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Analysing Migration Trends in the Arctic Region Through Data-Driven Simulation

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Abstract

Adopting a recently developed technique, Agent-Based Modelling (ABM), this paper aims to make estimations on the linkage between environmental crises and migration trends in Arctic regions. However, such a task requires setting a firm ground reflecting the real-world social complexities. Thus, the Artic region is divided into three as Alaska, Nordic and Russian Arctic. Then, all the values used in simulations are aligned with real world empirical data most of which are chosen among reports which are recently published. Then, an overarching category called 'environmental stress' including the melting ice rate, sea ice extent, temperature trend and permafrost loss. Also, the turtles (meaning the individuals living in these areas) are differentiated based on their socio-demographic variables such as annual income levels, age, gender and education levels. Also, by adding the inflow migration rates to the Arctic regions and governments measures against environmental crises into account, a comprehensive and rigorous simulation setting is designed. The ABM technique captures how individual actions and interactions lead to complex, emergent system-wide patterns that are not always predictable from the starting conditions or simple aggregation of behaviours. As such, by operating sensitivity testing to the parameters and working on varied scenarios, the model enabled the research make future estimations. The results show that moderate migration outflows from Russia and Alaska by 2050, with the situation becoming more severe by 2070–2100. However, the Nordic Arctic will remain relatively stable due to stronger governance and adaptation, but even this region will see some migration due to warming temperatures and sea ice loss. This results underscores the need for a sort of 'multi-level governance' approaches that combine local adaptation with global mitigation strategies especially for regions lacking socio-economic resources such as the Russian Arctic.

Keywords: Simulation, Agent-Based Modelling, Arctic, Migration

Veriye Dayalı Simülasyon Yoluyla Arktik Bölgesindeki Göç Eğilimlerinin Analizi

Özet

Bu çalışma kapsamında Ajan Tabanlı Modelleme (ABM) olarak bilinen ve son zamanlarda geliştirilen bir teknik benimsenerek, Arktik bölgelerde çevresel krizler ile göç eğilimleri arasındaki bağlantı araştırılmıştır. Bu durum, gerçek dünyadaki sosyal karmaşıklıkları yansıtan sağlam bir zemin oluşturmayı gerektirdiğinden, çalışma kapsamında Arktik bölgesi; Alaska, İskandinav ve Rus Arktik olmak üzere üçe ayrılmıştır. Simülasyonlarda kullanılan tüm değerler, yakın zamanda yayımlanan raporlar arasından seçilen gerçek emprik veriler kullanılarak hazırlanmıştır. Ayrıca, 'çevresel stres' olarak adlandırılan ve eriyen buzul oranları, deniz buzu kapsamı, sıcaklık eğilimi ve permafrost kaybı gibi değerleri içeren kapsamlı bir kategori oluşturulmuş ve simülasyonlarda kullanılmıştır. Daha gerçekçi sonuç elde etmek amacıyla, simülasyon kapsamındaki 'turtles' (bu alanlarda yaşayan bireyler), yıllık gelir seviyeleri, yaş, cinsiyet ve eğitim seviyeleri gibi sosyo-demografik değişkenler ile farklılaştırılmıştır. Aynı zamanda, Arktik bölgelere gelen göç oranları ile hükümetlerin çevresel krizlere karşı önlemleri göz önünde bulundurularak kapsamlı ve titiz bir simülasyon ortamı tasarlanmıştır. ABM tekniği, bu araştırmaya, bireysel eylemlerin ve etkileşimlerin her zaman tahmin edilemeyen karmaşık sonuçlarına ulaşmayı sağlamıştır. Bu nedenle, parametrelere duyarlılık testi uygulanarak ve çeşitli senaryolar üzerinde çalışılarak, geleceğe yönelik tahminler yapılmıştır. Simülasyon sonuçlarına göre, 2050 yılına kadar Rusya ve Alaska'dan orta düzeyde göç çıkışlarının gerçekleşeceği ve durumun 2070-2100 yılları arasında daha da şiddetleneceği belirlenmiştir. Ancak, daha güçlü önlemler ve adaptasyon nedeniyle İskandinav Arktik bölgesinin nispeten daha istikrarlı kalacağı, ancak yine de ısınan sıcaklıklar ve deniz buzu kaybı nedeniyle bir miktar göç göreceği tespit edilmiştir. Bu sonuçlar, özellikle Rus Arktik bölgesi gibi sosyoekonomik kaynaklardan nispeten daha yoksun bölgeler için, yerel sorunları küresel düzeyde azaltma stratejileriyle birleştiren 'çok seviyeli müdahale' yaklaşımına yönelik ihtiyacını vurgulamaktadır.

Anahtar Kelimeler: Simulasyon, Ajan Temelli Modelleme, Arktik, Göç

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1. Introduction

Climate change is increasingly recognized as a significant driver of global migration. It involves long-term changes in temperature, precipitation patterns, and natural disasters, with severe consequences for human populations. The Intergovernmental Panel on Climate Change (IPCC) identifies climate fluctuations as major contributors to migration, a finding supported by extensive research on the impact of environmental changes (Piguet, Kaenzig, & Guélat, 2018). In 2022 alone, 32.6 million people were displaced due to environmental disasters, accounting for 53% of all global internal displacements (IMDC, 2022; IDMC, 2023). Common triggers of these displacements include temperature escalation, irregular precipitation, and extreme weather events like wildfires, tsunamis, and hurricanes, which disrupt livelihoods and social structures, forcing people to seek safety and stability.

Arctic temperatures are rising four times faster than in lower latitudes (Rantanen et al., 2022; Wadhams, 2017), leading to permafrost thaw, rising sea levels, diminishing sea ice, and extreme weather. These changes threaten the sustainability and livelihoods of Arctic communities, likely resulting in population displacement or relocation. Given these challenges, simulating migration trends in Arctic regions is crucial for understanding how environmental shifts are altering the socio-economic landscape (Piguet et al., 2018). As sea ice retreats and permafrost thaws, traditional livelihoods and infrastructure are becoming less viable, leading to population displacement (Schuur et al., 2015). Accurate simulation models are essential for predicting future migration flows and informing policymakers about the socio-economic impacts of climate change in the Arctic.

This paper addresses the need for such simulations, particularly in integrating real-world data into models specific to the Arctic. It is structured as follows: the next section details the research design and simulation setup, focusing on key prerequisites. The third section integrates empirical data into the simulation, covering demographic, environmental, and socio-economic variables. It also explains the coding procedures used to align real-world data with the simulation. The following section presents the simulation results, and the final section discusses the validity of the findings and their implications for real-world scenarios.

This paper is structured as follows; the subsequent section sets the ground for explaining how the simulations are designed in order to fully cover the research problem at stake. The section highlights key pre-requisites for the research design. The third section focuses on integrating empirical data into the simulation analysis. It first provides the real-world data regarding demographic, environmental and socio-economic variables; after that; the paper delves into the coding procedures that are designed to calibrate the real-world data with the simulation codes. The section also elucidates how the migration decision making process is calculated by the collision of different variables so that the complexity of individuals' migration decisions could be obtained. In the penultimate section, the paper gives the results of simulations. The final section both discusses the validity of the results and provides comprehensive discussions regarding how these results could translate into real life scenarios.

2. Conceptual Framework

The main question being researched is how climate change affects migration patterns in Arctic communities. In order to obtain the most realistic and scientifically rigorous results, certain steps must be taken in regards to the conceptual framework of the analysis. This section highlights the key dimensions of the conceptual framework that ground the simulations. First and foremost, it is crucial that all simulations are calibrated using real-world data to ensure the most accurate and realistic outcomes. Integrating real-world data into simulations is critical for the validity and reliability of the model, as it grounds it in empirical evidence. This alignment allows for a more realistic representation of environmental, socio-economic, and demographic factors that influence migration patterns and responses to climate change in the Arctic. Additionally, this will enhance the predictive power of the model. Simulations that closely reflect actual conditions are better able to forecast future trends, providing insights into how populations may respond to worsening environmental stressors, such as rising temperatures, sea ice loss, and permafrost thaw. These predictions are valuable for policymakers and researchers, enabling them to make more informed decisions regarding climate adaptation and migration planning. By comparing the simulated outcomes with actual data from the past or present, we can assess the accuracy of the model and adjust it if necessary. This ongoing calibration process improves the robustness of the model and ensures that it remains a reliable tool for understanding the complex dynamics at play in Arctic migration.

First, it is essential that all simulations are calibrated with the real-world data to ensure the most accurate and realistic results. Integrating the real-world data to our simulations are critical in terms of validity and reliability of the model. It ensures the accuracy and reliability of the simulation results by grounding the model in empirical evidence. This alignment allows for a more realistic representation of environmental, socio-economic, and demographic factors that influence migration patterns and responses to climate change in the Arctic. Also, this will strengthen the predictive power of the model. Simulations that closely mirror actual conditions can better forecast future trends, providing insights into how populations might respond to worsening environmental stressors such as rising temperatures, sea ice loss, and permafrost thaw. These predictions are valuable for policymakers and researchers, enabling more informed decisions regarding climate adaptation and migration planning. By comparing the simulated outcomes with actual historical or current data, we can assess the model's accuracy and adjust it as necessary. This process of continuous calibration improves the model’s robustness and ensures it remains a reliable tool for understanding the complex dynamics at play in Arctic migration.

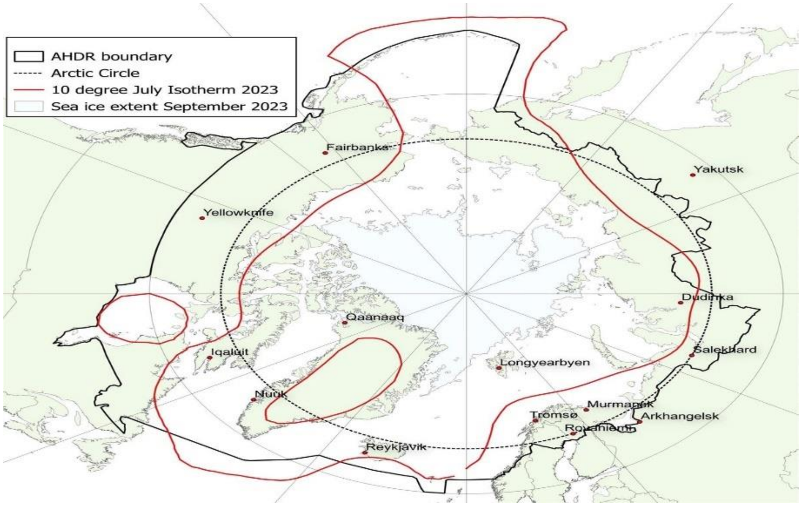

Figure 1. Definition of Arctic Regions

Source: Vitikka (2023).

Secondly, the Arctic is not a homogeneous region, either geographically or socio-economically. To capture this complexity, the area has been divided into three distinct regions: Alaska, the Nordic Arctic, and the Russian Arctic, based on real-world indicators (see Figure 1 above). All simulations account for this categorical division.

Socio-economically, the Arctic regions differ greatly in terms of population density, economic activities, infrastructure, and governance. For example, Alaska has a relatively high standard of living, with major industries such as oil, fishing, and tourism, supported by U.S. infrastructure and economic policies. In contrast, the Russian Arctic is characterized by remote, industrial towns heavily reliant on mining and oil extraction, facing distinct socio-economic challenges such as limited infrastructure and lower income levels. The Nordic Arctic, which includes parts of Norway, Sweden, Finland, and Iceland, is defined by well-developed social welfare systems, higher incomes, and more robust climate adaptation policies.

Third, environmental risks in the Arctic extend beyond ice melt. A comprehensive category of ‘environmental stress’ should be developed, encompassing factors such as temperature trends, sea-ice extent, ice melt rates, and permafrost degradation. Ice melt alone does not capture the full scope of climate challenges in the Arctic. Including temperature trends, sea-ice extent, and permafrost degradation offers a more holistic understanding of how interconnected environmental changes impact the region.

Fourth, the response of individuals living in different Arctic regions to environmental stress, and their mobility decisions, are influenced by socio-economic factors such as employment rates, income levels, and the cost of living specific to each region. Socio-economic conditions vary greatly across Arctic regions, and these factors play a critical role in shaping how individuals react to environmental threats, as populations with fewer resources may have limited options for adapting or migrating.

Fifth, focusing solely on out-migration from Arctic regions is incomplete without also considering inflow migration rates and trends from other parts of the world. Migration patterns are dynamic and bi-directional, so understanding how new populations may relocate to the Arctic is essential for analysing long-term demographic shifts and economic impacts in the region.

Finally, to generate meaningful scenarios, simulations should also incorporate governmental interventions aimed at mitigating environmental issues such as ice melt, temperature increases, and permafrost loss. This will allow for a more comprehensive examination of environmental stress in Arctic populations. Government policies and interventions have a direct influence on how regions adapt to climate change, and their inclusion in simulations allows for the exploration of different adaptive strategies and outcomes for Arctic populations.

3. Integrating Real-World Data to the Model

For making the simulations more valid incorporating the real-world conditions is vital. In order to reach that aim, this research took some steps. That is; in order to have the realistic simulation results, it is needed to create the agents (population in the simulation) aligned with the real-world data. As mentioned earlier, I differentiate the Nordic Arctic, Russian Arctic and Alaska in terms socio-demographical features. After compiling statistics from multiple sources, as each region has distinct characteristics and data is often collected by individual countries, I reached the real-world data as shown below.

3.1. Demographic data

In Alaska, the median age in Alaska is around 35 years (2020 U.S. Census). Rural areas tend to have a younger population due to higher birth rates in Indigenous communities. The male-to-female ratio in Alaska is around 52% male to 48% female, with a more significant male presence in rural and industrial regions. About 93% of Alaskans aged 25 and older have a high school degree, while around 29% have a bachelor's degree or higher (U.S. Census Bureau). In terms of the income levels, the median household income in Alaska is around $77,000 (2020 Census). Rural regions tend to have lower incomes than urban areas like Anchorage. In the Russian Arctic, however, population is aging, with a median age of around 40–45 years. Remote regions often have younger populations due to ongoing industrial activities (Rosstat, Russian Federal Statistics Service). There is a significant gender imbalance, with males often constituting around 55% or more in regions where industrial activities like mining dominate. Higher education levels are concentrated in urban areas (Murmansk, Norilsk), with around 24% of people having tertiary education (OECD). Wages are often higher than national averages in the industrial sectors, with median incomes varying between 45,000–70,000 rubbles per month (~$500–$800), depending on the region and sector (Rosstat). Finally, the median age across the Nordic Arctic tends to range from 38 to 45 years, with Finland generally having an older population. There is an aging trend in remote areas (Nordregio, 2020). Unlike other Arctic areas, the gender balance in the Nordic Arctic is approximately equal, with a slight male majority in rural regions where fishing and resource extraction are prevalent. The Nordic Arctic has high education levels. Around 30-40% of the population has completed tertiary education, especially in urban areas like Tromsø (Nordregio). When it comes to the average annual income, it is generally higher than the European average, ranging from €30,000 to €50,000 depending on the country (Nordregio, OECD, 2020).

3.2. Environmental data

The environmental data is aligned with the real-world environmental rates so that the simulation can create the realistic results. As such, environmental variables included the temperature trend, sea ice extent, melting ice rate and permafrost loss for each part of the designated Arctic areas (Alaska, Nordic and Russian Arctic). For Alaska, the temperature trend, over the past 50 years, has warmed at twice the rate of the global average, with an increase of about 2-3°C since the 1970s. The most significant warming has occurred during winter months, with some regions experiencing a rise of up to 4°C. The Bering Sea, which impacts Alaska's coastal areas, has seen a marked decline in sea ice coverage. Sea ice extent in the region has decreased by about 40% in the last three decades (NSIDC, 2021). Glaciers in Alaska are retreating rapidly, with some regions, such as the Juneau Icefield, losing over 25 meters of ice thickness per year. Alaskan glaciers contribute significantly to global sea-level rise, adding around 0.1 mm per year. As for the permafrost loss, warming temperatures are causing rapid permafrost thaw in Alaska. The permafrost in some regions is thawing at depths of up to 0.5 meters per decade, which is leading to ground subsidence and increased CO2 and methane emissions (NSIDC, 2021).

Second, the real-world environmental data used for simulating the Russian Arctic, it is one of the fastest-warming regions globally, with an average temperature increase of about 3-5°C in some areas over the past 50 years. The Siberian Arctic, in particular, has seen the sharpest rise in temperatures (IPCC, 2021). The Russian Arctic is experiencing significant reductions in sea ice, especially in the Barents and Kara Seas. Between 1979 and 2020, the summer sea ice extent in this region has decreased by approximately 50%, impacting marine ecosystems and shipping routes (NSIDC, 2021). The Russian Arctic glaciers have lost around 10-15% of their mass since the 1980s. The largest losses are observed in the Novaya Zemlya archipelago, where glacier retreat is accelerating due to both atmospheric and ocean warming (WWF, Russian Arctic Report, 2020). Permafrost degradation is particularly rapid in the Russian Arctic, where the active layer (seasonally thawed) has increased by 10-20% in depth since the 1970s. These thawing releases large amounts of methane and is causing infrastructural damage in areas like Norilsk and Yakutsk (Russian Academy of Sciences, 2021).

Finally, the environmental data for Nordic Artic (Norway, Sweden, Finland, and Iceland) shows that the area has warmed by about 2°C since the early 20th century, with northern Norway, Sweden, and Finland seeing a temperature increase of around 1.5-2.5°C. Winter temperatures in Svalbard have increased by 4-7°C over the last 50 years (Nordic Council of Ministers). The Nordic Arctic is heavily influenced by sea ice dynamics in the Barents Sea and the Greenland Sea. Since the late 1970s, the Arctic Sea ice extent during the summer has decreased by around 40% in these regions, contributing to the reduced seasonal sea ice cover (NSIDC, 2021). Glaciers in Iceland, Norway, and the Svalbard archipelago are retreating at increasing rates. Iceland's glaciers have shrunk by about 12% since the 1990s, and the melting trend is accelerating, contributing to rising sea levels (Icelandic Meteorological Office, 2020). Permafrost in the Nordic Arctic is thawing at a slower rate than in Siberia or Alaska, but significant degradation is occurring, particularly in Svalbard and northern Sweden. The active layer has increased by 10-30 cm in some areas, leading to ground instability (Nordregio, 2020).

3.3. Socio-economic data

For the simulation gets the best realistic results, this research used some real-world socio-economic data. We determine three variables which are employment rates, income levels and cost of living for Alaska, Nordic and Russian Arctic populations. First, Alaska's employment rate fluctuates due to its reliance on seasonal industries like tourism and fishing. As of 2022, Alaska had an unemployment rate of around 4.5% (U.S. Bureau of Labor Statistics), slightly higher than the national average. Employment is concentrated in resource extraction (oil, gas), government services, and tourism. The median household income in Alaska is about $77,000 per year (U.S. Census Bureau, 2020). There is significant variation between urban centers like Anchorage and rural or Indigenous areas, where incomes can be much lower. Alaska has one of the highest costs of living in the U.S., largely due to its remote location and high transportation costs. Goods and services are 28-30% higher than the national average, with housing, groceries, and utilities being particularly expensive (Alaska Department of Labor, 2021).

Second, the employment rate in the Russian Arctic varies greatly depending on the specific region. Industrial regions like Murmansk and Norilsk have relatively low unemployment rates (around 3-5%) due to ongoing mining and oil industries. However, more remote areas may have higher unemployment, reaching 10-12% (Rosstat, 2021). The average income in the Russian Arctic tends to be higher than the national average, particularly in industrial hubs. Monthly wages range between 45,000 to 70,000 rubles ($500–$800 USD), with some areas offering higher wages due to the harsh working conditions (Rosstat, 2021). However, remote areas without major industries may have lower income levels. The cost of living in the Russian Arctic is significantly higher than in other parts of Russia, especially due to transportation costs. In some regions, the cost of basic goods is 1.5 to 2 times the national average. For example, food prices are notably higher due to the expense of shipping (WWF Russian Arctic Report, 2020).

Finally, the employment in the Nordic Arctic is generally high, with unemployment rates averaging 3-4% in Norway, Sweden, and Finland. Iceland's unemployment is typically lower, around 2-3%, but varies seasonally (Nordregio, 2021). Key industries include fishing, tourism, energy production, and public services. Income levels in the Nordic Arctic are relatively high. In Norway, the average annual salary is around €50,000, while in Sweden and Finland, it's between €35,000 and €45,000. Iceland's average salary is around ISK 7 million (€45,000) per year (Nordregio, 2020). The Nordic Arctic has one of the highest costs of living in the world, particularly in Norway and Iceland. Housing, food, and utilities are expensive due to high taxes and transportation costs. For example, groceries can cost up to 30% more than in mainland Europe (Nordregio, 2021).

4. Creating the Simulation Procedure

In line with the data highlighted above, agent attributes, economic variables, environmental variables and migration decision making procedures were configured. In the simulation, the average age for agents is set around 35 years with a normal distribution. This is based on the demographic data for Arctic regions, where populations are generally younger in industrial and Indigenous areas (Alaska) and older in regions like the Nordic Arctic (e.g., Finland, Norway) (U.S. Census Bureau, 2021; Rosstat, 2021; Nordregio, 2021). As for gender, A simple 50-50 male-to-female ratio was applied, although in some regions like Alaska, males outnumber females slightly due to male-dominated industries (oil and gas, fishing) (U.S. Census Bureau, 2021; Nordregio, 2021; Rosstat, 2021).

When it comes to the education and income levels, the education levels were assigned based on general education statistics for each region. For example, in Alaska and Nordic countries, a significant portion of the population has tertiary education, while in Russia, there is a higher prevalence of secondary and vocational education (U.S. Census Bureau, 2021; Rosstat, 2021; Nordregio, 2021). The income levels for each region were assigned based on regional data:

- Alaska: Average income in Alaska is approximately $77,000 per year (U.S. Census Bureau, 2021).

- Russian Arctic: Income in industrial regions such as Murmansk and Norilsk ranges from $50,000 to $70,000 USD annually (Rosstat, 2021).

- Nordic Arctic: Average incomes in Nordic countries like Norway, Sweden, and Iceland are around €50,000 ($55,000–$60,000 USD) (Nordregio, 2021).

The Employment rates were based on real-world statistics. For Alaska, around 95% employment rate (4.5% unemployment) (U.S. Bureau of Labor Statistics, 2022) while for Russia employment is higher in industrial hubs, leading to a 90% employment rate in the Arctic (Rosstat, 2021). Finally in Nordic Arctic, employment is generally high, with around 96% of the population employed (Nordregio, 2021).

As for the environmental factors, the temperature trend values are based on scientific reports highlighting the warming in Arctic regions:

- Alaska: Temperatures have risen by about 3°C over the last few decades (NOAA, 2021).

- Russia: The Russian Arctic has seen a rise of around 4°C (IPCC, 2021).

- Nordic Arctic: Temperature increases have been around 2.5°C, with Svalbard seeing particularly strong warming (NOAA, 2021; Arctic Council Reports, 2021). The sea ice extent which shows the proportion of ice in Arctic seas are also differentiated in accordance with the three different Arctic areas. The percentage decrease in sea ice is based on long-term observations. For Alaska, sea ice extent in the Bering Sea has decreased by about 40% (NSIDC, 2021). For Russian Arctic, the Barents and Kara seas have seen a 50% reduction in sea ice (WWF, 2020). Nordic Arctic, the Greenland and Barents Seas have experienced a 40% reduction in sea ice (NSIDC, 2021; NOAA, 2021).

Also, permafrost loss rates reflect observed thawing: In Alaska, Permafrost is thawing at a rate of about 0.5 meters per decade (University of Alaska Fairbanks, 2021). In Russia, thawing is faster, with permafrost loss at 0.7 meters per decade (IPCC, 2021). In Nordic Arctic regions, permafrost thawing is slower at around 0.3 meters per decade (IPCC, 2021).

Income values used in the simulation reflect the real-world income levels in each Arctic region, as detailed above under "Agent Attributes" (U.S. Census Bureau, 2021; Rosstat, 2021; OECD, 2021; Nordregio, 2021). The employment rate values are consistent with real-world data from the U.S., Russian, and Nordic government statistics (U.S. Bureau of Labor Statistics, 2022; Rosstat, 2021; Nordregio, 2021). Although not explicitly modelled as an attribute in the initial code, the cost of living is implied in the decision-making process. Arctic regions typically have higher living costs due to transportation and heating expenses (Alaska Department of Labor, 2021; Russian Government Reports, 2021; Nordregio, 2021).

4.1. Migration decision-making procedure

The migration decision making process is far from simplistic explanations, mostly with a variety of factors involving in. This research created a complex variable called the environmental stress based on the real-world data of the temperature trend, sea ice loss and permafrost loss. These environmental factors increase steadily over time, contributing to the overall ‘environmental stress level’. The stress level is calculated as the average of the temperature trend, sea ice loss, and permafrost loss. As these values increase, the likelihood of agents (turtles) deciding to migrate or die increases. The environmental stress level is examined by the plots on the Interface (See Figure 2, Below).

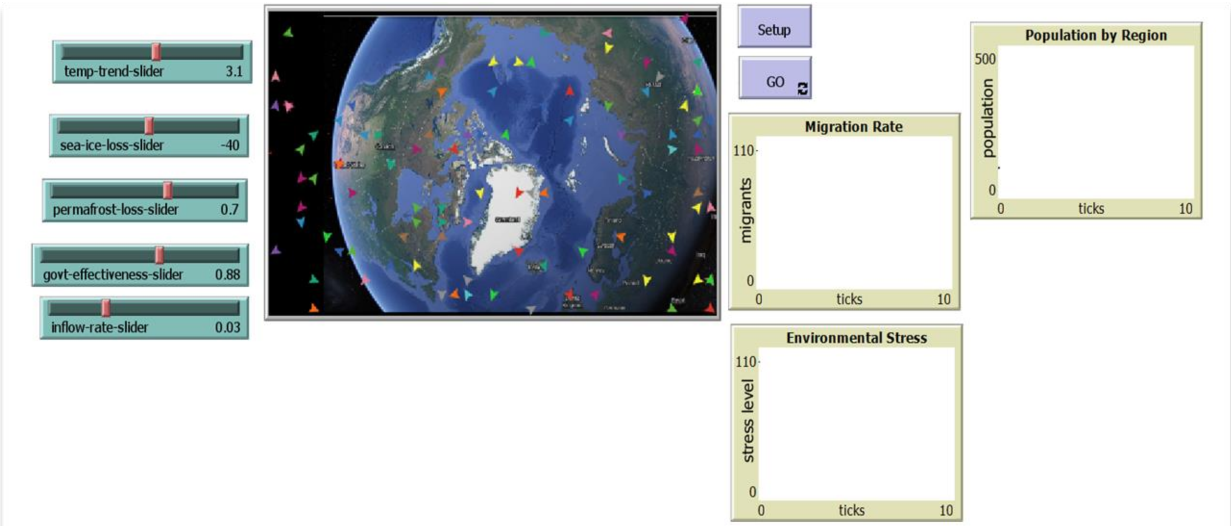

Figure 2. Interface of the Simulation

Government Intervention: This procedure mimics the levels of measures taken against the environmental crises happening in Arctic regions. Periodically, the simulation applies government intervention to mitigate environmental stress. The intervention adjusts temperature trends, sea ice loss, and permafrost loss based on the ‘government effectiveness variable’, which simulates how well the government handles the environmental crisis. If government effectiveness is high, it slows down environmental deterioration, reducing the push for migration. The government effectiveness is examined the slider called ‘govt-effectiveness-slider’ on the Interface, which allow the researcher to work on different scenarios (see image Above).

Economic factors also crucial element of migration decision making procedure of the simulation. Each agent is assigned an income level based on the region they belong to (Alaska, Russia, or the Nordic Arctic). Their economic well-being is represented by income, and whether they are employed or not. The economic pressure an agent feels is determined by their income: the lower the income, the higher the pressure to migrate. Agents calculate economic pressure based on their income. The formula used is:

let economic-pressure 1 - (income / 100000)

This means that agents with higher incomes experience less economic pressure to migrate. Also, environmental pressure is based on the overall stress level, which is calculated from the environmental factors (temperature trend, sea ice loss, permafrost loss). The higher the stress, the more likely agents are to migrate. This is represented by:

let environmental-pressure stress-level / 100

The likelihood of an agent deciding to migrate is based on the combination of economic and environmental pressures:

let migration-chance (economic-pressure + environmental-pressure) / 2

4.2. The complexity of migration trends

Migration decisions is complex; in order to get the complexity, agents make migration decisions based on two main pressures: economic and environmental. As environmental stress increases due to factors like rising temperatures, sea ice loss, and permafrost thawing, agents face higher chances of migrating or even dying if conditions become too severe. Government interventions can reduce this stress and slow the outflow of migration. Conversely, regions become less attractive to new migrants as stress increases, thus reducing inflow migration. This migration model allows this research to simulate the impact of climate change and economic factors on human migration in Arctic regions, while also factoring in government efforts to mitigate environmental crises. The code block of the migration decision and the death threshold due to environmental and economic crises are explained below.

a) Death Threshold: If the environmental pressure exceeds a certain threshold (0.5 or 0.7), the simulation increases the probability that an agent will decide to migrate or, in extreme cases, die. This introduces a critical risk of death if the environmental conditions become too severe, as represented by the following:

```
if environmental-pressure > 0.7 [
if random-float 1 < 0.4 [ ; Higher death chance under more stress
die
```

If the agent's calculated ‘migration chance’ is greater than a random number between 0 and 1, the agent will migrate:

```
if random-float 1 < migration-chance [
let new-region one-of regions
move-to-region new-region
```

b) Inflow migration: It is simulated periodically based on the environmental stress level. As the stress increases, the inflow migration rate is reduced, meaning fewer new agents (migrants) will arrive in the region when environmental conditions worsen. This simulates the idea that harsh environmental conditions make regions less attractive to newcomers:

```
if stress-level > 100 [
set adjusted-inflow-rate inflow-rate * 0.05
]
```

c) Migration to a New Region: When an agent decides to migrate, it moves to a random patch within a new region (Alaska, Russia, or the Nordic Arctic). The procedure for migrating agents to a new region ensures that they only relocate to valid regions within the simulation world:

```
let target-patch one-of patches with [region-name = new-region]
if target-patch != nobody [
move-to target-patch
]
```

5. Simulation Results

Based on scientific data and climate change projections, the simulation shows moderate migration outflows from Russia and Alaska by 2050, with the situation becoming more severe by 2070–2100. However, the Nordic Arctic will remain relatively stable due to stronger governance and adaptation, but even this region will see some migration due to warming temperatures and sea ice loss. Government interventions will play a key role in reducing outflows, especially in wealthier regions, but environmental stress will ultimately drive long-term population reductions across the Arctic.

5.1. Environmental Stress

The environmental factors (temperature trend, sea ice loss, permafrost loss) increase by 0.5 units per year (tick). By the year 100 (i.e. 100 ticks), the environmental stress level is projected to rise to 100 units. By year 200 (200 ticks), the stress level reaches its maximum cap of 200 units, reflecting extreme environmental conditions where most regions experience catastrophic temperature increases, total sea ice loss, and severe permafrost thawing.

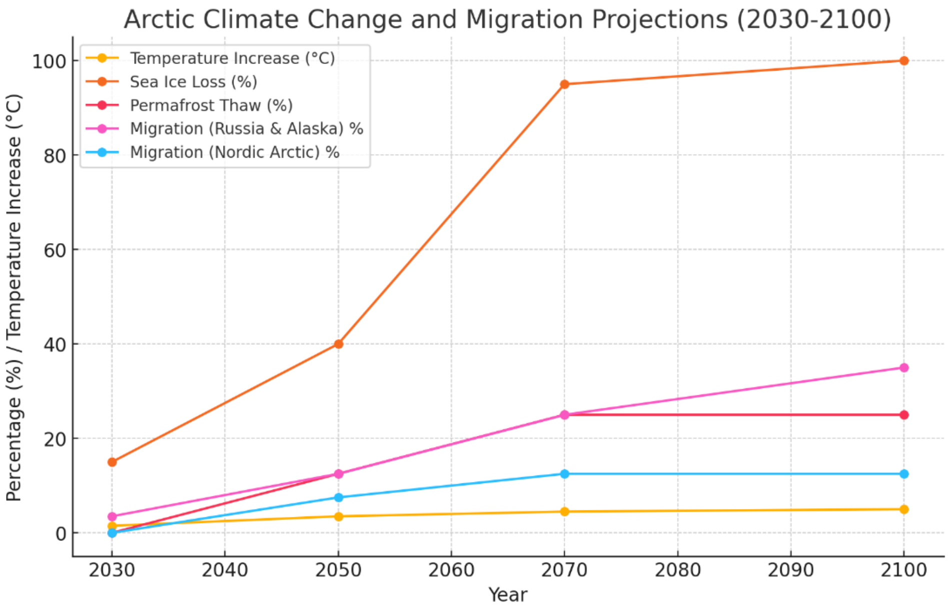

Figure 3. Simulation Results

What the results of the simulations would mean for real-world can be explained by touching upon the projections of temperature trends, sea ice loss and permafrost thawing. First, the Arctic is warming four times faster than the global average. According to estimates of this re, Arctic temperatures are projected to rise by 4–5°C by the end of the 21st century (2100). Arctic sea ice is expected to decline by 30–50% by mid-century (2050) and may experience ice-free summers by 2040–2060. Our results estimate that 25% of near-surface permafrost will thaw by 2100 under current warming scenarios, with significant losses in permafrost stability by mid-century.

5.2. Population decline in Alaska, Nordic and Russian Arctic Regions

The Russian Arctic, particularly Siberia, is already seeing increased outmigration from permafrost zones, and according to the results of the simulations, the situation is expected to worsen as climate-induced infrastructure failures continue. By 2050, it is possible that 10–20% of the population in these regions could relocate, especially from permafrost-affected areas. At the year 50, Russia begins to experience moderate environmental stress (stress level of around 50). At this point, the population begins to decline slightly due to both economic pressure (lower incomes) and early signs of environmental degradation. We estimate a 10-20% reduction in population due to migration and death. At the year 100, Russia's environmental stress level reaches around 100 units, significantly increasing migration outflows and mortality. We estimate that 30-40% of the population will have left the region or died. At the year 150, the environmental stress level exceeds 150 units, and Russia faces critical levels of outflow migration and mortality. At this point, 50-60% of the population could have either migrated or died. At the year 20, by the end of the simulation period, Russia faces near-total depopulation, with an estimated 80-90% of the population either migrating to other regions or dying due to severe environmental conditions

When it comes to Alaska and Nordic Arctic regions, at the year 50, both Alaska and the Nordic Arctic experience moderate stress levels (around 50 units). Population levels remain relatively stable due to higher incomes and the initial influx of migrants. The estimated population decline is limited to 5-10%. In year 100, by this point, stress levels in Alaska and the Nordic Arctic rise to around 100 units, prompting increased migration outflows. Population decline could reach 20-30% by this time, as environmental conditions begin to outweigh economic advantages. In the year 150, with stress levels approaching 150 units, migration outflows accelerate, and fewer migrants move into these regions. Population declines could reach 40-50%. In year 200, by the end of the simulation period, Alaska and the Nordic Arctic face similar stress levels as Russia, with population reductions estimated at 50-70%.

Thus, Alaska is projected to see increased migration outflow from Indigenous and rural communities due to environmental threats like coastal erosion, permafrost thaw, and the loss of infrastructure. However, urban migration to Alaskan cities may still occur due to higher economic opportunities. By 2050, it is estimated that up to 5–10% of the population in rural and coastal areas may relocate due to environmental changes. In regions like Norway, Sweden, and Finland, the Nordic Arctic is expected to remain more stable due to stronger economic conditions and better governance. However, some localized migration could occur from vulnerable areas such as Svalbard, where ice melting and warming are particularly severe. By 2050, migration outflow could be moderate, affecting 5–10% of the population in particularly vulnerable regions.

5.3. Inflow migration decline

At Year 50 in the simulation, inflow migration plays a crucial role in maintaining population stability, particularly in Alaska and the Nordic Arctic regions. During this period, 20-30% of the population in these areas consists of new migrants, making regions like the Nordic Arctic relatively attractive destinations for migration. However, as environmental stress levels gradually rise, the conditions become less favorable. By Year 100, when stress levels reach 100 units, inflow migration drops significantly, reducing to just 5% of its original rate. At this point, new migrants make up only a small fraction of the population, and migration inflows begin to taper off. By Year 150 and beyond, inflow migration becomes almost negligible as high environmental stress makes all regions unattractive for newcomers, causing population growth from migration to cease.

6. Discussions and Conclusion

The simulations suggest that government interventions can temporarily reduce environmental stress and slow population decline, particularly in the first 50–100 years. However, these interventions become less effective by year 150, as environmental degradation overwhelms mitigation efforts. This is consistent with real-world studies, which indicate that while adaptation strategies, such as improved infrastructure and disaster preparedness, can temporarily protect populations, they cannot fully prevent the long-term impacts of climate change (Nordic Council of Ministers, 2019). For instance, the Nordic countries have been praised for their proactive climate adaptation policies, including investments in renewable energy, infrastructure upgrades, and climate-resilient agriculture (IPCC, 2019). These policies have helped stabilize populations in the face of climate challenges. However, even these regions are not immune to the long-term effects of climate change. As temperatures continue to rise, Arctic regions will experience increased permafrost thaw, sea ice loss, and coastal erosion, limiting the effectiveness of local adaptation measures. A recent study estimates that by 2050, up to 70% of infrastructure in permafrost regions could be at risk, even with adaptation efforts (Shiklomanov et al., 2019). This aligns with the simulation's projection that by year 150, government interventions will no longer be sufficient to prevent mass migration and population decline.

This finding highlights the need for 'multi-level governance' approaches that combine local adaptation with global mitigation strategies. Without aggressive global action to reduce greenhouse gas emissions, adaptation alone will not be enough to protect Arctic populations from the severe impacts of climate change. The simulation results underscore the importance of integrating local adaptation policies with global climate policies, emphasizing the need for international cooperation to reduce emissions and limit long-term damage. The results also have important implications for global migration patterns and international policy. As Arctic regions become increasingly uninhabitable due to climate change, migration outflows will put additional pressure on neighbouring regions and countries. For example, the Nordic countries may face increased migration from Russia and Alaska, which could strain public services and create political tensions over resource allocation. This is consistent with findings from the World Bank, which suggests that climate-induced migration can lead to social tensions and resource conflicts in receiving areas, particularly if governments are unprepared for large-scale migration (World Bank, 2018).

The coding procedures developed in this research are highly adaptable, allowing for reuse, reconfiguration, and improvement in future studies, particularly in simulating migration flows in response to environmental crises such as global warming and earthquakes. The modular design of the code ensures that components like environmental variables—such as temperature trends, permafrost loss, and sea ice extent—can be easily replaced or adapted to new contexts, including seismic activity or rising sea levels. This flexibility enables the foundational code to be applied to various environmental and social crises without the need to rebuild the model. Additionally, the model's scalability allows for its application to broader geographic areas or global migration scenarios by integrating new datasets and socio-economic indicators. The code can be expanded to simulate larger regions or study migration responses to coastal erosion, for example. Furthermore, as new environmental and socio-economic data become available, the model can be updated to maintain its scientific relevance and rigor.

The model also offers opportunities for simulating the effects of policy interventions by adjusting variables related to government responses, allowing researchers and policymakers to explore how adaptation measures or disaster relief programs could influence migration outcomes. Beyond these applications, the model can be improved by incorporating machine learning algorithms for more accurate predictions and extending the simulation to account for social network effects, which would deepen insights into collective migration behaviours. In conclusion, the coding framework is highly flexible, making it a powerful tool for future research on migration patterns in response to diverse environmental challenges.

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