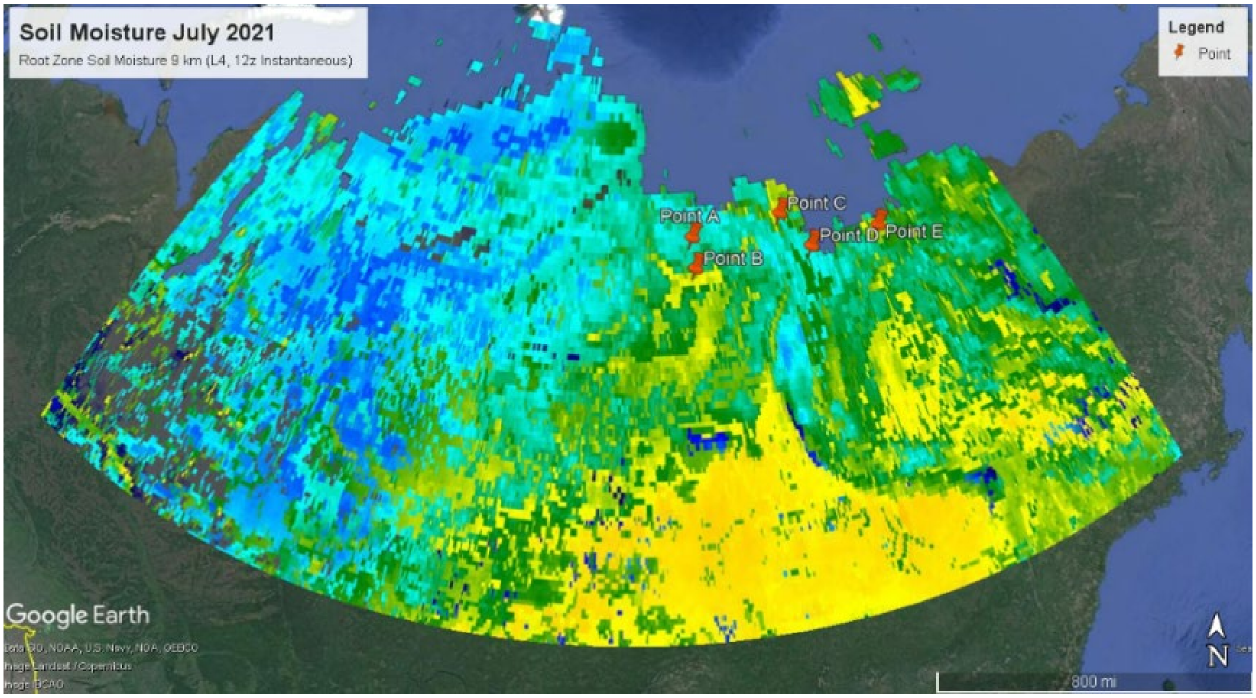


Fig. 4. Observed soil moisture (m3 water/m3) in the Siberian tundra and taiga in 2015 and in 2021. Moisture was measured using the Root Zone Soil Moisture 9 km (L4, 12z Instantaneous) layer. Soil moisture is scaled from yellow (lowest moisture) to blue (highest moisture). From 2015 to 2021, more green and yellow appear on the map in the northern tundra, indicating a general decrease in soil moisture across Siberia. (NASA Worldview).

Furthermore, in areas where permafrost is beginning to degrade and melt, water availability could become the chief constraint on plant growth. In locations with stable permafrost at low risk of degradation and melting, the primary constraint on plant growth is the amount of energy and heat available. In studies conducted on the Qinghai-Tibetan plateau, areas with unstable permafrost and only seasonal ground frost, constraints on plant growth switch from energy to water (Zhou et al., 2015, Yi et al., 2011), shifting the hydrology of the region. Similarly, as permafrost melts in the Northeast Siberian Tundra, plant species would also become constrained by the decreasing water supply. With water scarcity increasing due to greater soil water drainage, constraints on available water supply will increase. Vulnerable plants in these regions will struggle to absorb sufficient water for growth.

Discussion

Lack of soil moisture has a detrimental effect on plant species found in the Northeast Siberian Tundra. The Northeast Siberian Tundra is characterized by its long and harsh winters, short growing seasons, and by flora capable of surviving within the thin layer of soil above the permafrost. Plant species found on the tundra are well adapted to freezing conditions, able to survive under several feet of snow. However, if changes occur to either the climate or soil composition of the tundra, these plant species would be at high risk due to their narrow range of adaptability. One change that could severely impact flora of the Northeast Siberian Tundra is decreasing soil moisture. When soil drainage increases, wetlands and bogs found in the tundra can gradually drain into the ground and disappear, and many lakes slowly lose water through drainage (Smith et al., 2005). Several sedge and shrub species, including *Eriophorum vaginatum and Rhododendron tomentosum*, are found within wetlands and bogs on the tundra. These species require high volumes of water and peat located in these bogs in order to grow. Without these peat bogs, these plants would not have adequate access to water and nutrients, potentially destabilizing the ecosystem.

Additionally, the potential degradation of grassland plants throughout the region could result in a domino effect (Liu et al., 2017). As observed during a study on the Qinghai-Tibetan plateau, grassland degradation from decreased soil moisture could in turn impact the soil composition, causing decreases in the amount of nitrogen, phosphorus, and potassium typically present in the soil (Liu et al., 2017). These nutrients are essential to grassland ecosystems of the Northeast Siberian Tundra. Without phosphorus, for instance, plant cells would be unable to divide, slowing plant growth and increasing the severity of plant damage. Another observed effect of grassland degradation on the Qinghai-Tibetan plateau is the increase of soil pH by about 0.66 (Liu et al., 2017), causing the soil to become more basic. Due to the similarities between the Tibetan plateau and the Northeast Siberian Tundra ecosystems, it is likely that these changes in soil composition could also occur in the Northeast Siberian Tundra. Since many plant species in the Northeast Siberian Tundra, including *Eriophorum angustifolium, Betula nana, and Vaccinium uliginosum* thrive in acidic soil, decreases in these essential nutrients and soil acidity would result in further degradation of grassland ecosystems in the Northeast Siberian Tundra.

As a result of the negative impact permafrost melt has on soil moisture and composition, many animal species which rely on impacted plant species for food will also be affected. The major herbivorous animal species in the Northeast Siberian Tundra are the caribou, willow ptarmigan, and several species of lemmings and waterfowl. These species rely on plants that are highly vulnerable to the impacts of permafrost melt, such as sedges, shrubs, and berries. Populations of these species will likely decrease due to the increased scarcity of food, and many will be forced to migrate farther north where permafrost melt is not as severe due to cooler summer temperatures. This will affect the biodiversity of impacted regions in the tundra, causing higher concentrations of animal species in the north, placing more stress on northern plant species, and also decreasing the amount of herbivorous animals in the southern tundra. These changes will consequently force predators such as arctic foxes and wolves to migrate with them. By contrast, warmer temperatures and larger active layers could cause plant species from the Siberian taiga to expand into the tundra, potentially attracting animals from the taiga along with them. Moose, deer, elk, and various bird species would begin to enter the tundra, changing the biodiversity and essentially shifting the biome from tundra to taiga, leaving tundra species at risk of habitat loss. Further research on possible benefits of a deeper active layer on plant life would lead to more accurate predictions on the effects of global warming in Northeast Siberian Tundra. Future research efforts should also be directed towards the ability of plant species from the Siberian taiga to spread into the tundra in order to determine the future threat of habitat loss on the tundra.

Conclusions

Permafrost melt in the Northeast Siberian Tundra has detrimental effects that cause a domino effect, potentially affecting the entire tundra ecosystem. Due to increasing soil temperatures caused by global warming and climate change, the active layer has expanded and caused permafrost to recede deeper into the earth. Without permafrost in the surface layer of the soil, water drains through the soil at higher rates, causing soil moisture to decrease and causing many wetlands and bogs to dry out. There has been clear evidence to support decreasing soil moisture and rising soil temperatures in the majority of Northeast Siberian Tundra regions, shown through both satellite data and research studies. In the Qinghai-Tibetan plateau, a region similar to the Northeast Siberian Tundra, many investigations on the quality of the soil after permafrost melt have uncovered many troubling trends. Decreasing soil moisture and disappearing wetlands could potentially constrain plant growth and affect much of the plant population. Degradation of grasslands would likely follow, and as a result could possibly cause soil content of nitrogen, phosphorus, and potassium to decrease, as well as increasing soil pH, all of which would be detrimental towards plant growth. Loss of plant life would result in migrations of animal species, and changing soil conditions would allow new plant and animal species from the southern taiga to encroach on the Northeast Siberian Tundra. This could potentially lead to the shrinking of the tundra biome, resulting in the loss of habitat for many tundra species, calling for the need to slow the effects of global warming and climate change.

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