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Linking climate change and human systems: a case study of Arctic pipelines

November 2022

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2.0 Introduction

As climate change alters the physical Earth system, it becomes more difficult to maintain and construct infrastructure. The wide spatial distribution of climate change impacts on infrastructure leads to implications for broader human systems. In the Arctic, one of the most pronounced climate change impacts on the physical Earth system is ground subsidence triggered by permafrost thaw.

The Arctic is warming four times faster than the rest of the planet (Rantanen et al., 2022), and the temperature increase has resulted in significant physical changes, including permafrost thaw and associated surface subsidence (Grosse et al., 2016, Turetsky et al., 2020, Koven et al., 2013). In addition, permafrost regions are experiencing widespread negative impacts on human socio-economic development and infrastructure (ACIA, 2005, Streletskiy et al., 2012a, Anisimov and Reneva, 2006, Nelson et al., 2001, Melnikov et al., 2021).

In Russia, more than 60 percent of its land area contains permafrost, directly affecting human infrastructure (Streletskiy et al., 2019, Suter et al., 2019, Melnikov et al., 2021). Particularly, the Russian oil and natural gas industry has thousands of kilometers of oil and gas transmission pipelines built on permafrost ground that are vulnerable to surface deformation. Since Russian pipelines are often buried, they are especially vulnerable to small changes in ground conditions and reductions in bearing capacity to support pipelines (Streletskiy et al., 2012a). The natural gas production complex and its associated infrastructure in Northwest Siberia are especially at high risk (Nelson et al., 2001).

Permafrost-pipeline interactions are inherently hazardous regardless of climate change. Oil pipelines that are operated at higher temperatures than surrounding soil are subjected to thermal stress, which can cause pipelines to buckle. The differential in operational temperature compared to soil temperature can also cause the soil beneath pipelines to thaw and settle, leading to a loss of stability for the pipeline (Li et al., 2019, Li, 2022). When the active layer thaws during the summer, pipelines are subjected to harsh conditions, which can induce corrosion and instability. In addition, it is difficult to monitor and repair pipelines in warmer months when winter roads are inoperable. Permafrost also tends to settle unevenly, which can cause ruptures or buckling in pipelines (Bartsch et al., 2021). When soil surrounding a pipeline liquifies, the additional buoyancy can cause pipelines to uplift through the ground surface (Li, 2022, Li et al., 2022). The development of thermokarst lakes and the accumulation of corrosive materials in sagging portions of pipelines also pose corrosion risks. Stress corrosion cracks are cracks in pipelines from the combination of corrosion and mechanical stress. According to Gazprom, Russia's major producer of gas, the propagation of stress corrosion cracks was the leading cause of pipeline accidents in 2019 (Gazprom, 2019a). As the Arctic continues to warm and undergo major projected ground subsidence in the coming decades, there is a need to assess the potential vulnerability and socio-economic effects on oil and gas infrastructure.

Numerous works have studied climate change impacts on Arctic infrastructure (Bartsch et al., 2021, Schneider von Deimling et al., 2021, Streletskiy et al., 2012a, Streletskiy et al., 2012b, Hjort et al., 2022, Alvarez et al., 2020, Melnikov et al., 2021). For example, Wols & Van Thienen developed models to predict pipeline failures from climate change-induced soil settlement within a Dutch water distribution network (Wols and Van Thienen, 2014). Hjort et al. created a detailed infrastructure hazard map for regions located on permafrost and estimated the total length of pipelines in the Arctic subject to low, medium, and high hazards from permafrost thaw (Hjort et al., 2018). This study, however, did not provide estimates of potential replacement costs. Several studies assessed the economic impacts of permafrost thaw on infrastructure in Russian permafrost regions (Streletskiy et al., 2019, Melnikov et al., 2021, Badina and Pankratov, 2021). Potential costs of damage of public infrastructure in these studies were estimated based on the value of assets reported at the administrative district level by the Russian Federal State Statistics Service or companies. As a result, the cost estimates are limited by the accuracy and resolution of value reporting.

This study aims to combine the strengths of existing literature by linking detailed geospatial data on permafrost thaw and gas and oil pipeline networks to estimate the potential pipeline replacement costs associated with projected permafrost thaw in Russia over the period 2020 to 2040. This work also provides a framework that can be used to assess various climate change impacts between the physical Earth system and human infrastructure systems.

The approach we have developed can also be useful to better understand other human-natural system dynamics in the Arctic and their ties to global systems. For example, pipeline replacement cost estimates could be linked to increased shipping demands or fluctuations in energy markets. Finally, our approach provides a framework to characterize the wide range of potential impacts from uncertainty in multiple parameters, not addressed in the existing literature.

This paper begins with the methodology, which describes the development of permafrost thaw projections over the period from 2020 to 2040, the rationale used to predict pipeline failure from ground subsidence projections, the digitization of pipeline networks in ArcMap, and the approach to estimate replacement costs. Next, the article provides results, including detailed maps of permafrost subsidence projections and central estimates for oil and gas pipeline replacement costs. Finally, we discuss the results and their potential implications associated effects on markets, energy security, geopolitics, and the environment.

3.0 Materials and methods

3.1 Permafrost thaw and ground subsidence projections

The Community Land Model Version 4.5 (CLM 4.5) pan-Arctic simulations using RCP 8.5 from Permafrost Carbon Network Model Intercomparison Project (PCN-MIP) (Oleson et al., 2013) was used to calculate the projected 20-year (2020-2040) change in active layer thickness (ALT) (Andresen, 2020). CLM4.5 simulations are gridded at a horizontal resolution of 10. To minimize interannual variability when comparing 20 years of change, the mean and standard deviation in the projected 20-year ALT change between years 2020 and 2040 were calculated for each grid cell using a seven-year average centered around years 2020 (2017-2023) and 2040 (2037-2043). Probability density functions were created to account for variability and uncertainty in ALT change.

To assess potential ground subsidence, we combined projections of ALT as well as geophysical permafrost and ground ice distributions. Particularly, gridded CLM projections of ALT change were spatially merged with Brown et al.'s Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Brown et al., 2002) in ArcGIS to combine geometric and spatial attributes of these datasets. The Circum-Arctic Map of Permafrost and Ground-Ice Conditions geographically partitions permafrost by permafrost type, excess ice content, and overburden type. For example, the permafrost extent is estimated in percent area at intervals of 90-100 percent, 50-90 percent, 10-50 percent, <10 percent, and no permafrost. The relative abundance of ground ice in the upper 20 m is estimated in percent volume at intervals of: >20 percent, 10-20 percent, <10 percent, and 0 percent. These characteristics were used to generate probability density functions to describe ice content within geographic partitions. The CLM ALT projections and Circum-Arctic Map of Permafrost use different partitioning, so merging the two shapefiles created new subdivisions, which will henceforth be referred to as permafrost vulnerability areas (PVAs).

Subsidence projections within each PVA were calculated by multiplying PVAs' projected change in ALT by their respective ground ice content, using Monte-Carlo sampling to quantify uncertainty associated with ALT change and ground ice content. Maps were then generated for the mean, low (5th and 25th quantiles), and high (75th and 95th quantiles) subsidence projections.

3.2 Determination of subsidence threshold for pipeline replacement

Relative pipeline-soil stiffness, pipeline age, pre-existing imperfections, operation methods, material, burial depth, ground slope, and the degree to which soil settles differentially influence how vulnerable pipelines are to ground subsidence. Given the complexities tied to pipeline mechanics and the multiple possible failure modes, a range of ground subsidence depths can trigger pipeline failure. We combined empirical estimates and engineering analyses to select a range of subsidence heights likely to

trigger pipeline replacement and incorporate these estimates subsidence projections described above to predict pipeline failure.

Studies suggest that even a few centimeters of ground subsidence can trigger a pipeline replacement. In Streletskiy et al. (2019), infrastructure subjected to 10 cm of ground subsidence is assumed to trigger a response. Within the framework of the stressor-response model, ground subsidence exceeding 0.10 m triggers the response for infrastructure (Melvin et al., 2017). Faeli et al. suggested 0.08 times the pipeline diameter as a conservative threshold for allowable differential settlement and 0.12 times the pipeline diameter as a moderate threshold for allowable differential settlement (Faeli et al., 2010). These guidelines come out to subsidence thresholds of 11 cm and 17 cm, respectively, for the large diameter pipelines common in Russian oil and gas transmission networks. Russian pipeline design documentation limits subsidence to 25 cm (Mazur and Ivantsov, 2004, SNiP 2.05.06-85, 1985). Based on the listed estimates, we estimated a range of 5 cm to 25 cm of ground subsidence would likely trigger a pipeline replacement event.

We also used a predictive model developed by Wols & Van Thienen(2014) to corroborate the estimate that ground settlement ranging from 5 cm to 25 cm could induce failure in pipes common in Russian oil and gas transmission networks. The model schematizes the pipe as a simple beam and develops a parametric function for climate change induced soil settlement to predict if pipelines are likely to fail from overstressing. Driving inputs to the model included pipeline geometric and material properties, maximum ground settlement, and the horizontal distance over which settlement occurs, which is referred to as transition length. When subsidence occurs over a shorter transition length, the induced stress is higher. Based on Wols et al.'s predictive models, a pipeline with characteristics similar to those used in oil and gas transmission in the Russian Arctic could be overstressed from 5 cm of ground subsidence when transition length is less than 7 m; 10 cm of ground subsidence when transition length is less than or equal to 10 m; 25 cm of ground subsidence when the transition length is less than or equal to 16 m. These results suggest that pipelines located in permafrost vulnerability areas with projected subsidence of 5, 10, and 25 cm are likely to require replacement, especially in combination with other stressors such as corrosion, temperature differentials, and aging pipeline infrastructure. Detailed calculations and assumptions we used for the pipeline impact model are included in Supplement A.

Given the agreement between empirical estimates and Wols et al.'s analytical model for the amount of subsidence likely to trigger a replacement event, we selected a range of 5 cm to 25 cm as the amount of ground subsidence likely to trigger a replacement event in pipelines. We used 10 cm as the threshold for our central estimate. We assumed that pipelines located in PVAs with projected subsidence multiple times as large as the selected subsidence threshold would need to be replaced that many times over the 20-year study period. For example, if the selected subsidence threshold was 10 cm, it was assumed a pipeline located in a region projected to subside 20 cm would be replaced

twice over the period. Roads have been more subject to early climate impacts, and segments do in fact undergo major reconstruction on a regular basis. For example, along the Yukon Alaska Highway, differential permafrost settlements have driven annual repair costs up an additional 40,900 USD/km (2020 USD) per year in 2012 (Oldenborger, 2015).

Although some technologies, such as thermosiphons have been used to prevent warm pipelines from thawing permafrost, we did not include the potential for their use in our study because they are not effective in preventing thaw induced by climate change. When the air temperature is higher than that of the soil, thermosiphons are ineffective (Wagner, 2014). For example, about 65,000 thermosiphons were installed for the Vankor-Purpe oil pipeline. However, they are ineffective because the temperature is rising and 40 percent of thermosiphons do not provide a sufficiently cold temperature in the Vankor-Purpe oil pipeline (Shmelev et al., 2013).

3.3 Identification of at-risk pipelines

We collected pipeline geospatial data from several sources, including Russia's Federal State Statistics Service (Rosnedra, n/d), energybase.ru (Energybase, N/A), Transneft (Transneft, 2021b), and Gazprom (Gazprom, 2021b). We cross-checked pipeline locations between the various sources. We compiled pipeline paths and diameters in ArcGIS. We then intersected the subsidence projections described in section 2.1 (mean, 5th quantile, and 95th quantile) and pipeline data in ArcGIS to determine the likely range of ground subsidence each pipeline segment in Russia will undergo over the period 2020 to 2040. Then, we used ArcGIS to measure the length of pipeline segments. Our study does not include costs associated with gathering and distribution lines because there was not adequate geospatial data. We also do not include costs associated with compressor and pumping stations, even though costs are potentially very high, because the diversity of equipment makes it difficult to establish thresholds for damage and estimate replacement costs.

3.4 Pipeline replacement cost estimation

The cost of pipeline replacement includes several cost categories, including pipes and other materials, labor, equipment required for pipeline installation, transportation costs, land rights, and others. The high-quality steel used for pipes is a globally traded commodity, and these material costs are often similar in different countries. However, construction costs and other expenses tend to be much higher in the Russian Arctic, and we use an Arctic multiplier which is described below to account for this difference. We do not include the cost of compressor stations in our analysis.

The most difficult component to assess is the construction cost. Historical evidence shows that reported Russian costs do not always reflect true costs. For example, the reported investment cost of the Power of Siberia pipeline did not change even after the

pipeline length was reduced by a third (Korchemkin, 2018). Reported Russian costs may also be distorted by government subsidies to the oil and gas industry. For example, in 2014, there were an estimated 25 billion USD in subsidies to fossil fuel production annually (Ogarenko, 2015). According to the IEA, the Russian government gave 10.4 billion USD to the gas industry in 2019 (IEA, 2020). As a result of these limitations, we used U.S. data to estimate pipeline construction costs instead of Russian data. We included the cost estimated for two recent Russian pipeline and gathering line in Supplement B and C, respectively. According to experts, oil and gas transmission pipeline construction costs are not significantly different, especially when costs do not include other types of infrastructure such as compressor and pumping stations. Russian oil and gas transmission pipeline costs can also be assumed to be similar since most are made with the same high strength steel (UMC, N/A). Since oil and gas pipeline construction costs are comparable, the same relationship was used to make cost estimates for oil and gas pipelines.

Since costs such as materials and transportation to remote areas are likely to be similar across the Arctic, with the major cost differential labor costs in different areas, U.S. costs should provide a reasonable basis for replacement cost estimation. To estimate the cost of replacing segments of pipeline, we used construction costs from pipeline projects across the United States over the period 2011-2020 (O&GJ, 2020, Smith, 2014, Smith, 2020). We used the International Monetary Fund's GDP deflator indices to convert the historical pipeline construction costs and all other monetary values in this paper to 2020 USD, unless noted otherwise (IMF, 2021). Although pipeline replacement and construction costs are not identical in practice, we used construction costs since replacement costs are not widely reported. Moreover, the scope of replacement can vary from checking on small portions to full replacement. Experts indicate that it is common in Russia to abandon damaged pipelines and build new ones in parallel instead of repairing them. Most pipeline repair projects use the continuous pipe replacement method, which is the most expensive way to fix pipelines (Veliyulin et al., 2009). Under this method, an entire segment of pipeline is built parallel to the existing line. Continuous pipeline replacement is preferable when the dismantling and construction time is a factor, for example, when losses from idling pipelines are higher than the cost of replacement.

We also used construction cost data from the United States because the available data was more detailed. The dataset we used includes costs and diameter for over 70 natural gas pipelines constructed between 2011 and 2020 with diameters ranging from 8 to 36 inches (200 to 900 mm). This dataset allowed us to make a linear model to estimate pipeline construction cost based on pipeline diameter. We considered using a quadratic model since it fit the data slightly better, but we rejected it because extrapolation to larger diameters included in this study produced unrealistically high construction cost estimates, based on comparison to western project costs. Figure 1 shows the linear regression of construction cost vs pipeline diameter, which we used to estimate pipeline replacement costs.

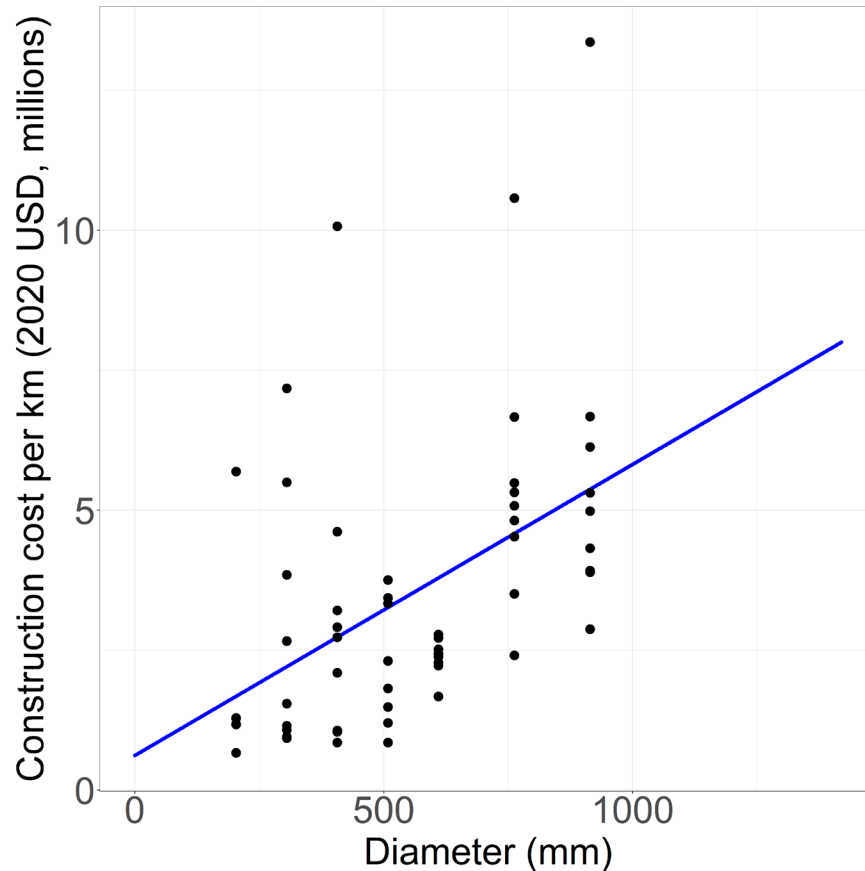


Figure 1. Pipeline construction cost estimates per km vs diameter. A linear regression line is extended to a diameter of 1420 mm since that is a common diameter for transmission pipelines in Russia.

The second large parameter in estimating costs of pipeline replacement in permafrost zones is the harsh conditions in the Arctic that drive the costs up. Arctic construction costs are higher than those elsewhere due to remote working conditions, the harsh climate, limited construction season, reduced availability of infrastructure (roads, power lines, communication), cost of shipping materials, and need to thermostabilize permafrost. To account for these conditions, we used a range of cost multipliers to adjust for Arctic costs. For our central estimate we selected a cost multiplier of 5 with cost multipliers of 3 and 7 for lower and upper bounds. We came up with the lower bound cost multiplier of 3 by comparing reported construction costs reported by Transneft in Arctic and non-Arctic regions (Transneft, 2021a). A regulator with extensive experience in cost permitting provided the higher bound cost estimate of 7.

Equation 1 shows the linear relationship between pipeline diameter and construction cost, which was used to calculate costs.

$$T = C \times (5.20 \times 10^3 D + 6.20 \times 10^5) \quad (\text{Equation 1})$$

Where T = total pipeline construction cost, 2020 USD/km,

D = pipeline nominal diameter, mm,

C = cost multiplier.

Given the many factors that affect pipeline construction cost, including terrain and labor rates, there is large uncertainty in pipeline cost estimation. That said, comparison to other studies and Arctic pipeline construction costs suggest our linear model is within reason. For example, a 2016 Interstate Natural Gas Association of America study estimated that the average pipeline construction cost in the United States would be 6,380 USD per millimeter of pipeline diameter per kilometer in 2020 (Petak et al., 2018). The construction cost for a proposed 42-inch natural gas pipeline for the LNG project in the Alaskan Arctic was estimated at 29.8 million USD per km in 2020 (Brehmer, 2020). According to our linear model with a cost multiplier of 5, a 42-inch pipeline would cost 30.8 million USD per km. The calculations for our linear model are included in the supplementary data.

We used Equation 1 to estimate the replacement cost for each at-risk pipeline segment identified in section 2.3. We then took the sum of all segment replacement costs to estimate total replacement costs over the study period.

To provide a point of comparison for pipeline replacement costs, we estimated annual Russian oil and gas values using available public data. Since gas prices fluctuate widely based on where it is sold, we calculated gas revenues using Gazprom's reported sold volumes and prices domestically and abroad (Gazprom, 2019b). We estimated oil value by multiplying Russian 2019 production levels by the 2019 price of Brent crude oil reported by the U.S. Energy Information Administration (EIA, 2021a, EIA, 2021b).

4.0 Results

4.1 Permafrost pipeline mapping

We used ArcGIS to create maps that show which pipelines are affected by permafrost thaw induced subsidence over the study period. Figure 2 shows the map of subsidence projections and existing oil and gas transmission pipelines. The figure illustrates that most of these large-diameter pipelines on thawing permafrost are gas lines. Short segments could show connections between production sides and refineries for oil or production and consumption for gas.

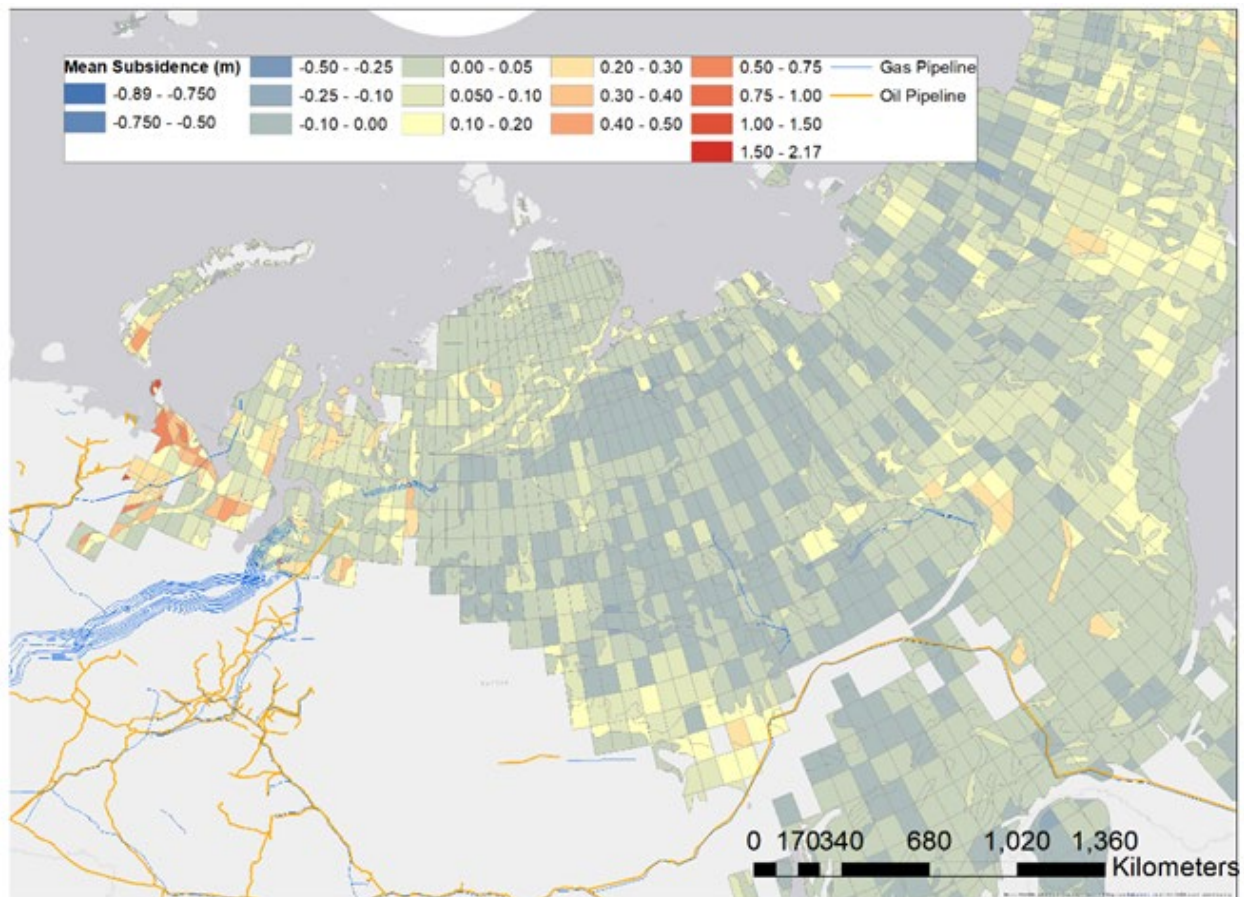


Figure 2. Map of subsidence projections with pipelines. Positive values represent subsidence.

Figure 3 provides a zoomed-in view on Northwest Russia.

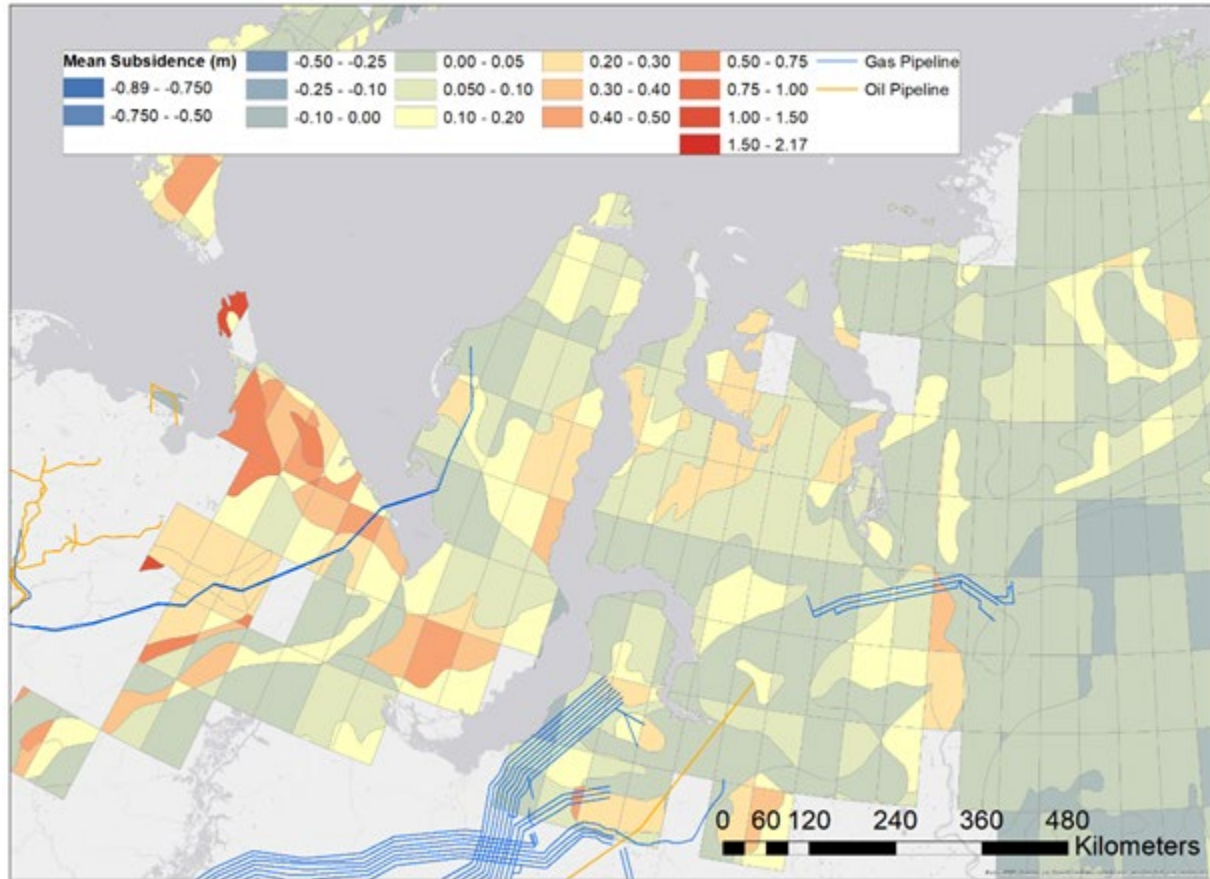


Figure 3. Map of subsidence and pipelines, focused on the Yamal Peninsula.

Given the region's large deposits of natural gas, extensive pipeline infrastructure, and high subsidence projections, it is especially vulnerable. Additional pipelines are planned for this region.

4.2 Cost estimates

The results suggest that damage from pipeline subsidence over the 20-year period from 2020 to 2040 could incur billions of dollars of costs. If 10 cm of subsidence is assumed to trigger a pipeline replacement event and five is taken as the Arctic cost multiplier, the total estimated replacement cost for oil and gas pipelines could be 109 billion USD (Figure 4).

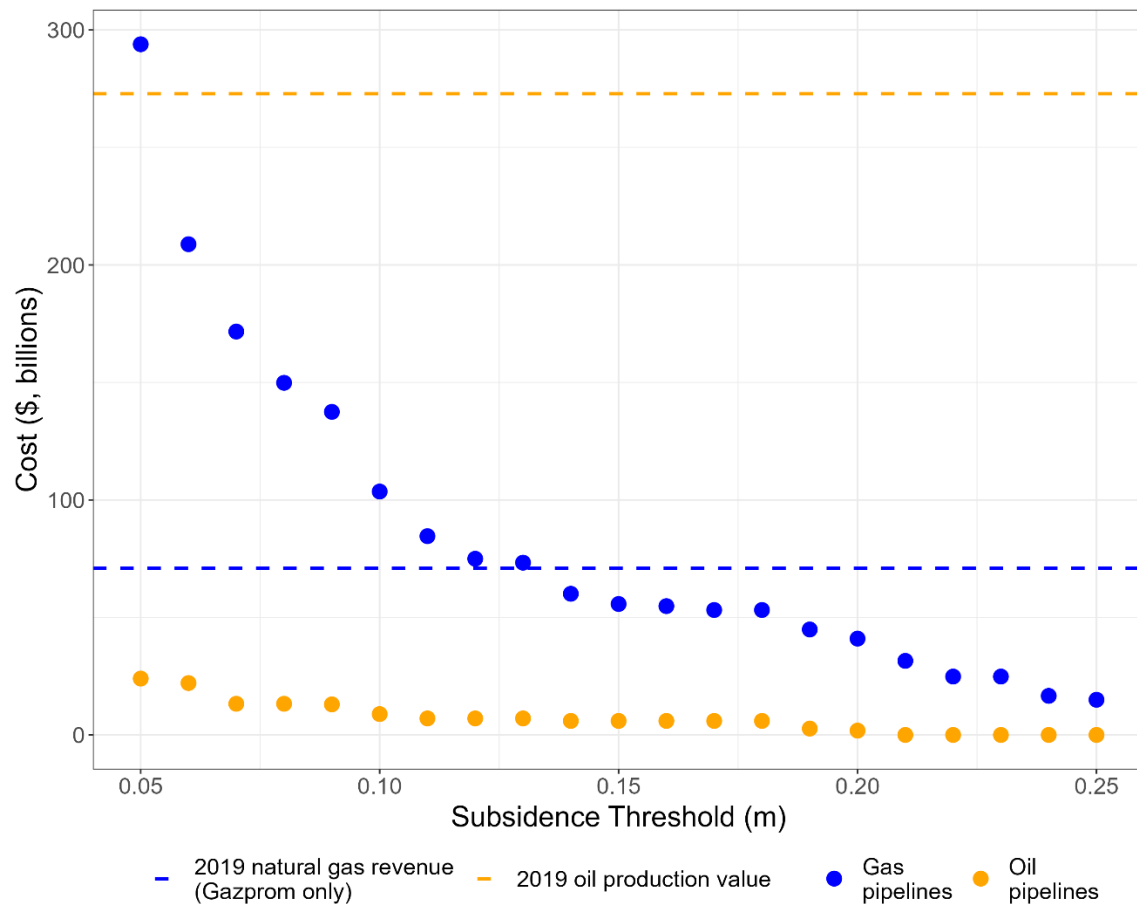


Figure 4. Estimates of pipeline replacement cost (dotted lines) under various estimates of permafrost subsidence that trigger pipeline replacement.

For example, if 10 cm of subsidence triggers pipeline replacement, the total cost of replacement of gas pipeline could be higher than the annual sales of natural gas (All costs are converted to 2020 USD).

The total cost estimates are much higher for gas pipeline replacements than those for oil pipelines because more gas lines are located on thawing permafrost. Supplement D shows additional results from uncertainty analysis for with low, central, and high estimates of permafrost subsidence, Arctic cost multiplier, and replacement threshold.

5.0 Discussion and conclusions

The results indicate climate change induced ground subsidence from 2020 to 2040 could incur massive costs for Russian oil and gas pipeline networks, which are comparable in magnitude to the historical annual value of gas produced in the country. Gas pipelines are especially vulnerable to subsidence, since a larger total length of gas pipelines are in permafrost regions projected to undergo significant subsidence. The central estimate for gas pipeline replacement costs over the study period exceeds the historical annual estimate for gas revenues. It should also be noted that gas revenues could decrease as pipelines undergo repairs and capacity is reduced. The pipeline replacement cost presented in this paper show the potential investments needed to replace old pipelines that are built on thawing permafrost. Cost estimates do not include the replacement costs associated with in-field line failures or other types of oil and gas infrastructure. While it is difficult to separate the costs of replacing pipelines due to their natural lifetime ending and operational factors, findings from this study suggest ground subsidence attributed to climate change could push large portions of vulnerable infrastructure systems to failure.

As ground conditions change more rapidly in the Russian Arctic, there will be shifts in the oil and gas industry beyond increased replacement costs. Contingency will need to be built into pipeline designs, which will add cost and time to initial construction. In affected regions, pipelines will need to be buried deeper to reach stable permafrost or built above ground. It will also become necessary to implement costlier technologies such as access mats, which are platforms used to increase ground stability to allow for pipeline access and provide stability for machinery during construction. Even with such technology changes, maintaining pipelines under changing ground conditions will be expensive and incidents will become more likely. There are also logistical concerns tied to changing ground conditions. Much of the Russian oil and gas industry depends on frozen ground conditions for construction. As a result, it may become logistically challenging to maintain construction routines in warmer conditions. These factors could lead to movement away from pipelines to shipping and trucking petroleum products.

Since most of the oil and natural gas produced in Russia is transported via pipeline, an increase in system failures and ensuing capacity reduction could reduce energy security in Russia and dependent countries.

Pipeline gas is much cheaper than liquified natural gas, so if Russia is unable to continue supplying pipeline gas at low costs, import-dependent countries may turn to other countries for natural gas. In addition, the transition to shipping would make for less permanent ties between Russia and the countries it supplies to than those created by pipelines. If countries that currently rely on Russian piped gas diversify their gas supplies, Russia would lose political and economic leverage in those regions.

In any scenario, permafrost thaw will make oil and gas transport more expensive, which could be a major stressor to the Russian economy and affect global pricing.

The potential climate change impacts on the Russian oil and gas industry could increase emissions and environmental impacts in several ways. First, increased shipping rates on the Northern Sea Route would likely result in higher greenhouse gas emissions, including black carbon, which has an especially strong climactic effect in the Arctic (Yumashev et al., 2017, Makarova et al., 2022, Evans et al., 2017). The increase in emissions could create feedback to accelerate subsidence related to climate change. An increase in pipeline accidents could also have disastrous environmental effects. Methane leaks in Russian pipelines are already a large contributor to global emissions, and increased stress on pipelines could worsen the situation (IEA, 2021). An increase in pipeline failure rate and proximity to thermokarst lakes from permafrost thaw pose a compounded threat for widespread contamination.

These broader implications are especially pertinent now, as the Arctic warms twice as fast as the rest of the world and Russia has plans to significantly expand resource extraction in the Arctic by 2035 (Klimenko, 2020). They also highlight the importance for additional research that links changing physical systems and human systems. In the future, we would like to use similar probabilistic methods to link permafrost change with other types of infrastructure. We would also like to look at how other climate impacts, like river erosion and flooding may impact pipelines. Lastly, we plan to use integrated assessment modeling to see long-term developments that changing pipeline costs or capacity in the Arctic may have on global markets and emissions.

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7.0 Annex

7.1 Annex A. Predictive models used to substantiate subsidence thresholds

We used predictive models developed by Wols and Van Thienen to support empirical estimates that a range of ground subsidence heights 5 cm – 25 cm could trigger a pipeline replacement event (Wols and Van Thienen, 2014). The Wols and Van Thienen model was originally developed to predict failure rates in buried drinking water networks due to climate change induced soil settlement. We adjusted the parameters to match the characteristics of Russian oil and gas transmission pipelines.

Wols and Van Thienen (2014) developed a parametric function to approximate differential soil settlement profiles induced by climate change. The parametric model intakes maximum settlement and characteristic transition length between different soil types. If the characteristic transition length input is smaller, the settlement occurs over a shorter distance, and vice versa. Transition length is largely variable. They assume a total transition length of 2-60 m. Equation S1 and Figure S1 below show the parametric model and resulting settlement curve when total settlement length = 10 m, and maximum vertical settlement = 0.05 m.

$$S_v(x) = -0.5S_{max} \left(1 + \operatorname{erf}(-x/(i\sqrt{2})) \right) \quad (\text{Equation S1})$$

Where S_{max} = maximum settlement,

i = characteristic of transition length between different soil types.

The settlement profile generated by Equation S1 is shown below.

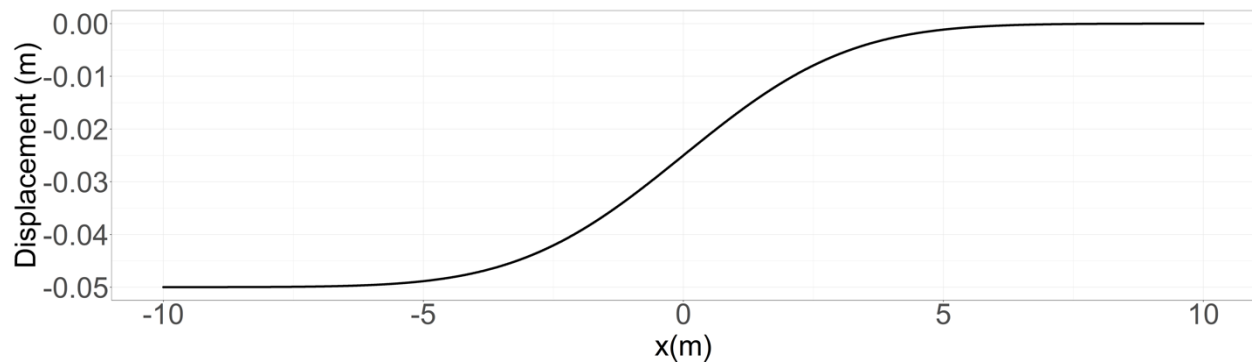


Figure S1. Soil settlement profile generated by equation 1, $i = 2.5 \text{ m}$, $S_{max} = .05 \text{ m}$.

Wols and Van Thienen derived an analytical model from the differential settlement profile, which also intakes the selected pipeline's material and geometric properties to estimate the bending stress-induced. The model is shown below in Equation S2.

$$\sigma_{p,max} = EM_{norm}(\exp(-1/2)S_{max}D)/(i^2\sqrt{8\pi}) \quad (\text{Equation S2})$$

Where $\sigma_{p,max}$ = maximum stress in the pipe,

E = Young's Modulus of pipeline material,

M_{norm} = pipe maximum bending moment normalized to the situation where pipe matches ground displacement. For cases where pipe movement matches ground movement, $M_{norm} = 1$,

S_{max} = maximum settlement,

D = pipe diameter,

i = transition length = ¼ of total transition length.

From there, Wols and Van Thienen estimate that if $\sigma_{p,max}$ exceeds the pipeline's yield stress, failure occurs. Yield stress is the amount of stress that causes permanent deformation, the pipeline is assumed to fail.

$$Z = \sigma_f - \sigma_{p,max} \quad (\text{Equation S3})$$

Where σ_f = yield stress of pipe material

If $Z < 0$, failure occurs.

Inputs to equation S1 were set to match the range of settlement heights thought to cause damage to pipelines and a range of plausible soil transition lengths. Inputs to equations S2 and S3 were set to match characteristics common in Russian oil and gas pipelines. Young's Modulus is a material property that describes the elasticity.

Russian pipelines are made of steel, which typically has a Young's Modulus of 200 GPa. Most Russian transmission lines have a diameter of 1420 mm, so the diameter was set at 1420 mm. According to Russia's major pipeline producer, the United Metallurgical Company, Russian transmission lines are made of X80 steel. X80 steel has a yield stress of 550 MPa (UMC, N/A), so yield stress was set accordingly. It was assumed that pipelines conform to ground movement, so M_{norm} was set to 1. The models and selected inputs were used to predict pipeline stresses induced by 5 cm, 10 cm, and 25 cm over a range of characteristic settlement transition lengths.

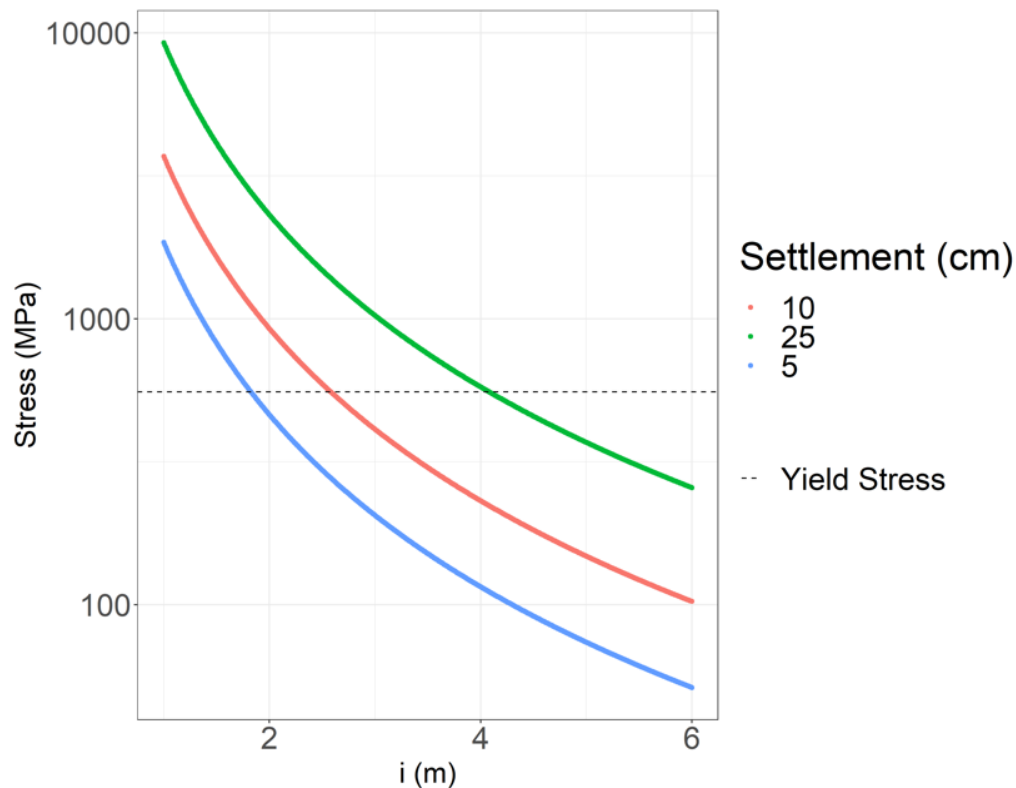


Figure S2. Stress predictions vs transition length for settlement heights of 10 cm, 25 cm, and 5 cm.

When calculated stress is above the dotted line, which represents yield stress, we assume pipelines require replacement. Figure S2 demonstrates that the likelihood of pipeline failure is driven not only by settlement height but also transition length. Shorter transition lengths produce more stress in pipelines. Settlement height of 5 cm is likely to cause overstressing in pipelines when $i \leq 1.82$ m (transition length less than 7.28 m). Settlement height of 10 cm is likely to cause overstressing in pipelines when $i \leq 2.57$ m (transition length less than 10.28 m). Settlement height of 25 cm is likely to cause overstressing in pipelines when $i \leq 4.07$ m (transition length less than 16.28 m). These results suggest that settlement heights of 5, 10, and 25 cm could induce failure in pipelines, especially in combination with compounding stressors such as corrosion, temperature differentials, and pipeline age.

7.2 Annex B. Russian cost estimates

We used project costs from pipelines recently built in the Russian Arctic, Bovanenkovo-Ukhta and Zapolyarye-Purpe, to come up with alternative replacement cost estimates based on Russian costs.

Bovanenkovo-Ukhta I and II pipelines transport natural gas from the Yamal Peninsula to the Russia Unified Gas system (Gazprom, 2021a). Construction on the 2,112 km pipeline system began in 2008 and was completed in 2014. Reported construction costs for Bovanenkovo-Ukhta I and II were 37.1 billion in 2020 USD. The reported project cost also includes nine compressors, each of which is 32 MW in capacity (Gazprom, 2021a). Since costs associated with compressor stations are not included in our analysis, we estimated pipeline construction costs without compressor stations. According to *Oil and Gas Journal*, the average cost for a compressor in 2020 was 3,206,379 USD/MW (O&GJ, 2020). We used that information to estimate the cost of compressor stations. Then we subtracted the costs of compressor stations from the entire project cost and then divided them by pipeline length. The resulting pipeline construction cost was 16.3 million USD/km in 2020 dollars. Calculations are summarized below.

Total project cost = 37.1 billion USD

Compressor stations cost = 9 compressor stations $\times$ 32 MW/station $\times$ 3,206,379 USD/MW = 923 million USD

Pipeline construction cost = 37.1 billion USD $-$ 923.4 million USD = 36.1 billion USD

Pipeline construction cost per km = 36.1 billion USD / 2112 km = 16.3 million USD/km

According to Transneft Investment Report, construction of the Zapolyarye-Purpe pipeline, not including pumping stations and other facilities, cost 133,769 million rubles in 2016 (Transneft, 2016). The 485 km pipeline was built in 2016. After converting to cost per km and 2020 USD, the reported construction cost of the pipeline is 4.5 million USD/km.

7.3 Annex C. Approximations for the potential costs associated with other types of oil and gas infrastructure

To come up with an estimate for the potential costs of replacing gathering lines damaged by permafrost thaw, we estimated the length of gathering lines located on permafrost and multiplied that by American cost estimates for gathering lines and an Arctic cost multiplier of 5. According to (Mazur and Ivantsov, 2004) there are 265,000 km of oil gathering lines in Russia, which we multiplied by 0.17, since approximately

17% of Russian oil production occurs in the Arctic. According to the American Petroleum Institute, the cost for a 2-inch gathering line was 45,363 USD/km.

Cost of oil gathering pipelines = 265,000 km oil gathering lines $\times$.17 $\times$ 45,363 USD/km $\times$ 5 = 10.2 billion USD

7.4 Annex D. Additional results from uncertainty analysis

Numerical values for gas pipeline replacement cost estimates are provided in Table D1. The fourth column combines all sources of uncertainty to get minimum and maximum estimates. For comparison, in 2019, the estimated value of oil produced in Russia was 272 billion USD and the estimated revenues from natural gas in Russia in 2019 were 71 billion USD.

Table D1. Gas pipeline replacement cost estimates calculated with low, central, and high different sources of uncertainty. Permafrost projections are the largest contributor to uncertainty.

	Permafrost projection (5 th , mean, 95 th percentile)	Cost multiplier (3, 5, 7)	Replacement threshold (25 cm, 10 cm, 5 cm)	Combined
Low (USD, billions)	44	62	14	4.0
Central (USD, billions)	100	100	100	100
High (USD, billions)	350	150	290	1100

Table D2. Oil pipeline replacement cost estimates calculated with low, central, and high different sources of uncertainty. Permafrost projections are the largest contributor to uncertainty.

	Permafrost projection (5 th , mean, 95 th percentile)	Cost multiplier (3, 5, 7)	Replacement threshold (25 cm, 10 cm, 5 cm)	Combined
Low (USD, billions)	0	5.3	0	0
Central (USD, billions)	8.9	8.9	8.9	8.9

High (USD, billions)	28	12	24	92
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