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Spatial Permeability of Finnish Russian border

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Current geopolitical climate in European Union land border is volatile amid Russian hybrid influence operations. There have, for example, been attempts at using migrants to destabilize border control measures of European Union member states. This has led to a closure of official border stations and temporal cease in handling of visa applications by Finnish authorities in Finnish Russian border. Regardless of the border closure, an elevated risk of illegal attempts to cross the border remains. While the authorities are monitoring the border area and preventing illegal crossings, it is important to have an understanding of spatial permeability along the border.

Spatial permeability of Finnish Russian border was studied in 40-kilometer buffer area around the border line. Refined land cover data along with slope degrees and locations of border stations were used to produce friction layers that illustrate spatial permeability in the study area. Two scenarios were studied, the former considering effects of land cover and slope data, and the latter combining these with the locations of border stations. Friction layers were used for cost distance and cost pathway analyses, and optimal routes for border crossing were calculated from 10 towns in Russia to 13 destination towns in Finland.

Results show that dense road networks in southern border areas effectively facilitate human mobility in otherwise challenging environments, while in the north the rural nature of the landscape combined with longer travel distances and lack of road networks acts as a barrier that decreases spatial permeability. Optimal paths across the border mostly used secondary roads to get close to the border and traverse short distances of less than a kilometer on either forests, grasslands or croplands to cross the border line. Spots of crossing the border line were mostly located in areas where secondary roads were closest to each other on both sides of the border, leaving the shortest possible distances to be covered on other less suitable land cover types.

Key words: Spatial permeability, border security, migration, hybrid influencing

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Euroopan Unionin vihreän rajan tilanne on muuttunut epävakaammaksi geopoliittisten jännitteiden kiristyttyä Venäjän harjoittamien hybridivaikutusoperaatioiden vuoksi. EU:n maarajalla on nähty esimerkiksi yrityksiä horjuttaa jäsenvaltioiden rajavalvontaa, mikä on Suomen ja Venäjän rajalla johtanut rajan väliaikaiseen sulkuun sekä matkustusasiakirjojen tarkistuksen lopettamiseen. Riski laittomiin rajanylityksiin on silti pysynyt korkeana. Viranomaiset valvovat aktiivisesti rajaa ja pyrkivät estämään laittomat rajanylitykset, mutta kattava tilannekuva raja-alueen läpäistävyydestä on tärkeää.

Tämä pro gradu -tutkielma käsittelee Suomen ja Venäjän maastorajan spatiaalista läpäisevyyttä 40-kilometrin puskurialueella rajan ympärillä. Tutkielmassa on käytetty jalostettua maanpeiteaineistoa, rinnekaltevuusmallia sekä raja-asemien sijainteja tuotettaessa kitka-aineistoja, jotka kuvastavat tutkimusalueen spatiaalista läpäisevyyttä. Analyysissä on käyty läpi kaksi skenaariota, joista ensimmäinen sisälsi maanpeite- ja rinnekaltevuusaineiston, ja jälkimmäinen yhdisti näihin raja-asemien vaikutuksen. Tuotettuja kitka-aineistoja käytettiin kustannus-etäisyys- sekä kustannus-reittianalyyseihin, joiden perusteella määritettiin optimaaliset reitit 10 venäläisen ja 13 suomalaisen taajaman välillä.

Tutkielman tulokset näyttivät, että tiheät tieverkot eteläisillä raja-alueilla edesauttavat ihmisten liikkumista muutoin haastavissa ympäristöissä. Pohjoisessa syrjäisyys, pitkät etäisyydet ja harvempi tieverkosto taas vaikeuttavat maantieteellisessä tilassa liikkumista ja vähentävät raja-alueiden läpäisevyyttä. Optimaaliset reitit kulkivat pääosin sivuteitä pitkin rajan läheisyyteen, jossa ne ylittivät rajan kulkemalla lyhyitä, alle kilometrin pituisia matkoja metsien, ruohikoiden tai viljelysmaiden läpi. Rajanylityskohdat olivat pääosin alueilla, joissa sivutiet rajan molemmilla puolilla olivat verrattain lähimpänä toisiaan, jolloin vähemmän läpäistävillä maanpeitteillä kuljettava matka oli mahdollisimman lyhyt.

Avainsanat: Spatiaalinen läpäisevyys, rajaturvallisuus, muuttoliike, hybridivaikuttaminen

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1 Introduction

Safeguarding the national borders and maintaining border security is an important part of each well-functioning society. In Finland, the responsibility of upholding the border security has been allocated to Finnish Border Guard by the Border Guard Act (Border Guard Act, 578/2005). Among others, Finnish Border Guard's legal duties include surveillance tasks of borders, prevention of crimes, as well as measures that aim to prevent crimes before they have taken place. Further definitions of the crimes in the context of border areas have been given in the Criminal Code 39/1889, amended by the Criminal Code 146/2014, which defines that border offences include, for example, crossing the border without an authorized travel document, visa, residence permit or other document equivalent to a travel document. In addition, unauthorized presence or movement in a border zone is defined as a state border offence. The same law also defines organizing illegal entry as a crime against public order. Active border surveillance is one of the main ways in which the Border Guard is carrying out its statutory obligations regarding prevention of crime and, where necessary, intervening illegal activities by the means provided by law.

During the recent years, there have been significant changes in the security environment of the European region, not least because of the rise in the number hybrid operations amid geopolitical tensions between Russia and European Union. Intentional and deliberate compromising of border security is one of the means of hybrid influencing, which is aimed at affecting the national security of the targeted state to create political pressure and to foster general disorder among the population. Humans are one of the key components of hybrid operations and they can be used as a means of hybrid influencing in a variety of ways. Means of hybrid influence include, among others, disinformation campaigns, which aim to manipulate public opinions to apprehend certain agenda, or to foment general disorder and polarization. Humans can also be used in hybrid operations in the form of instrumentalized migrants. In this kind of procedure, large numbers of migrants are directed or forced into the border zone of the target country, with an aim to overload or completely cripple the ability of a targeted country to maintain law and order in its border areas. Organized instrumentalization of migrants as a means of hybrid pressure has been identified as a concrete form of hybrid influence by the Ministry of the Interior (Sisäministeriö, 2025), European Union and NATO. A recent example of hybrid operations is the Polish Belarusian border crisis of 2023, when the Belarusian border authorities organized large numbers of migrants to the border area separating Poland and Belarus. It has also been noted that Russia has increased its hybrid operations, especially against NATO member states. Finland shares a long land border with Russia, most of which is in sparsely populated areas, making it difficult to carry out comprehensive and active border control. Finland has also recently had to close its border crossing points with Russia because of the threat of hybrid operations.

The means of countering hybrid operations include active maintenance of situational awareness, as well as preventative actions, that are based on up-to-date information about the operating environment. Therefore, scientific research into the border areas is considered an important way to provide valuable information about the areas in question. In the field of geographic information sciences, one of the interesting research topics is spatial permeability of national borders, which has been studied by various actors in the European region. In this context, spatial permeability indicates physical possibility of crossing national borders, according to a pre-defined criterion. Regarding previous studies of the topic, criteria usually consider the possibility of crossing the border area on foot. Additionally, in some cases the possibility of crossing the border zone undetected (i.e. without being seen or caught by the border guards or other authorities) has been studied as well. In 2006, European Commission's Joint Research Centre (JRC) conducted research, in which a model of spatial permeability of European Union's 25-member state's land border (green border) had been produced (Stephenne & Pesaresi, 2006). This article has served as a basis for several similar studies, for example at a more local level in a Ukrainian city of Uzhhorod (Stephenne et al. 2008). Permeability of the Polish Ukrainian border has been studied in a similar manner, considering both individuals' ability to walk and stay hidden during an attempt to cross the border (Malinowski, 2010).

Individuals' walking speeds and optimal paths have been studied by estimating slope degrees, vegetation density and terrain roughness using LIDAR data (Campbell et al. 2024). They created a model estimating average travel rates on different surfaces and compared their findings to field experiment data, where they had participants walk short distances on different terrain types. Using the model, they produced least-cost paths in a case study of a mountainous area in Alta, Utah to compare them with least-cost paths produced with models that solely relied on slope data. Using LIDAR data to assess least-cost paths was seen as an adequate method as the paths produced by the studied model were deemed more realistic and accurate regarding travel rates than the ones produced by models relying only on slope data.

Finnish Russian green border can be viewed as a relevant research topic, because of the recently heightened threat of hybrid operations against the Finnish state, as well as current geopolitical environment. Regarding these qualities of the contemporary security environment, it is possible to produce actual significant and valuable new information about current state of the border zone, which enables sufficient allocation of resources into areas where they are most needed. Public research on the topic is also relatively outdated, since most of it was conducted over 10 years ago, and therefore, additional research is needed (Stephenne et al. 2006 & Malinowski, 2010). It is possible, however, that spatial permeability has been studied by private organizations, and that the studies conducted have not been published because of the need for discretion with the research areas. In addition, research of the topic so far has not sufficiently considered the effect of seasonal variabilities for spatial permeability of borders, a factor that notably affects different parts of the Finnish Russian border zone because of its sheer length and north-south orientation, especially when compared to other national borders along European Union green border. My goal is to consider seasonal variabilities of border permeability by using summer, winter, and spring flood seasons and their characteristics when evaluating the variables in this thesis. Each of the seasons have their unique characteristics, which I'm trying to quantify with land cover values of different seasons.

The main aim of this MSc thesis is to study spatial permeability of Finnish Russian border zone, applying similar approach as Stephenne et al. (2008). In existing public research, border zones separating two countries have been studied on a same, more local scale, but so far there has not been a public study that has focused specifically on the green border between Finland and Russia. Methodologically, this study approaches the topic with the basic assumption that an adult individual with average physical capabilities has, for an unknown reason, decided to cross the border zone illegally on foot. Two separate methodological approaches are studied. The first solely focuses on physical permeability, i.e. the possibility to walk across space, and the latter includes the assumed effect of border surveillance stations. Therefore, permeability of the border is a combination of the geographical and the presumed surveillance characteristics of the area. Spatial permeability of border areas is a very interesting topic from the viewpoint of geographic information science, for example, because the contemporary spatial datasets allow more precise analysis with raster data.

In this thesis, I am looking to answer the following research questions:

1. How physically permeable is Finnish Russian border in a hybrid influencing scenario during different times of a year, with or without increased border control measures.
2. What are the most potential routes for illegal crossing when assessing pathways from the potential sources of travel from Russia to the assumed preliminary destinations in Finland.
3. How suitable are the chosen geospatial data and methods regarding the spatial permeability analysis.

My goal is to answer the first research question with the friction layer analysis, while answers to the second question are derived from the cost pathway analysis. I will be using land cover and slope datasets by ESA with OpenStreetMap national data to produce raster layers with friction values describing spatial permeability of the study area. Additionally, I will map location of border control stations to examine their effect paired with physical permeability.

2 Theoretical framework

2.1 Border permeability

Border permeability can generally be defined as a degree at which national borders allow or facilitate cross-border interactions. According to Varol & Söylemez (2017) these interactions can be attributed to the flow of commodities, capital, people, and information across borders. They described that border permeability is regulated by political entities, while cross-national commerce usually acts as a conduit to increased permeability. They have stated that cross-border cooperation consists of four permeability domains, i.e. economic, social, spatial and political of which economic permeability refers to economic metrics, such as trade flows, cross-national investment, foreign direct investment, etc. Social permeability is characterized by the level at which populations of the neighboring countries interact with each other. In most cases, this can be measured by population density within certain distance of the border. Political permeability is understood as border control measures, level of visa regulations and national security posture. Spatial permeability in the article has been defined as consisting of spatial characteristics like slope, natural and human-made barriers, as well as facilitating infrastructures (road and rail networks).

Spatial permeability has been studied by Stephenne & Pesaresi (2006) who defined spatial permeability in more detailed manner as the easiness of crossing the border area on foot, which is determined by weather, land cover, and infrastructural characteristics. Their study also considered an additional aspect of spatial permeability, namely, individuals' ability to hide while walking across the border area, a variable depending on land cover suitability to hide, human settlements, nighttime lights, and slope degrees. However, in this thesis the definition of spatial permeability only considers physical permeability, with an added effect of border stations.

2.2 Research on border permeability

In general, there seems to be very little public research on border permeability, perhaps because of the sensitive nature of the topic. Permeability research methods vary between broader studies using mathematical indexes to illustrate permeability of different aspects of the borders (Deutschmann et al. 2023), to spatial permeability studies using geospatial methods to create spatial permeability maps that quantitatively describe spatial permeability pixel by pixel

(Stephenne et al. 2006). Additionally, different aspects that affect permeability of borders, i.e. walking speeds on different terrains (Xie et al. 2024) and environmental effects on human mobility (Richmond et al. 2019) have been studied before.

Deutschmann et al. (2023) have studied permeability of nation-state borders broadly on global level with a creation of border permeability index, which is calculated using an equation that combines effects of border length, transport infrastructure, border checkpoints, and border enforcement. Here, permeability of national borders has been linked to the existing transport infrastructure and political checkpoints, finding that permeability index is linked to population density and economic level of development of the area.

Varol & Söylemez (2017) have studied border permeability in Turkish and EU border region by considering economic, social, spatial, and political domains of permeability. They have stated that cross-border cooperation programs, usually in economic domain are increasing permeability, while geopolitical tensions work in the opposite way. It has also been underlined that non-governmental organizations, municipalities and businesses are the driving factors of cooperation, and supranational entities and national policies usually act as regulators of this cooperation. It has been stated that economic permeability of Turkish Bulgarian border is higher than with Greece, while socio-cultural permeability is higher in Turkish Greek border. This observation has been, however, partly explained by different characteristics of spatial permeability between the border regions.

Spatial permeability of border regions has been previously studied by the Institute for the Protection and Security of the Citizen in European Commission’s Joint Research Centre (JRC) (Stephenne & Pesaresi, 2006). In the study, spatial permeability of EU25 land border was examined. The study area encompassed the land border separating Norway and Russia in the north, to Slovenia-Croatia border area in the south, along with the separate Greek border further south. Spatial permeability modelling is based on various geographical variables that are considered to affect permeability of land border areas. Methodologically, the study considers a scenario, where “a standard adult person having illegal behavior” has decided to cross the land border on foot. The scenario has been approached in three separate categories, which, firstly assess the walkability of the border zone, secondly a person’s ability to hide in their environment in the border zone, and third the probability of a person getting caught by the authorities while crossing the border. Geospatial research methods used in this study include fuzzy scaling, weighted linear combination and multi-criteria evaluation to combine various datasets to friction layers that described land area permeability. Additionally, Boolean and weighted overlays have been used to combine datasets into composite friction layers. The resulting datasets are raster layers, which indicate the permeability of the EU25 land borders in the three categories. Later, border permeability model was applied to global and local settings, and related data processing specifications for both settings were provided (Stephenne & Zeug, 2008). Study conducted on local level focused on the city of Uzhorod, which is located in the vicinity of the border between Slovakia and Ukraine. The main difference on local level is that a slightly fewer number, but higher resolution datasets have been used in spatial permeability analysis, than on regional or global level.

Spatial border permeability of the Polish Ukrainian border has been studied in a similar manner, applying the previous JRC permeability model for the case study of Polish Ukrainian border (Malinowski, 2010). In this study, the surveillance category of the JRC study has been secluded and the two other categories have been combined into an overall border permeability model. While JRC permeability study has applied fuzzy scaling for data classification, Malinowski has standardized datasets of his study by a reclassification of values into 5 classes.

An anonymous, local level border area has been studied as a part of research presented at the Joint Intelligence and Security Informatics Conference in 2014. The study has contributed to the EUROSUR system, developed by Frontex to increase border management capabilities of the European Union’s member states (Broek et al., 2014). A critical basis for the EUROSUR system is a Common Pre-Frontier Intelligence Picture (CPIP), which has been produced in a permeability risk analysis by considering spatial variables that affect the risk of border area in the light of illegal cross-border activities. The permeability analysis by JRC has been used as a methodological background for the analysis. However, the research has added to the original border permeability model in the JRC study by using very high resolution (VHR) raster data for analysis, and considering the aspect of surveillance more thoroughly, for example, by including assessments of the experts when evaluating the impact of different spatial variables in the study area. Additionally, the potential density of migrants on the border has been assessed, based on calculations about migrants’ expected movements in the so-called Pre-Border Zone (PBZ), which refers to an area in the vicinity of the actual border zone. The resulting border permeability model is therefore more sophisticated, refined to the local setting, and the results can be applied when planning the regional security and surveillance operations.

2.3 Effects of terrain variabilities on human movement

Different terrain types (land cover classes) significantly affect human ability to move across different geographical areas. Kowalsky et al. (2021) have examined effects of five different surface types on metabolic energy expenditure of humans in outdoor setting. Respirometers, inertial measurements units, and GPS data were used to determine how energy costs of walking along with foot paths varied between sidewalk, dirt, gravel, grass, and woodchip terrains. They found that woodchip terrain was the most energy consuming to traverse, while sidewalks were the easiest to walk on.

Campbell et al. (2024) introduced a STRIDE model to estimate walking travel rates in both on-path and off-path terrains. The model is based on mathematical equations and uses LIDAR data to predict travel times based on slope degrees, vegetation density, and surface roughness. Least-cost paths derived from the model have been described as more realistic and safer than the ones produced by models that solely use slope data. The authors have also observed that paths produced by their model were approximately 1.5 times longer than those of slope-only models. Results of the study have been cross validated with field experiments using human participants, as well as by comparison with crowdsourced datasets, showing an average error of less than 16 percent with predictions.

Both Xie et al. (2024) as well as Finnis and Dalton (2008) have studied the ways in which different environmental factors affect individual’s average walking speed. Both studies have observed an average walking speed of approximately 5 kilometers per hour on a level surface, with significant decreases on uphill slope degrees. Conversely, slight increases in walking speeds have been observed when walking downhill in gentle slope degrees. Xie et al. (2024) have studied the effects of 0-, 3-, 7-, 12-, 17- and 22-degree slope angles on walking speeds of 48 university students of which half were females and half were males. It should be noted that participants in the study were relatively young (21.52 years on average). Finnis and Dalton (2008) used field observations to study pedestrian walking speeds of 1847 individuals in Auckland and Palmerston North in New Zealand, observing significantly faster average walking speeds with commuters that regular civilians. They also observed increased walking speeds on milder slopes with degrees less than 6, and decreased speeds on steeper slope with degrees over 7.

Kafetzakis et al. (2024) have similarly studied effects of varying slope degrees on spatiotemporal gait parameters (i.e. step lengths, step widths, foot rotations, step times, and cadence), vertical ground reaction forces, and stances. The study was conducted on a treadmill that was adjusted to degrees of 0%, +10%, +20%, -10%, and -20% to examine uphill and downhill effects on varying walking speeds. They found that walking uphill reduces step lengths, cadence and causes increased foot rotations, while walking downhill increased step width and cadence, among other variations. Researchers have attributed most of the variations to individuals seeking to control their postures and energy consumption, while trying to minimize the risk of slipping or injuring themselves in different slope degrees.

Obuchi et al. (2021) studied human walking speeds, step lengths and cadence on different seasons, attempting to find connections between temperatures and human mobility. Using smartphone tracking, the study was conducted in Japan with over 15209 participants and various age groups. They found that average walking speed and cadence increased during mild temperatures in winter compared to warmer conditions during summer, indicating that temperatures may influence human ability to move in outdoor spaces.

Metabolic cost of walking over snow-covered terrain has been studied by Richmond et al. (2019) who presented a new terrain coefficient to improve predictions of energy consumption. Terrain coefficient considers sinkage of snow, depending on snow layer’s physical attributes, such as depth and density. The authors have mainly attributed human energy expenditure to snow depth, density, slipperiness and carrying capacity, describing that metabolic rate increases exponentially with higher sinkage into snow cover. Additionally, it has been concluded that walking speed decreases with increased sinkage.

2.4 Geospatial methods

Weighted overlay is one of the methods for multi-criteria evaluation, using multiple datasets to produce an output that is based on weighted criteria. In general, multi-criteria analysis is used to study suitability, susceptibility or risks related to the subject matter, for example, susceptibility of a border area to be crossed illegally, as is a case in this thesis. The method combines multiple raster layers with assigned weights to produce an output raster layer. This means that if a layer has a weight of 1 in weighted overlay analysis, its values in the output are based on the layer’s original values. However, if a layer has a weight of 0.5, its original values weight 50 percent relative to the layer's original values in the overlay analysis. Weighted overlay has been used as a part of analytical hierarchy process to determine suitable sites for large-scale photovoltaic projects in Peru (Rios & Duarte, 2021), as well as to map optimal locations for solar and wind power plants in Colombia while considering social aspects of power plant production (Bernal-del Rio et al. 2025).

Cost-distance is a GIS analysis tool provided by WhiteboxTools geospatial data analysis platform (Lindsay, 2017). Cost-distance tool is used to produce accumulated cost surfaces from source raster cells. In this thesis, this means an accumulated cost of traveling from the determined source points in Russia (i.e. the source cities and towns) to each other raster cell in friction surfaces. Source points were marked in separate raster files as single pixels with a value of 1, while other pixels had value of 0. In addition to the cost-accumulation surfaces, cost-distance analysis produces back-link rasters of cost-accumulation surfaces that are used in cost pathway analysis to determine least-cost paths. Back-link rasters contain directional values that are based on cost-accumulation layers, describing cost of travel between neighboring raster cells. The algorithm producing the back-link raster works similarly to flow accumulation procedure, using priority-flood method to allocate directional travel costs based on cost-accumulation values.

2.5 Legislative framework in Finland

In Finland, maintaining of border security has been a task assigned to Finnish Border Guard (in finnish. Rajavartiolaitos) by legislation, as stated in section 3 of the Border Guard Act (Border Guard Act 578/2005). The article states that "To perform this duty, the Border Guard cooperates with other authorities, communities and residents. The Border Guard is responsible for the cooperation with the European Border and Coast Guard Agency and engages in international cooperation pertaining to its duties. The Border Guard performs, in cooperation with other authorities, surveillance duties separately provided by law, and actions to prevent, detect and investigate offences and to refer them for consideration of charges". This definition of the legal obligations of the Border Guard is crucial as it provides the basis for why the Border Guard operates. Additionally, the Border Guard Act provides guidelines for Finnish Border Guard and its operational principles, an example of which is the Principle of Least Harm. Finally, the

Border Guard is obligated to provide official assistance to other Finnish authorities and participate in military defense.

Section 7 of the Criminal Code defines a state border offence as follows:

1) crossing or attempting to cross the border or Finland without a valid travel document, visa, residence permit, or other document equated with a travel document, or doing so elsewhere than through a valid point of entry or departure, or in violation of a statutory prohibition other an entry ban,
2) otherwise violating the provisions on border crossing, or
3) staying, moving, or undertaking of measures in the border zone in violation of section 51 of the Border Guard Act or without a permit required under section 52 of the Act

Here, it should be specified that section 51 of the Border Guard Act describes restrictions related to the border zone, for example, construction of structures and movement of people, and section 52 lists activities, which are subjected to a permit in the border zone, namely: staying; moving in border waters in daytime and moving in the border strip; building structures closer than 50 meters to the borderline; possessing firearms, ammunition, explosives and spring-operated weapons; using the articles and substances referred to in paragraph 4; excavating earth and mineral aggregates and searching for minerals closer than 20 meters to the borderline. Additionally, section 8 of the Criminal Code defines Articles regarding facilitation of illegal entry and aggravated facilitation of illegal entry.

Section 29 (9/2019) of the Border Guard Act separately defines framework for technical monitoring in border control. The section defines technical monitoring and how it is conducted by the Border Guard. It specifies the limitations for technical monitoring in private areas and describes the conditions for installing surveillance equipment. Section 29a (28.6.2024/429) gives specifications on radio-technical surveillance, for example, tracking of mobile devices in the vicinity of the border region.

3 Data and methods

3.1 Study design

This thesis approaches spatial border permeability by considering both the physical aspects of permeability and the presumed effects of increased border control measures. The studied scenarios are centered around the physical permeability of the Finnish Russian border; however, they also consider some elements that can be assumed to be present in the event of Russian hybrid influencing operation. In the event of Russian hybrid influencing, there is naturally an increased risk of illegal border crossing attempts by migrants that Russia has instrumentalized for their hybrid operations. In these scenarios migrants are often pushed to the official border crossing stations in masses to overwhelm the target country's capabilities to enforce their borders, or to completely destabilize the border. This act has usually caused the target country to close its border temporarily, as happened with Finnish Russian border after the last Russian hybrid operation in autumn of 2023. The border crossing stations have been closed ever since, however, there was a period in which the stations were reopened and closed again after the hybrid influencing continued. This led to a situation where numerous migrants stayed in towns near the border to wait for the official border crossing stations to reopen. It is this prolonged stay of migrants near the border region that is expected to lead to an increased risk of attempts at illegal border crossing and is therefore considered in this thesis by the selection of border towns as sources of travel in the pathway analysis (Figure 1). The selection was made to reflect the presumed realistic places from where the migrants would begin their journey when attempting to cross the border without using the official border crossing stations. Additionally, the destinations were picked to reflect the preliminary end points of travel in Finland after crossing the border.

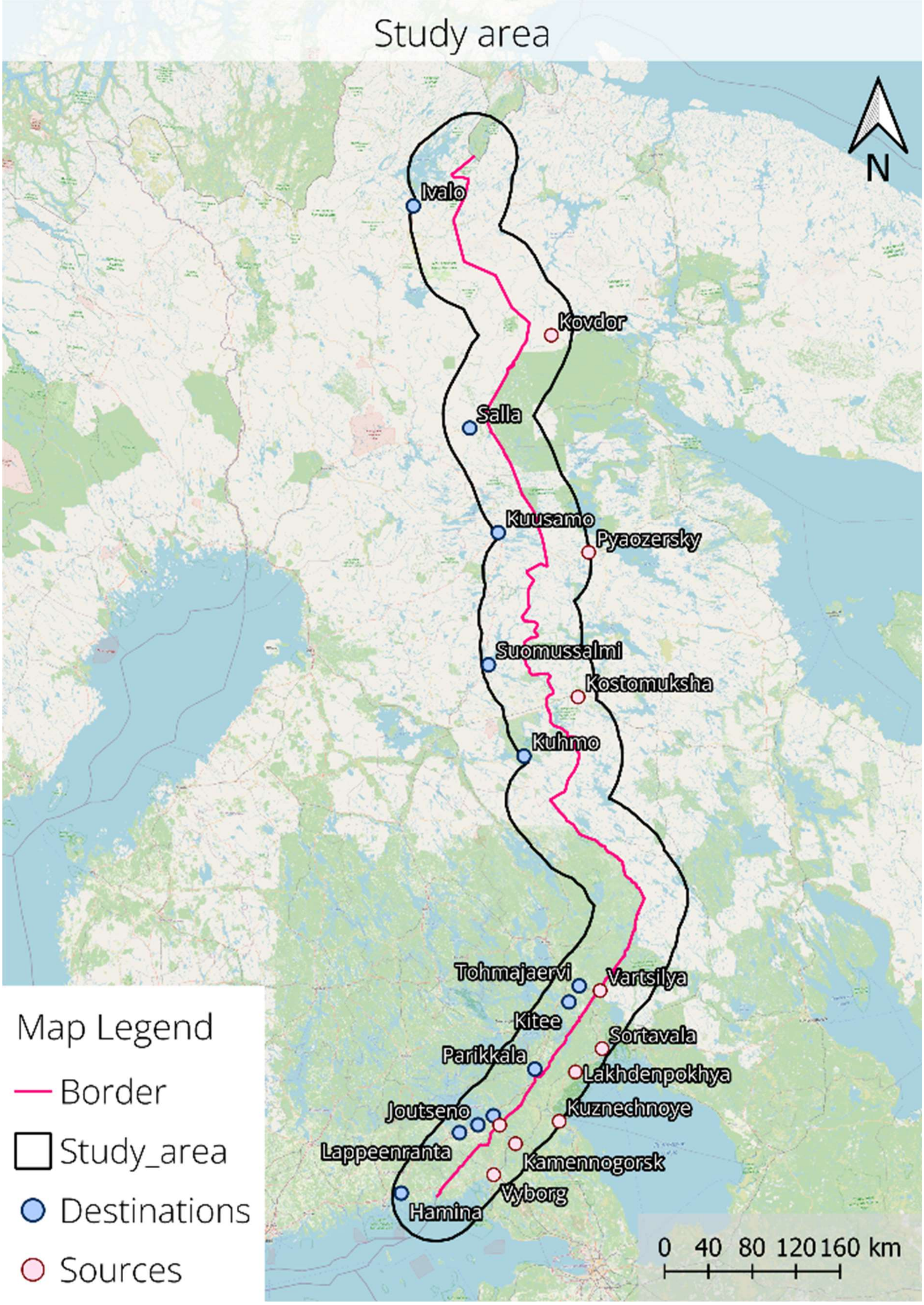

Figure 1. Study area with the potential sources and destinations.

It is also assumed that increased border control measures would take place in an event of hybrid influencing scenario. Therefore, Finnish border control stations were identified from a satellite image, and a decaying friction is assumed in a five-kilometer radius around each station. This is meant to account for the presumed effect of increased surveillance methods near the border control stations in a hybrid influencing scenario. While this is not by far a sufficient method to observe the effects of border control measures, it is an acceptable way to represent the possible psychological effect of border stations in the context of illegal border crossing.

When assessing the physical permeability of Finnish Russian border, this thesis considers a scenario where a standard adult with an average physical condition is attempting to cross the border illegally. The study area of this thesis was therefore determined by an approximation of the maximum distance that an average adult can travel on foot in one day. Studies focused on the walking speeds of adults have observed an average speed of around 5 kilometers per hour for an average adult on a level surface (Xie et al, 2024). In this thesis, the maximum distance for an adult to travel on foot in one day was estimated to be 40-80 kilometers. By this estimation, the study area created is a buffer area of 40 kilometers around the border line (Figure 1). Study of permeability is done for three different seasons, reflecting actual seasonal variabilities in Finnish Russian border. Three seasons studied include winter, summer and spring flood season. These seasonal variabilities were considered when assigning friction values to variables before the weighted overlay analysis. Additionally, the output values of weighted overlay sum were rescaled depending on the season to reflect the distances of tolerated detours in relation to the pixels with highest possible friction.

A total land cover and slope data account for the physical permeability of the border area, while border crossing points add the aspect of surveillance to the analysis (Figure 2). These layers were evaluated, and a weighted overlay sum was used to produce the friction layers for two scenarios studied. Produced friction layers are combining the assigned friction values of the evaluated datasets, describing total friction in the resulting layers. It should be noted that border crossing points were only applied for scenario 2, which considers the presumed effects of increased border control measures. The weights applied for layers were the following: 1.0 for land cover and 0.5 for slope and border crossing data. While the weight of 1.0 for the slope data would be more adequate considering the desired effect on permeability, the weight of 0.5 was applied for analytic purposes.

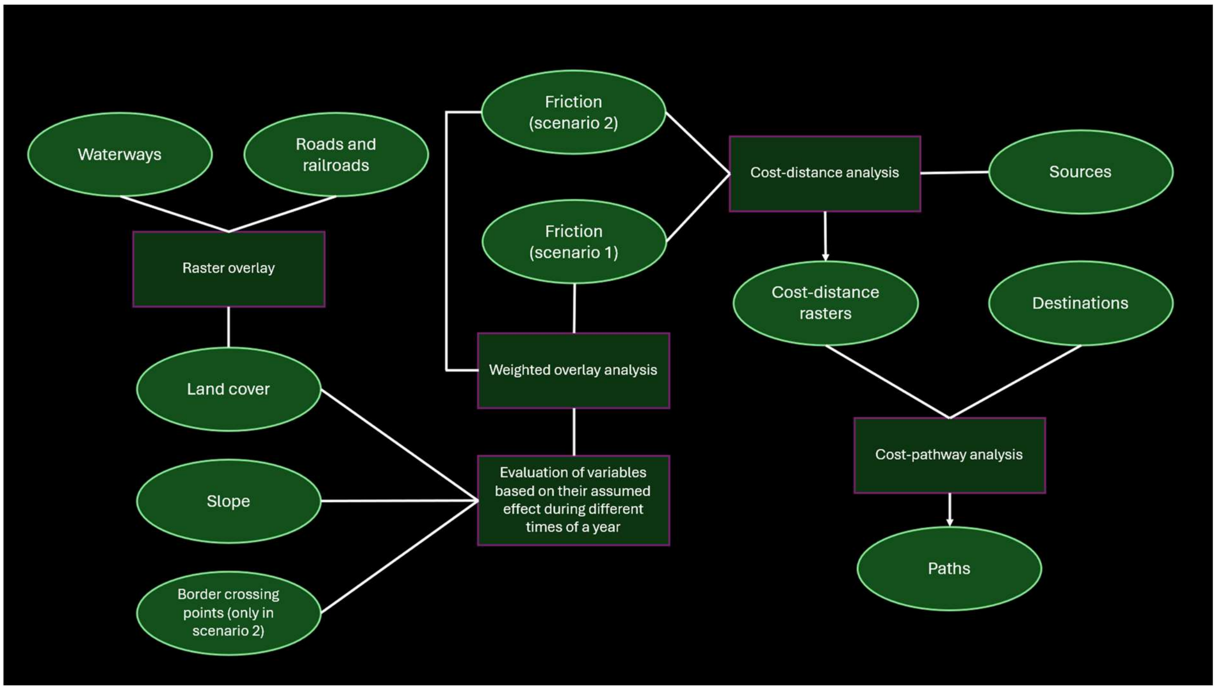

Figure 2. Methodological research design described as a flow-chart showing key steps of the analysis.

Friction layers were used to produce cost-distance layers using Whitebox toolkit in python. Here, assumed sources of travel in Russia were used as source points for cost-distance layers (figure 1). Therefore, an accumulated friction cost from each border town considered a possible point of embarkment was calculated for each of the three seasons studied. In total, 10 possible points of departure were identified in Russia: Vyborg, Kamennogorsk, Svetogorsk, Kuznechnoye, Lakhdenpokhya, Sortavala, Vyartsilya, Kostomuksha, Pyaozersky and Kovdor. Cost-distance layers produced for each of the towns were used in cost-pathway analysis along with the chosen preliminary destinations in Finland to calculate the least-cost pathways between sources and destinations. In total, there were 12 assumed preliminary destinations in Finland: Hamina, Imatra, Ivalo, Joutseno, Kitee, Kuhmo, Kuusamo, Lappeenranta, Parikkala, Salla, Suomussalmi and Tohmajärvi. Truthfully, some of the identified towns in the north are more unrealistic destinations than others, but I still wanted to include them in the analysis. It should be noted that one source point in Russia can have multiple presumed destinations in Finland.

Least cost pathways were calculated for the following itineraries (Source – Destinations):

Vyborg - Hamina, Lappeenranta, Joutseno, Imatra
Kamennogorsk - Lappeenranta, Joutseno, Imatra
Svetogorsk - Lappeenranta, Joutseno, Imatra
Kuznechnoye - Imatra, Parikkala
Lakhdenpokhya - Parikkala
Sortavala - Parikkala, Kitee, Tohmajärvi
Vyartsilya - Kitee, Tohmajärvi
Kostomuksha - Kuhmo, Suomussalmi
Pyaozersky - Kuusamo, Salla
Kovdor - Salla, Ivalo

The entire workflow is summarized in a flow-chart on figure 2.

3.2 Datasets and pre-processing steps

Various datasets that were used in this thesis are listed in Table 1 along with their sources and other properties. ESA WorldCover 2021 v200-dataset was used to analyze different types of land cover in the study area (Zanaga, et al. 2022). The dataset had a spatial resolution of 10 meters, which was resampled into target resolution of 20 meters. WorldCover-dataset had a total of 11 land cover classes: Tree cover, Shrubland, Grassland, Cropland, Built-up, Bare/sparse vegetation, Snow and Ice, Permanent water bodies, Herbaceous wetland, Mangroves, and Moss and Lichen. Out of these, classes for mangroves and snow and ice were excluded, since they were not relevant in the study area.

Table 1. Datasets and analysis variables.

Name	Variables	Aspect	Provider	Type	Area	Resolution	Access
ESA WorldCover 10m 2021 V200	Tree cover, grassland, cropland, built-up, bare/sparse vegetation, permanent water, wetlands, moss and lichen.	Physical	European Space Agency	Raster	Global	10 m	https://worldcover2021.esa.int/
Copernicus GLO-30 Digital Elevation Model	Elevation values as meters.	Physical	European Space Agency	Raster	Global	30 m	https://dataspace.copernicus.eu/explore-data/data-collections/copernicus-contributing-missions/collections-description/COP-DEM
OpenStreet Map national data.	Road types, railways, wetlands, rivers, streams and canals, drains, buildings.	Physical	OpenStreet Map Contributors	Vector	Global	-	https://download.geofabrik.de/europe.html
Border stations	Identified border stations as vector points.	Surveillance	Referenced from Google Satellite Imagery	Vector	Finland	-	-
Harva ja tiheä taajama-alue	Finnish urban areas as vector polygons.	Physical (used to refine OSM data)	Finnish Environment Institute	Vector	Finland	-	https://ckan.ymparisto.fi/dataset/%7B394B169F-2AE6-4966-8055-C593488F8898%7D

WorldCover 2021 v200 is a global dataset, and on a more local level the land cover classes can be relatively generalized. For example, while containing a class for herbaceous wetlands, this classification excludes unvegetated sediments and swamp forests, the latter of which is extremely relevant in the context of Finnish Russian border region. In WorldCover, swamp forests are classified as tree cover. However, in OpenStreetMap national datasets, wetlands include swamps in addition to the dataset being more refined for a local setting. Since wetlands and permanent water areas are among the most important land cover classes in this study, to guarantee higher data quality and accuracy, OSM data regarding the two classes was combined with the WorldCover data.

OpenStreetMap (OSM) waters and wetlands consist of vector data, which were rasterized into a selected spatial resolution of 20 meters. Rasterized layers were then overlayed with the WorldCover data in a manner that OSM wetlands became a unique class, and OSM waters were attached to the permanent water bodies-class. Additionally, three types of waterways were extracted from the OSM national datasets, i.e. rivers, streams and canals, and drains. Each of these variables were layered on top of the Worldcover dataset by masking the overlapping pixels with the new variable values. Therefore, each of the three types of waterways formed a unique variable class in the land cover dataset.

(*Order of the overlay process on the land cover layer was the following: waterways drains, waterways streams and canals, waterways rivers, tier 3 roads, railways, tier 2 roads, tier 1 roads, scattered settlements, linear settlements, compact settlements.)*

The digital elevation model used in this study is Copernicus Digital Elevation Model GLO-30 from ESA. GLO-30 DEM was first reprojected into EPSG:3067 using nearest neighbor resampling method in transformation, and the resulting layer was used to produce slope data with a raster slope algorithm in QGIS. In the resulting slope layer with 20 meters resolution, the slope values were presented as degrees.

The road data in this thesis was derived from OSM national datasets. Finnish and Russian national datasets were merged in QGIS, and the merged file was clipped with the study area polygon. Then, different types of roads were grouped and extracted from the combined data. The grouping of roads was made based on an fclass-value, which contains information about the road types in the OSM dataset. The first group (tier 1) of roads was extracted to represent the main roads. This group consisted of roads with the following fclass-values: motorway, motorway_link, primary, primary_link, secondary, secondary_link, trunk and trunk_link. The second group (tier 2) represents more permeable pathways than the third class. This class consisted of roads with the following f-class values: residential, service, tertiary, tertiary_link, track, track_grade1 and unclassified. The third group (tier 3) of roads was extracted to have information about the less permeable roads, especially during the winter period. This group consisted of roads with the following fclass-values: bridleway, cycleway, footway, living_street, path, pedestrian, steps, track_grade2, track_grade3, track_grade4, track_grade5 and unknown.

Tier 1 group consisted of main roads, including highways, primary and secondary roads that connect cities and towns. Tier 2 group contained link and residential roads, which usually connect smaller settlements and towns. While they have paved surface in most cases, roads in this group are second to tier 1 roads in hierarchy. Tier 3 group is characterized by unpaved tertiary roads; however, it also includes paved pedestrian roads and walkways in urban areas. It should be noted that in the context of Finnish Russian border, tier 3 group also includes trails and paths in the border region. Separation into these groups of roads was made especially for the purpose of the winter season analysis because it was assumed that, for example, minor roads (tier 3) are not as well maintained as the main roads, which can lead to increased friction for a person trying to pass them on foot. Three groups of roads were layered on top of the existing land cover dataset by masking the overlapping pixels with the new ones. After the operation, each of the three road types formed an additional land cover class.

Human settlement, while having a limited effect relative to land cover variables, is still important to note when assessing physical permeability of the border region. Supposedly, a person crossing the border is not able walk directly through different types of buildings on the border region, therefore, buildings are considered as impassable terrain when assessing physical permeability of space. While it is possible that a person can enter, for example, public buildings, especially in more densely populated areas, walking through buildings is not considered possible in this study.

Human settlement, i.e. building data, was derived from OSM national datasets, which contain buildings as vector polygons in a shapefile. Vector dataset containing urban and semi-urban areas was used to separate buildings into three groups based on their location (Finnish Environment Institute, 2020). The first group had buildings in densely populated areas, the second group had buildings on semi-urban areas, and the third group contained buildings on sparsely populated areas. Three groups of settlement data were rasterized and overlayed in the land cover layer. Buildings located in the sparsely populated areas were buffered by 20 meters, so that their visibility in the rasterized layer with a pixel size of 20 meters would be ensured.

A vector shapefile containing border stations was produced of all the spots in the border region, where there was a road that could be used to cross the border based on its characteristics on a satellite image, as well as a building that is supposedly used by Finnish Border Guard to monitor the immediate surroundings of the location on Finnish side of the border. This includes the official border crossing stations, as well as other spots that were identified as possible border surveillance points. In the analysis, it is assumed that a person attempting to cross the border illegally would want to avoid these areas to decrease the likelihood of them being caught. A raster file was produced with decaying friction values up to 5 kilometers from each of the border crossing points. Here, it was expected that the possible surveillance in these areas is the most intense closer to the stations and starts decreasing when the distance increases.

3.3 Friction classification of variables

Geographic features were assigned values based on their presumed effect on person's ability to walk across geographical space (Table 2). The JRC study by Stephenne et al. (2008) of border permeability of European Union land border was used as a main reference for the evaluation of land cover data used in this thesis. However, JRC study included a five-step classification of variables, which was not sufficient for the purpose of seasonal variability mapping, since five classes would not be enough to evaluate relations between various land cover classes and their seasonal changes. Malinowski (2010) has also used five-step classification of variables in a similar border permeability study. It should be noted that seasonal aspect of permeability is one of the major differences between the previous studies and this thesis. It seemed that 10-step classification was enough to both represent the differences in friction between land cover classes, as well as considering their seasonal variability. Therefore, values assigned to the variables varied between 0 and 10, with 1 being the base friction cost in land cover dataset.

Table 2. Land cover and slope friction values used to determine permeability of the variables.

Variable Name	Spring	Summer	Winter
LC Class = Tree Cover (10)	6	4	6
LC Class = Shrubland (20)	3	2	5
LC Class = Grassland (30)	4	2	3
LC Class = Cropland (40)	5	4	3
LC Class = Built-up (50)	1	1	2
LC Class = Bare/sparse vegetation (60)	4	3	5
LC Class = Permanent water bodies (80)	10	8	7
LC Class = Herbaceous wetland (90)	9	8	7
LC Class = OSM Wetlands (95)	9	8	7
LC Class = Moss and lichen (100)	3	3	4
Main Roads (204)	1	1	2
Secondary Roads (203)	1	1	2
Tertiary Roads (201)	3	2	5
Railways (202)	2	2	3
Waterways = Rivers (107)	10	8	7
Waterways = Streams and canals (106)	6	3	3
Waterways = Drains (105)	6	6	6
Compact settlement buildings (303)	10	10	10
Linear settlement buildings (302)	10	10	10
Scattered settlement buildings (301)	10	10	10
Slope (0–3 degrees)	0	0	0
Slope (3–7 degrees)	0,6	0,6	0,6
Slope (7–12 degrees)	1	1	1
Slope (12–17 degrees)	1,7	1,7	1,7
Slope (17–22 degrees)	3,4	3,4	3,4
Slope (22–30 degrees)	4,5	4,5	4,5
Slope (30–40 degrees)	6	6	6
Slope (over 40 degrees)	10	10	10

Friction classification of land cover classes is largely based on the local classification in JRC study of the city of Uzgorod in the border area between Ukraine, Slovakia and Hungary (Stephenne et al. 2008). However, I have also used my own assessment when interpreting the reference classification in the regional context of Finnish Russian border. The base logic in the classification was that primarily I determined values for different land covers in summer season and then adjusted their values for autumn and winter seasons based on the assumed differences in permeability for each class. In the local application of land border permeability, Stephenne et al. have determined forests, tree patches, water bodies, wide rivers, railway stations and airports as the least permeable terrain types when assessing walking accessibility levels. Wetlands and intertidal flats were also among the least permeable, while grasslands, bare soils, and built areas were categorized as more permeable terrains. Shrubs, young forests and park areas were among the terrains with moderate accessibility levels. I applied the framework of this classification to the land cover data composed of ESA Worldcover and OSM national datasets for this thesis. However, it was necessary to make some exceptions to the framework classification to better represent the assumed effect of different land cover types in the context of Finnish Russian border region. Additionally, some land cover types present in land cover data of this thesis were not part of the previous permeability studies. When applying my own assessments to the framework classification, I gave emphasis to the roughness, ruggedness, softness and slickness of the terrain types.

Based on the reasoning explained above, I categorized permanent water bodies, wetlands, rivers, and different types of buildings as least permeable terrain types with friction values between 7 and 10. In the opposite end of the classification, shrublands, grasslands, built-up areas, mosses and lichens, and different types of roads were among the most permeable with values typically between 1 and 3 depending on the season. Tree cover (forests), croplands, bare/sparse vegetation, streams and canals, and drains were classified as semi-permeable with friction values varying mostly between 4 and 6 depending on the season.

Primary and secondary roads along with built-up areas were assigned a base friction cost of 1 with an exception made during the winter season, where friction value was 2 due to a presumed effect of snow. Tertiary roads that consist of unpaved roads have friction value of 2 on summer, and an increased friction values of 3 and 5 on spring and winter seasons due to assumed poor road conditions. During spring season, the effects of rapid melting of snow cause unpaved roads to become muddy and sometimes unusable, whereas during winter snowfall can simply render roads difficult to traverse, because tertiary roads are not maintained similarly to secondary or main roads.

Permanent water bodies, wetlands and rivers had the highest friction values during spring season, when water is dangerously cold, that it is practically impassable. Additionally, wetlands hold excessive water content during spring season, because of an increased amount of meltwater caused by receding snow cover. In summer, friction values of these terrains were slightly lower, because warmer water presumably enables individuals to attempt crossing limited areas of watery surfaces by either swimming or wading. In winter, watery surfaces are expected to freeze, which allows crossing them more easily, however, all the surfaces are still expected to be relatively difficult to cross. Permanent water bodies can be slippery during winter, or snow cover can effectively prevent movement across otherwise unblocked areas, like lakes or rivers. It is also uncertain whether, and which rivers would be frozen in winter. Regarding wetlands, it is assumed that thawing and freezing would cause the terrain to become slightly more permeable. However, wetland surfaces remain rough and rugged, being among the most difficult types of land cover to traverse. An exception in the group of watery surfaces are more narrow waterways, i.e. streams and canals that have friction value of 3 in summer and winter seasons, and an increased friction of 6 during spring. It is expected that an adult of average physical ability is able to jump over these waterways in most parts along them.

Tree cover, shrublands, grasslands, croplands, bare/sparse vegetation, and moss and lichen had winter values determined mainly based on assumed accumulation of snow cover on the terrain types. It was assumed that snow accumulation would be higher in forests (tree cover), shrublands, and moss and lichen, whereas on grasslands and croplands wind would effectively limit the depth of snow, since these areas are more open and prone to higher wind speeds that can blow away snow cover. In other seasons, friction values of these land cover types were decided based on terrain roughness, slickness, ruggedness and different features that can limit human movement. For example, in forests and shrublands it is expected that trees, shrubs and bushes effectively limit the ability to move around, while the terrain is also relatively rugged compared to more even land cover types, like grasslands or croplands. However, during the spring even the latter terrains are likely to become slippery and muddy, therefore being more difficult to cross than in summer or winter.

While this categorization is merely a generalization of the possible ways in which the chosen land cover types affect human mobility, it was necessary to make broad choices when conducting the friction classification so that the resulting friction values would be applicable to the entire study area, stretching around 1300 kilometers from north to south. The resulting classification of friction values is presented in table 3 at the end of this chapter.

The research by Xie et al. (2024) was used to assess the effect of slope data to border permeability. However, their study highlighted that until reaching a slope angle of 7 degrees, the average walking speed increases while moving downhill and decreases significantly while moving uphill. This observation brings an issue for interpretation of the study results, because in this thesis it is not known whether a person is moving uphill or downhill. Therefore, an average percentage change in walking speed was calculated, consisting of both uphill and downhill speed changes. While choosing this procedure causes an overturn of the possible walking speed increase in a scenario where an individual is moving downhill, it is a reasonable way to estimate the effect that the slope gradients have on individuals' ability to move across space.

While Stephenne et al. (2008) applied fuzzy scaling to rescale continuous values like slope data, I used raster reclassification and threshold values to determine permeability (friction) values for slope degrees. Observed effects of slope angles on walking speeds by Xie et al. (2024) were used to determine these thresholds, which were then used to turn slope degrees into friction values. The reasoning is that the effects of slope degrees on walking speeds inversely illustrate the friction of slope gradient, with friction 0 meaning flat terrain ideal for walking, and value 10 meaning that an individual is forced to stop because the terrain is too steep. The steepest slope degrees have a friction value close to 10, because they are most effectively preventing movement forward. While Xie et al. had assessed effect of slopes up to 22 degrees, in the original dataset slope degree values went up to 53,25. Therefore, it was necessary to find additional reasoning for slope degree classification. Malinowski (2010) has used thresholds of 20 and 40 degrees, stating that walking becomes more difficult after 20 degrees and almost impossible after 40 degrees. Using this reasoning, I determined additional thresholds of 30 and 40 for higher slope degrees. An assumption was made that an individual attempting to cross the border illegally would also intentionally avoid the steepest of slopes, and therefore, all the slope angles that were over 40 degrees were assigned friction value of 10. The resulting friction values of land cover variables and slope degrees are illustrated in Table 3. Preliminary unique values of land cover classes are shown after the variable name in parentheses.

3.4 Weighted overlay analysis

Friction layers were produced for two scenarios, first analyzing the physical permeability of border and the second including the presumed effect of border stations. Friction layer of the first scenario is therefore a combination of land cover and slope datasets, including the border station data in the second scenario. Layers were combined using weighted overlay sum, assigning weight of 1 for land cover layer and 0.5 for slope data. In the second scenario an identical operation was applied, with a weight 0.5 assigned for the additional layer containing border stations. The original layers having values between 1 and 10, the resulting friction layers then had theoretical minimum and maximum values between 1 and 15, or 1 and 20, depending on a scenario. These conceptual minimum and maximum values were used to re-scale values in friction layers depending on the season. Resulting values were between 1 and 800 in spring season, 1 and 600 in winter season, and 1 and 400 in summer season. The reasoning behind this is that the pixels with the base cost of 1 are main roads with an even surface, while pixels with maximum values would mean next to impassable surface. Rescaled values are then indicating how many base cost pixels an individual would presumably be willing to travel to avoid one pixel with a maximum value. Having a resolution of 20 meters in this study, this would mean that in spring flood conditions an individual would be willing to walk 16 kilometers on even main road surface to avoid one pixel with the highest possible friction. The same would be 12 kilometers in winter conditions, and 8 kilometers in summer conditions.

3.5 Cost distance and pathway analysis

Cost pathway analysis is used to determine least-cost pathways from source raster cells to destination raster cells. Similarly to cost-distance analysis, destinations were marked in separate raster files as single pixels with a value of 1, while other pixels in the destination layers had value of 0. Least-cost paths are then calculated by using values in the cost-accumulation backlink file.

Friction layers were used to produce cost-distance layers of the chosen points. Cost distance is an equivalent of accumulated movement cost calculated from a single pixel that marks the point of departure. Cost distance surfaces were produced of all 10 towns, using friction layers of different seasons. This resulted in 3 cost distance layers per source point, total of 30 cost distance surfaces per scenario. Cost-distance backlink surfaces were then used to calculate least-cost pathways to destinations, as described in Figure 2 at the end of chapter 3.1.

Least cost pathways were calculated from each identified source point (10) to all potential preliminary destinations in Finland. Again, this means that one source point can have multiple destinations. It should be noted that paths in the northern part of the border area are not realistic in a scenario where an individual tries to cross the border on foot. This is simply because the paths to travel become too long and further in the north the distances between towns are greater.

4 Results

4.1 Permeability of Finnish Russian border

A general observation that I made was that the network of elongated areas with lesser friction indicating surfaces that facilitate movement, i.e. roads and railways, are more frequent in Finland than in Russia. It is highly likely, however, that this is at least partly because the OSM national data used in this thesis is not as comprehensive in Russia than it is in Finland. Regarding the road and railway network it can also be observed that their density decreases towards the north, which is in line with the known characteristics of more peripheric border area.

The study area is characterized by different types of water areas that generally are oriented from south-east to north-west, as was the retraction direction of the ice sheet during the last glacial period. The most prominent land cover classes were forests (tree cover) with 63.95% coverage of the study area. Permanent water areas cover 13.46%, grasslands 9.88%, and wetlands 6.58%. Secondary roads are significant with 2.56% of the study area, compared to 0.15% with main roads, and 0.77% with tertiary roads. Rivers covered 0.55% of the area, while streams and canals covered 0.37%. Other land cover types like croplands that cover a seemingly insignificant 0.70% of the area, but their effect on local level can be notable regarding least-cost path analysis. Regarding natural barriers and high friction land cover types, lakes, rivers and wetlands are the dominant land covers of the area, except for the northernmost parts where their prominence slightly decreases. There are also some fells and other points of elevation in the border area, but their effect on the general landscape is confined to small geographical areas. There are, for example, no mountain ranges that would effectively restrict movement across the border area and therefore the effect of slope data in total friction is limited.

When analyzing the friction layers in general it can be noticed that the high friction areas are the most abundant in the spring season. This is because the water areas are deemed mostly next to impassable terrain, since the water during springs is dangerously cold and seasonal floods are typically occurring as well. Additionally, wetlands are high friction areas especially during springs, which also shows in the friction layers. Generally, the friction values on land are lower during the summer and increase in winter. In winter, a major change comes with the presumed freezing of water areas as well as wetlands, which then become more passable when land areas have increased friction values during the season. This change leads to a situation where there seem to be no major differences in friction between areas. Winter season also highlights lesser friction areas that are not visible in summer or spring friction layers. When comparing these areas to a satellite imagery or the land cover layer used in this thesis, it seems that the areas are mostly grasslands or croplands.

Especially in Karelian area, there are numerous roads that can effectively facilitate movement near the border area. Road network is slightly denser on Finnish side of the border, but there are roads that run aligned with the border on both sides. On the other hand, the number of roads that run across the border line is very limited, and these types of roads usually include a border station, which caused higher friction in this analysis. However, while the number of roads crossing the border is limited, the roads that run in the vicinity of the border zone can be used to get near the border to then cross it over other types of land covers, like forests. Example of a road network close to the border is visible in Figure 3, where roads are easily seen in spring friction layer on the left side of the figure. In addition, the effect of seasonal variabilities on water areas can be seen when comparing total friction of the three seasons.

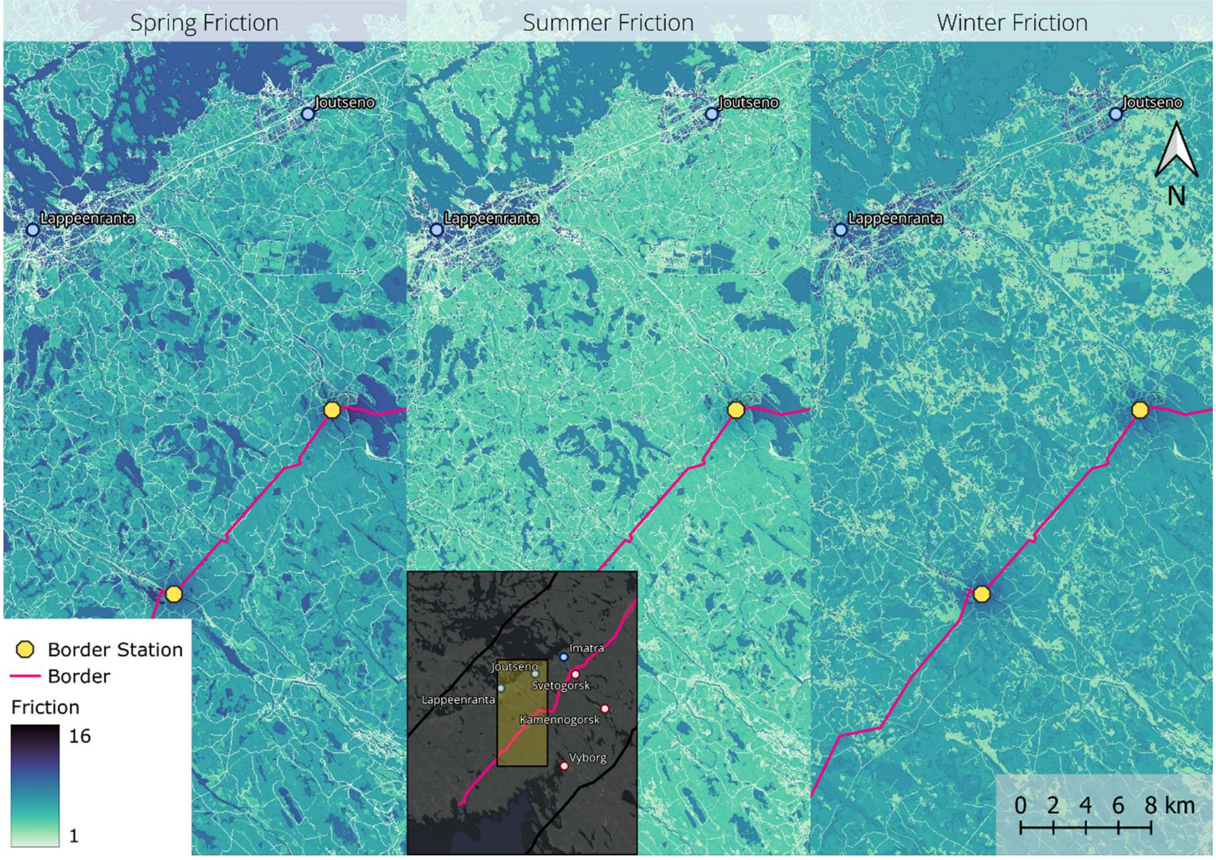

Figure 3. Friction in Southern Karelia border area. While there are many high friction areas, dense road networks effectively facilitate movement across otherwise challenging friction landscape.

Similar characteristics in road networks can be seen in Figure 4, which shows seasonal friction around Svetogorsk and Imatra. There is a main road running through the border station between the towns, which is usually used to control cross-border traffic. No other road runs across the border near the area, however, there are side roads and pathways along the border that can be used to get close to the border zone. Figure 4 also highlights the splintered nature of the Karelian landscape with river Vuoksi meandering between the two towns, as well as various lakes and wetlands showing as higher friction areas especially in the spring friction layer. Additionally, winter friction layer shows numerous areas with lesser friction on a light green color. When comparing these areas to the land cover layer or a satellite image, they can be identified as croplands and grasslands.

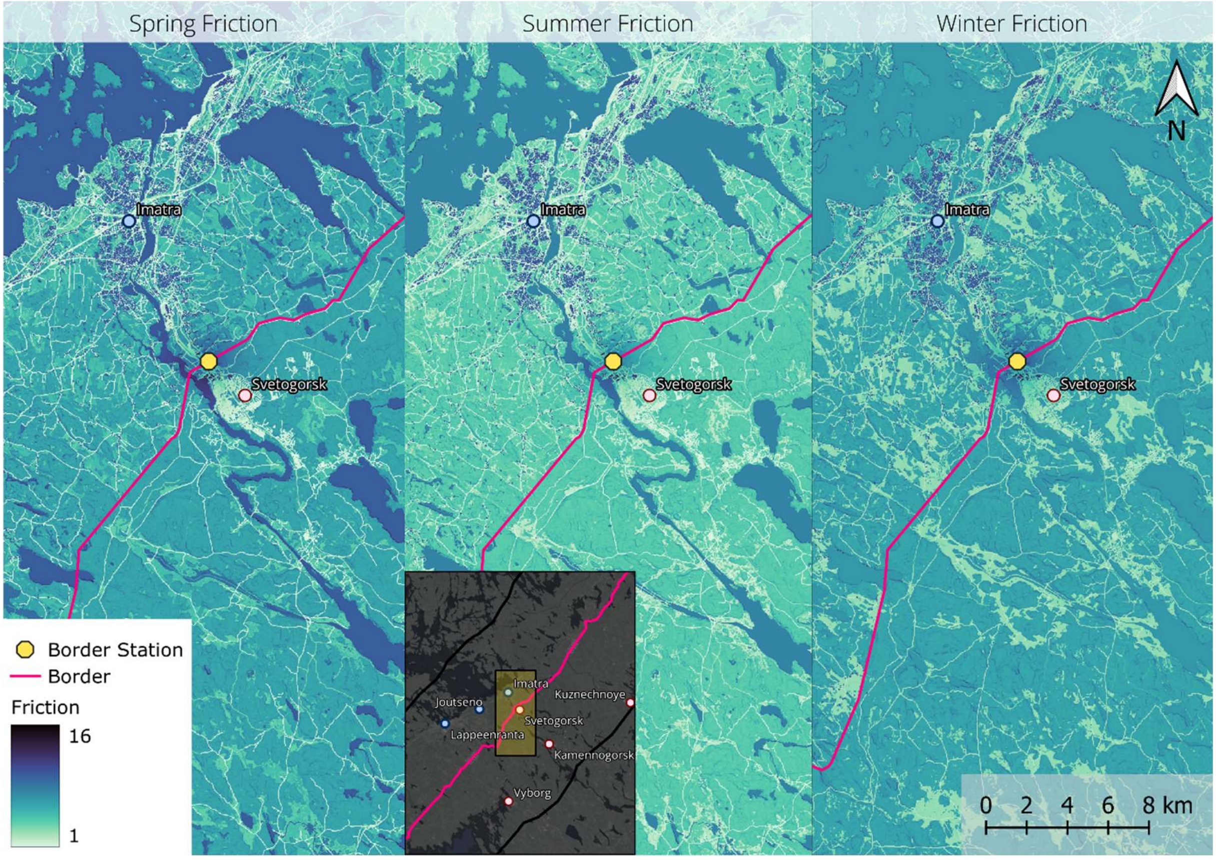

Figure 4. Friction near Svetogorsk and Imatra.

In the area around towns of Vartsilya, Kitee and Tohmajaervi, the landscape is again dominated by lakes and wetlands (Figure 5). Here, differences between the densities of road networks can be observed more easily. There are also five border stations along the border line that add to the total friction in the area. In spring, it can be noted that the landscape is relatively difficult to traverse if it is not possible to use main roads that run through the border stations. In winter, however, the landscape in the area generally becomes more passable with the presumed freezing of lakes and wetlands.

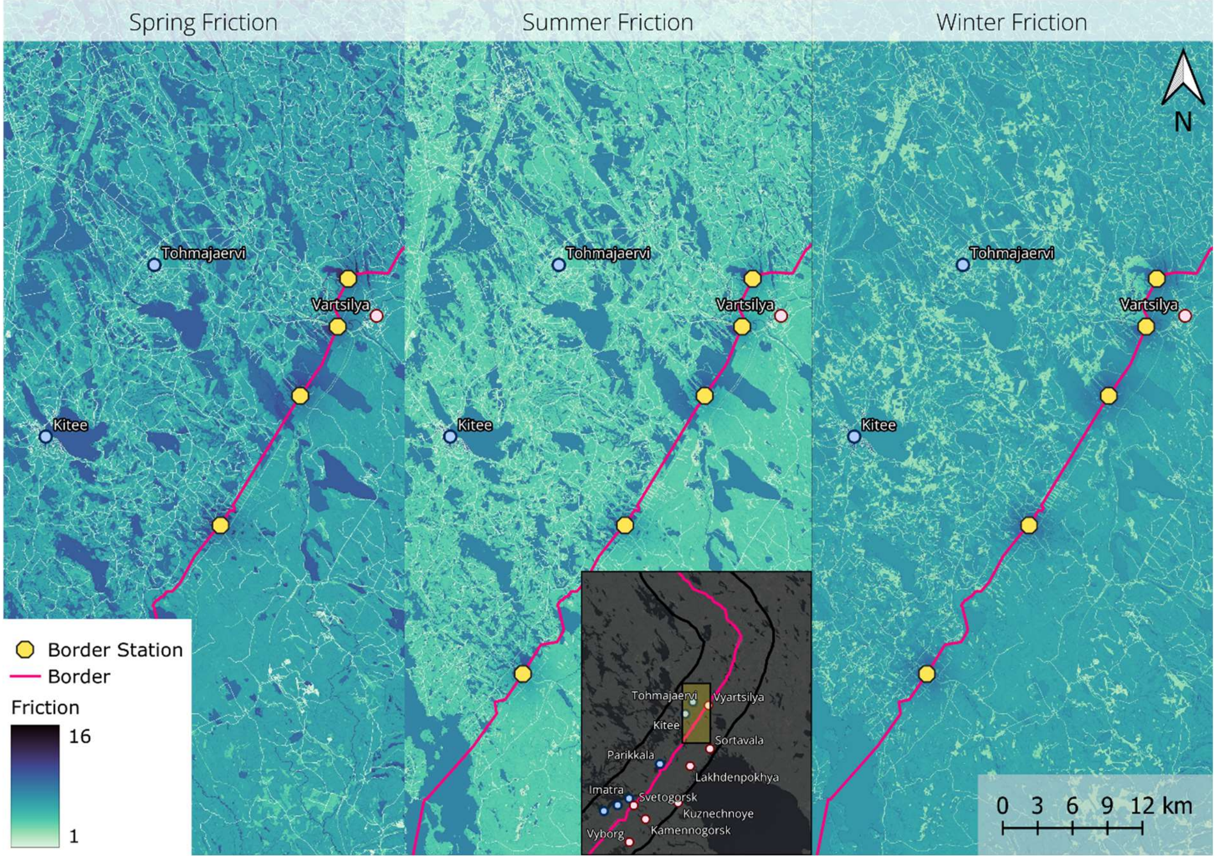

Figure 5. Friction around Vartsilya, Kitee and Tohmajaervi.

Around 400 kilometers further north, around the area of the border station of Kuusamo, some changes can be noticed in the friction landscape (Figure 6). The road network becomes a lot less dense and there is only a single road running across the border that goes through the border control station. Other than that, the number of roads that can be used to get near the border zone is also very limited, with only a few side roads or paths running along the border. Another change can be observed in winter, when the croplands that were visible in the Karelian area are not as prevalent in the north. However, the effect of grasslands can still be seen in the winter friction layer. Regarding the permeability of the area around Kuusamo, the largest contrast to the southern part of the study area comes from the limited road network. Similar characteristics can also be seen near the Russian town of Kovdor, where the lack of road network becomes more significant and there are very few water areas limiting movement across space (Figure 7).

In the northernmost parts of the study area, great distances and the lack of road networks are the main factors preventing the possibility of crossing the border areas on foot.

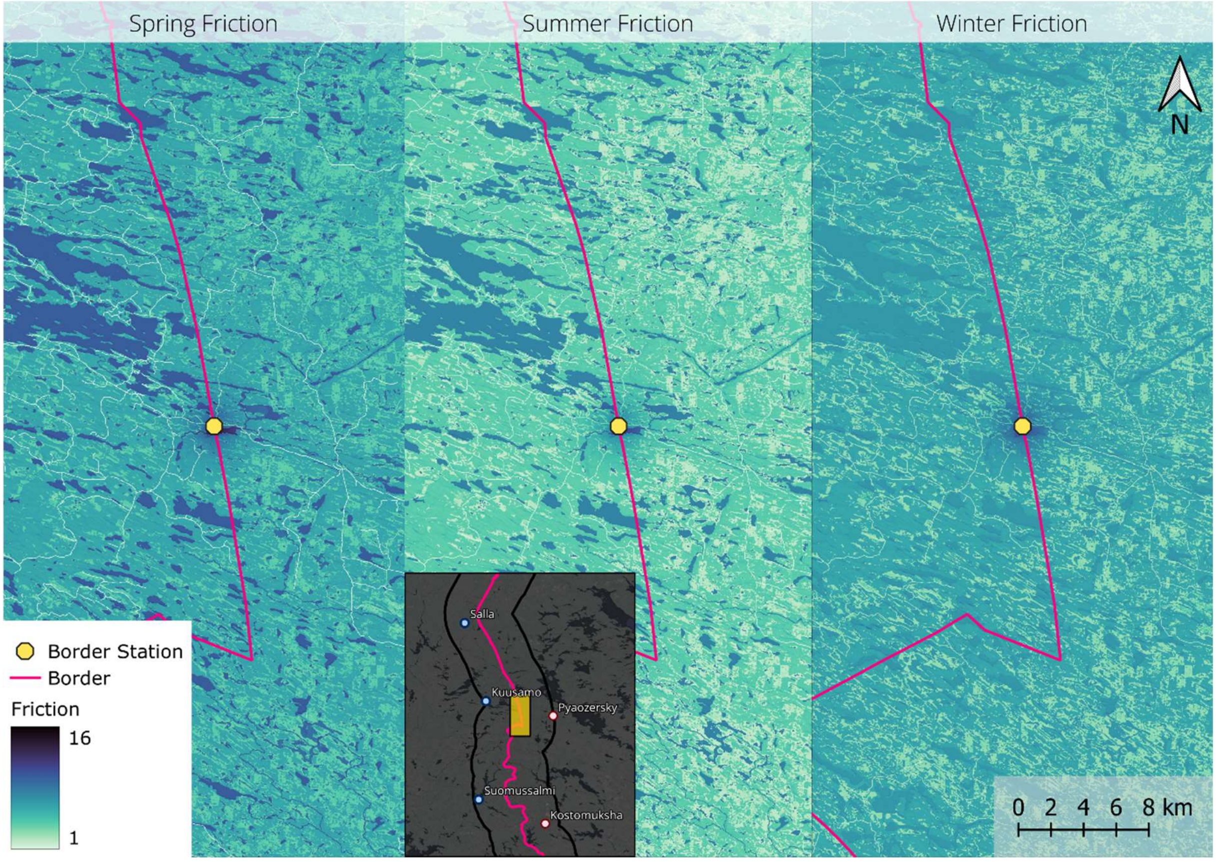

Figure 6. Friction around the border station of Kuusamo.

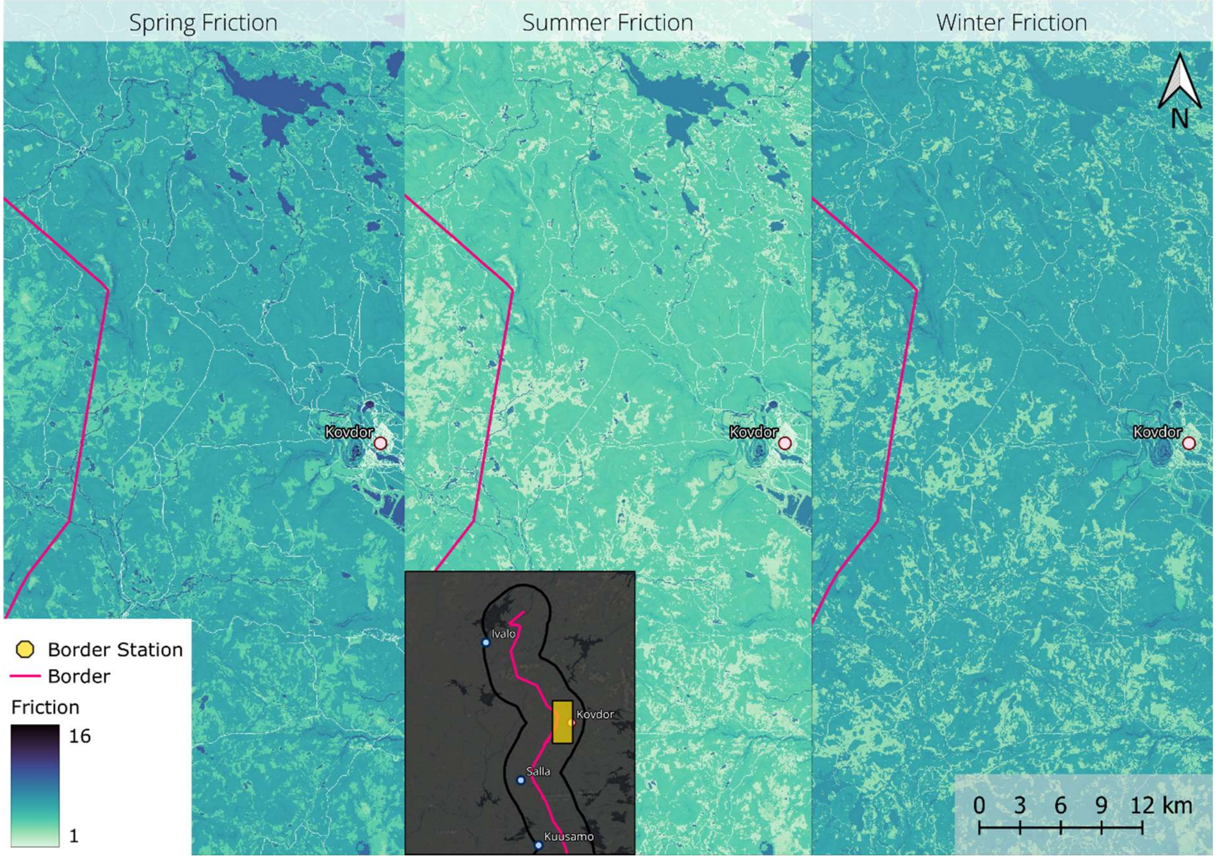

Figure 7. Friction around the Russian town of Kovdor.

4.2 Optimal routes across the border

The paths that were formed are presented starting from the southernmost locations. It should be noted that paths in scenario 1 simply follow the main roads connecting the towns, with only a few exceptions. Therefore, in this chapter I mostly focus on observations in scenario 2. Paths in scenario 2 also follow the main roads outside the areas that are close to the border area. However, the main interest is what happens to the paths near the border, and the map figures are produced accordingly. I also compared paths to land cover types within 3- and 1-kilometer buffer areas around the border to determine which terrain types were most prominently used by the optimal routes.

Secondary roads were by far the most used land cover type, covering 87.98% in spring, 85.87% in summer, and 83.68% in winter season in 3-kilometer buffer area. Main roads contributed 7.68% in spring, 7.20% in summer, and 5.61% to paths in winter season, while grasslands covered 0.98% in spring, 2.87 in summer, and 4.76 in winter season. Cropland surprisingly covered 0% in spring, 0.05% in summer and 0.94% in winter season. Streams and canals were used significantly in winter season, covering 2.64% of the total area used by paths, while having

0% in both spring and summer seasons. Other land cover types were not significantly used by paths. In 1-kilometer buffer area, secondary roads covered 87.91% in spring, 81.28% in summer, and 75.12% in winter season of the total area used by the paths. Grasslands contributed 2.48% in spring, 7.43% in summer, and 9.59% in winter season, while tree cover was 5.04% in spring, 5.39% in summer, and 3.30% in winter season. Main roads were less significant closer to the border, with 2.84% in spring, 3.15% in summer, and 2.87% usage in winter season. Tertiary roads covered 1.60% in spring, 2.32% in summer, and 0.18% of the paths in winter season. Streams and canals were, again, of significant importance in winter season, with 6.89% of the total area used by paths within 1-kilometer of the border, having 0% in spring and summer seasons. Cropland covered 1.76% of the area used by paths in winter season, having 0.16% in summer, and 0% in spring season. Other land cover classes were not significantly used within 1 kilometer around the border.

Paths from Vyborg to Hamina in scenario 1 go along the main road that goes through the border station of Vaalimaa (Figure 8). In scenario 2, the paths run around 5 kilometers north of the Vaalimaa station, following side roads to the near vicinity of the border line, going across the border in forest areas, and continuing along the side roads on Finnish side of the border.

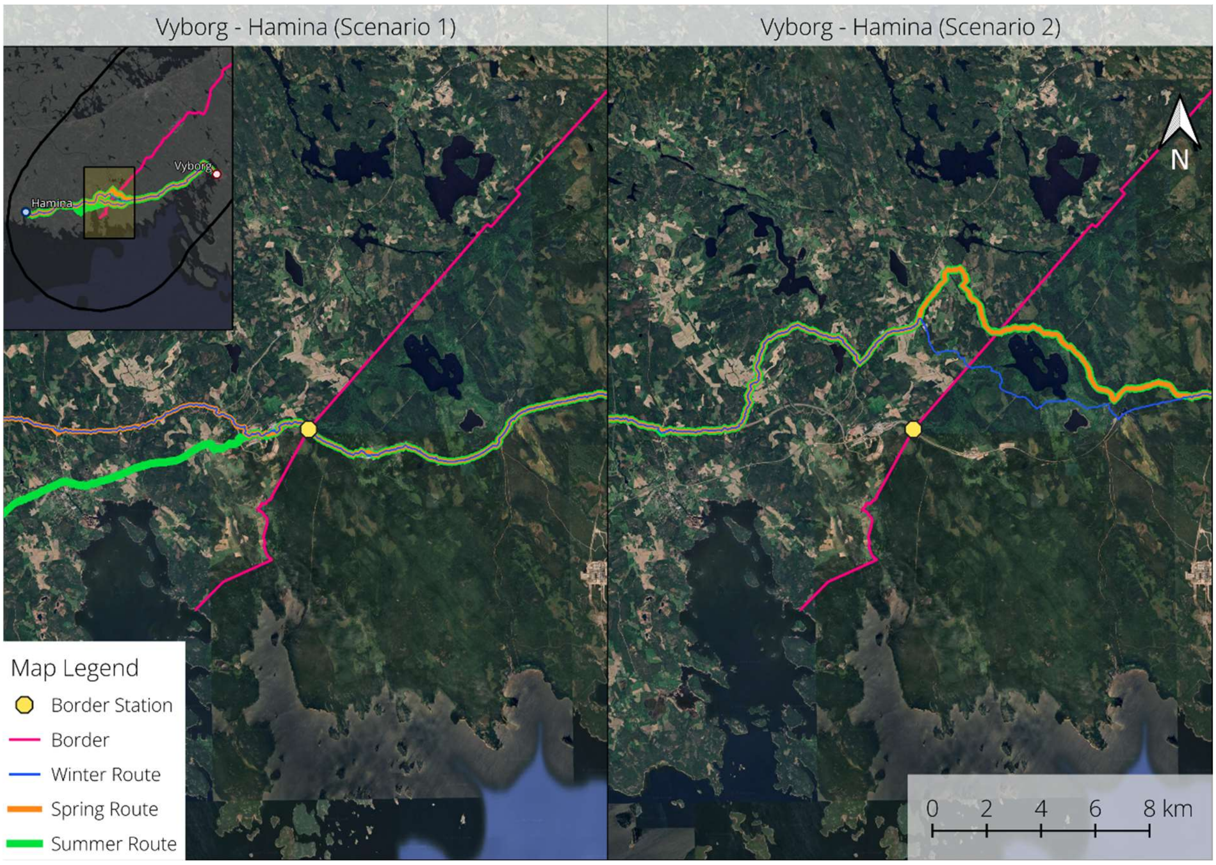

Figure 8. Paths from Vyborg to Hamina.

Paths from Vyborg to Lappeenranta, Joutseno and Imatra in scenario 2 all run along the same route until reaching the Finnish side of the border, where the winter routes to Joutseno and Imatra split to a different direction after the border line has been crossed (Figure 9). However, the qualities of the paths are similar: they use secondary and tertiary roads to get to the border zone and go about 100 meters across a patch of forest to get over the border line. Then, the paths use similar side roads to move across agricultural areas in the Finnish side of the border to reach the main roads that are used to get to destinations. An exception in scenario 1 is the summer route, which seems to follow the same route as the paths of scenario 2, until after the border zone is crossed, when the path diverts from the scenario 2 routes.

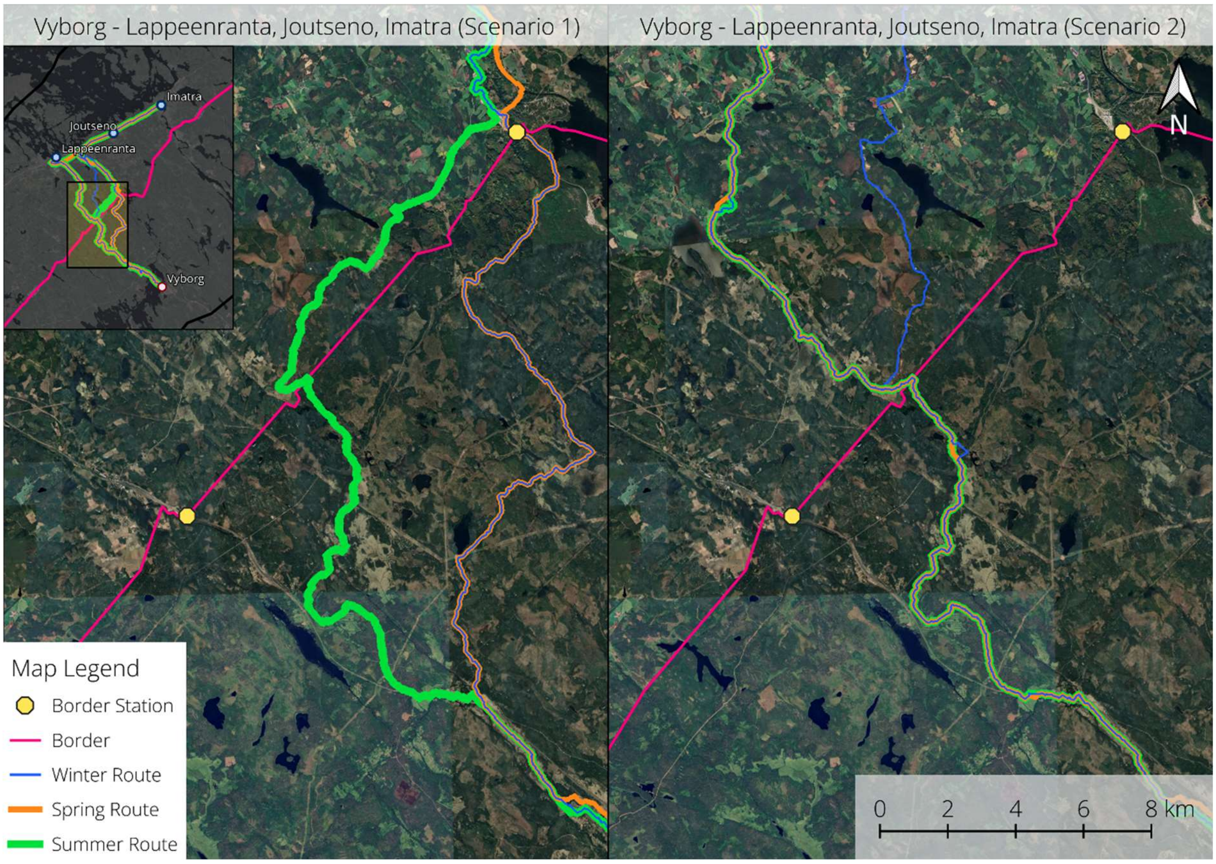

Figure 9. Paths from Vyborg to Lappeenranta, Joutseno and Imatra.

Paths from Kamennogorsk and Svetogorsk to Lappeenranta, Joutseno and Imatra are relatively similar, since paths from both sources to Lappeenranta and Joutseno follow mostly the same routes after reaching the border (Figures 10 and 11). The characteristics of the routes are similar in the use of secondary and tertiary roads to get to the border zone and moving over the border line in grasslands or forests. Only the paths from Svetogorsk to Imatra take a northern route, but even there the paths are similar to the southern ones. However, some differences in paths are observed, especially between the winter and spring paths.

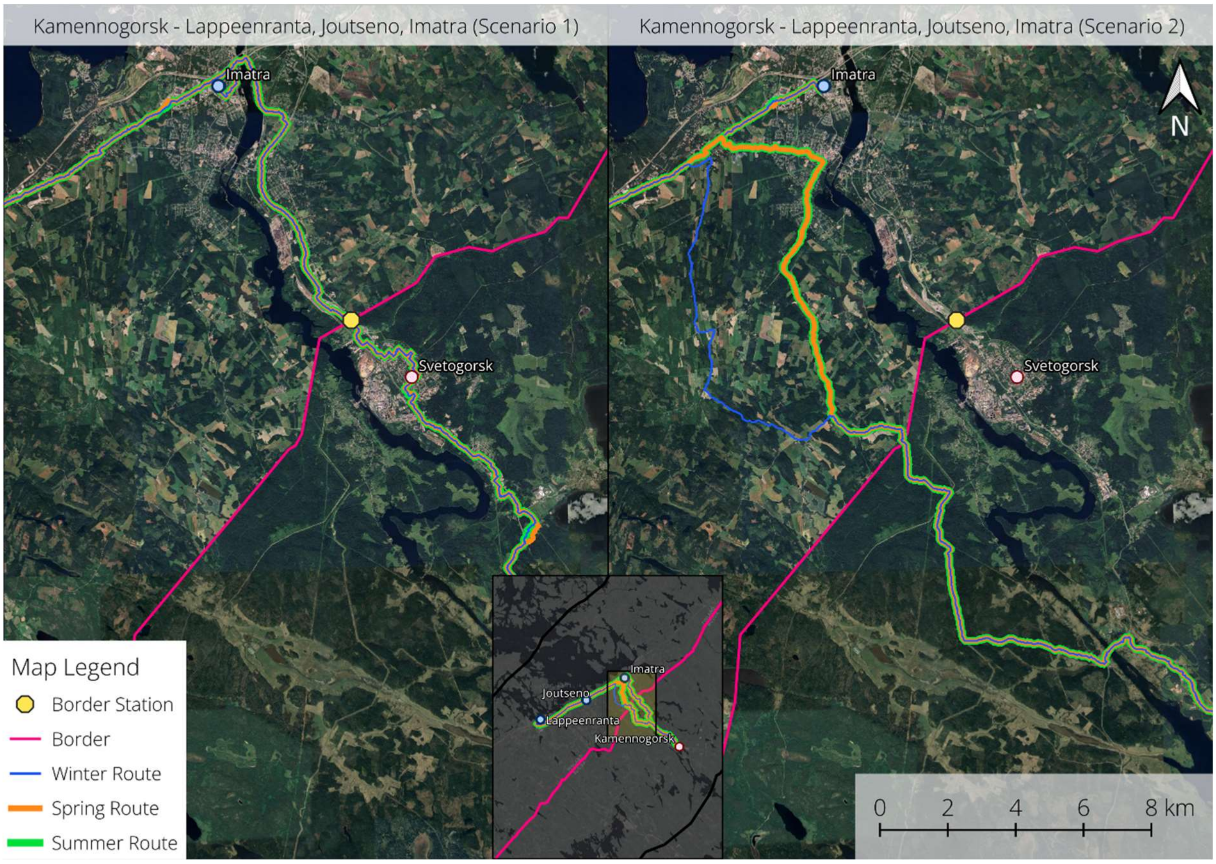

Figure 10. Paths from Kamennogorsk to Lappeenranta, Joutseno and Imatra.

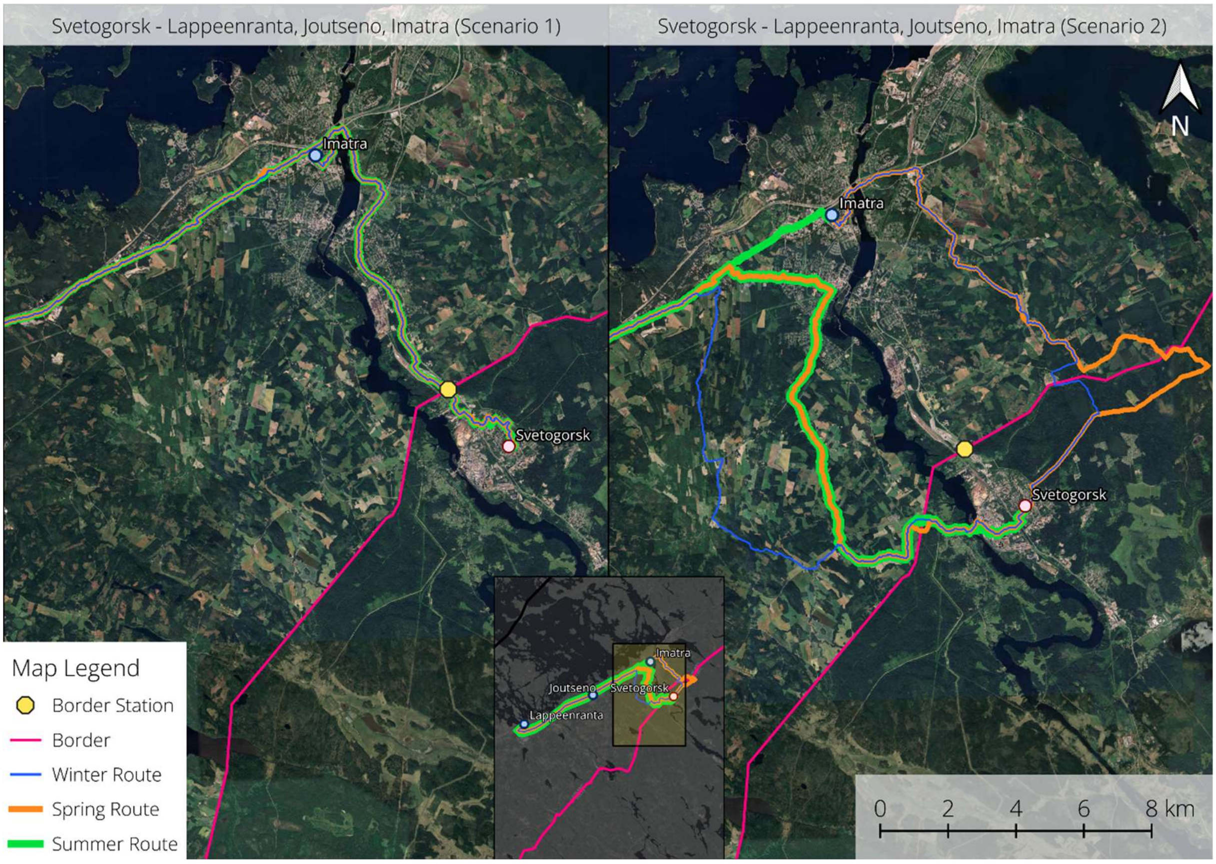

Figure 11. Paths from Svetogorsk to Lappeenranta, Joutseno and Imatra.

Figure 12 shows quite uninteresting results, however, illustrating that in the absence of border control stations the paths naturally follow the exact same routes in both scenarios. This is true with paths from the town of Kuznechnoye to Imatra and Parikkala. Here, the absence of border stations is also seen in the lack of larger roads, which leads to a similar situation as in the previous paths. Secondary and tertiary roads are used to get to the border, where the path goes through a small patch of forest or grassland to get to another side road in the Finnish side of the border. These skips from side road to another are usually not longer than a few hundred meters, depending on how close to the border it is possible to get using the road network and how far the closest side road is located on the other side of the border. An observation can be made that the spring path to Parikkala follows the same route as paths to Imatra until diverting back to north, eventually reaching the same route as summer and spring paths to Parikkala.

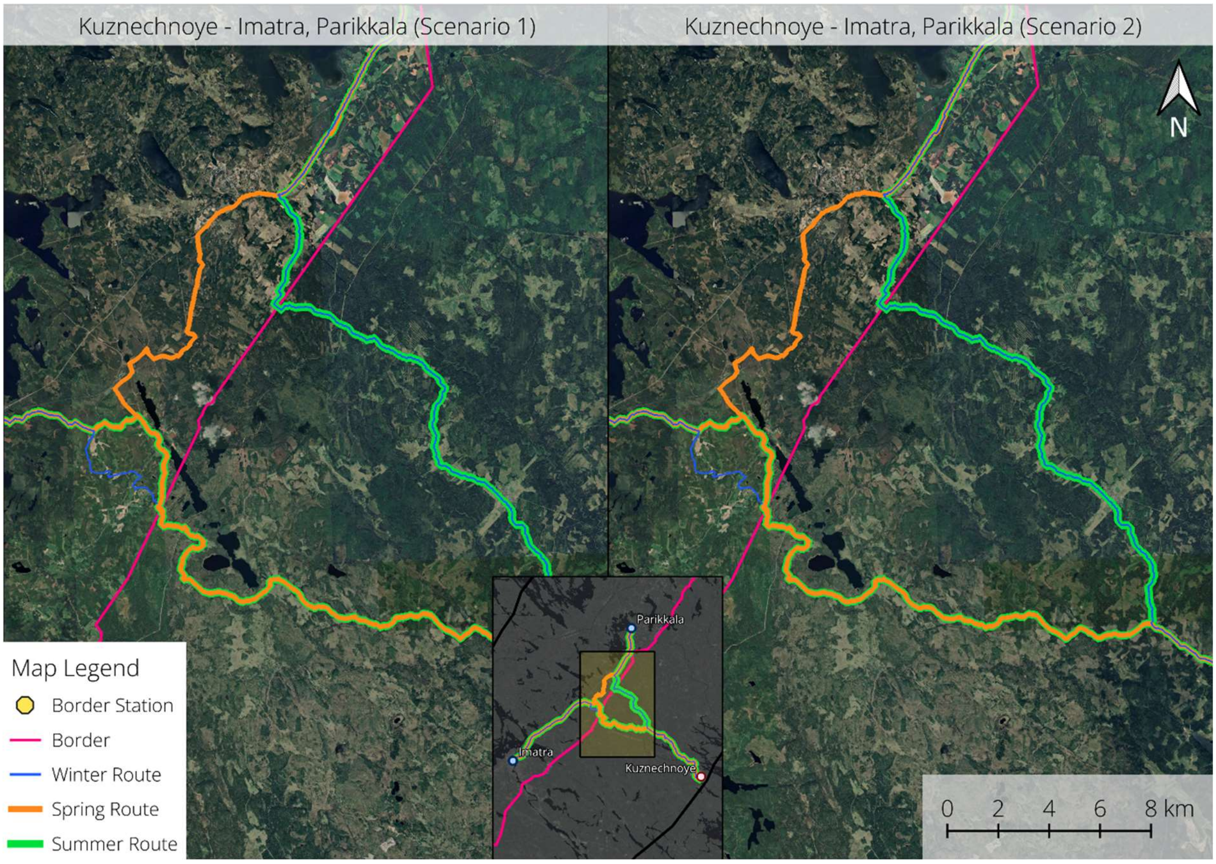

Figure 12. Paths from Kuznechnoye to Imatra and Parikkala.

Figure 13 shows paths from Lakhdenpokhya to Parikkala, which in scenario 1 are following the main road connecting the towns. Paths on scenario 2 are 4 to 6 kilometers north of the border station of Parikkala and move along tertiary roads and forest patches to get over the border. The winter path is slightly different next to the border line but still mainly follows the same routes as spring and summer paths.

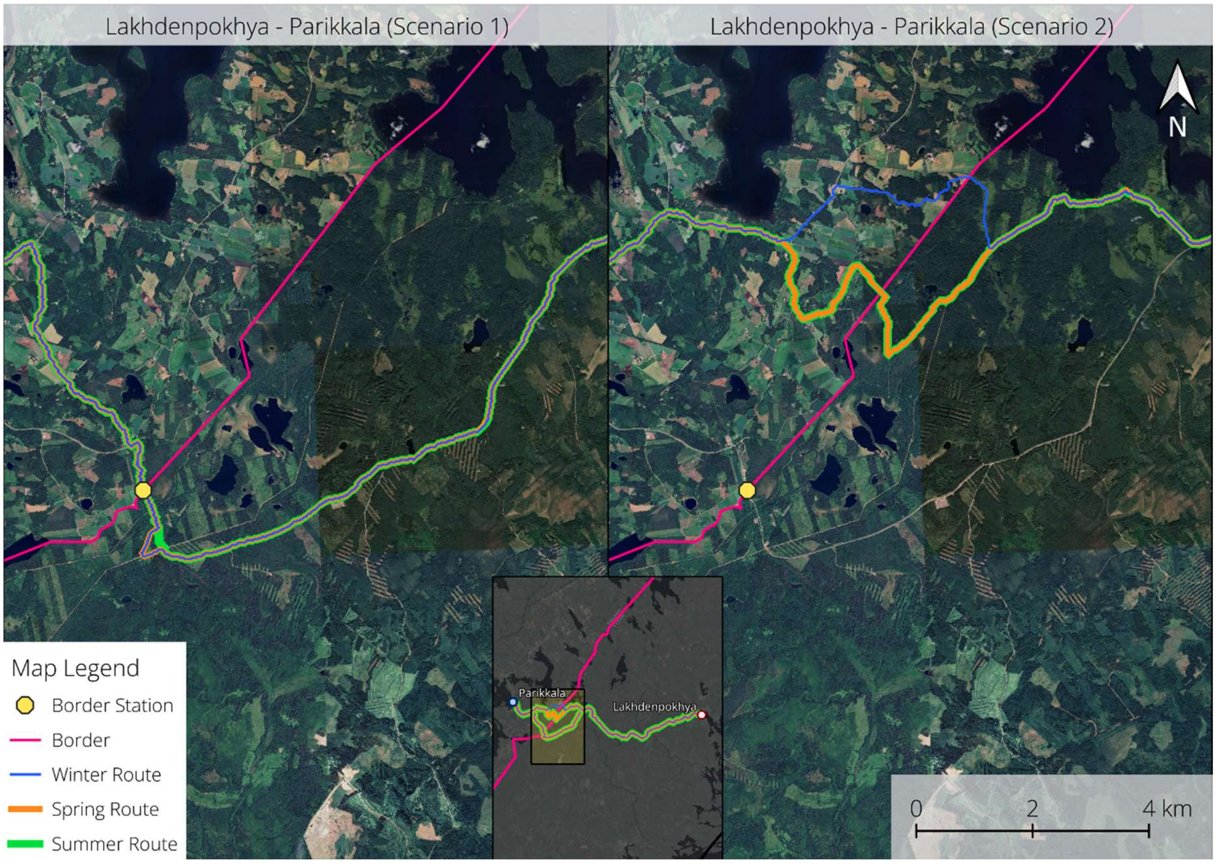

Figure 13. Paths from Lakhdenpokhya to Parikkala.

Paths from Sortavala to Kitee and Tohmajaervi have great variations depending on the season in scenario 2 (Figure 14). While characteristics of the paths remain the same as in the previous cases, greater diversions of spring routes are noticeable in paths starting from Sortavala. This could indicate that summer and winter routes move across areas with higher friction in spring flood scenario, which would cause the diversions. Again, the paths move along secondary and tertiary roads to the border zone, where the paths go through small patches of forests to get over the border and continue moving along side roads in Finnish side of the border. Paths from Vartsilya to Kitee and Tohmajaervi are similar, with several border stations forcing the paths to divert to north in scenario 2 (Figure 15). All the paths from Vartsilya follow almost the exact same route, with only the winter paths taking a slightly different route when moving over the border. This slight difference, however, is not visible in the map figure but was only observable in GIS.

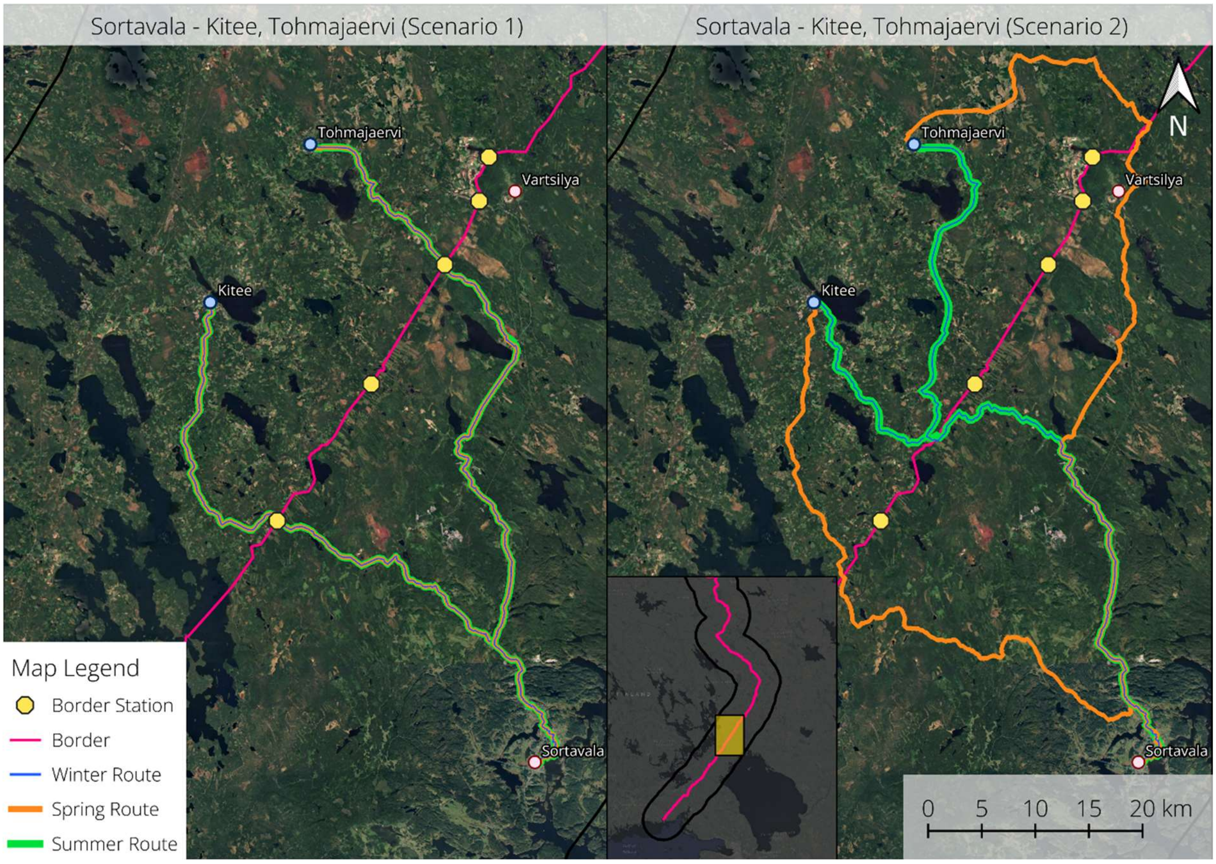

Figure 14. Paths from Sortavala to Kitee and Tohmajaervi.

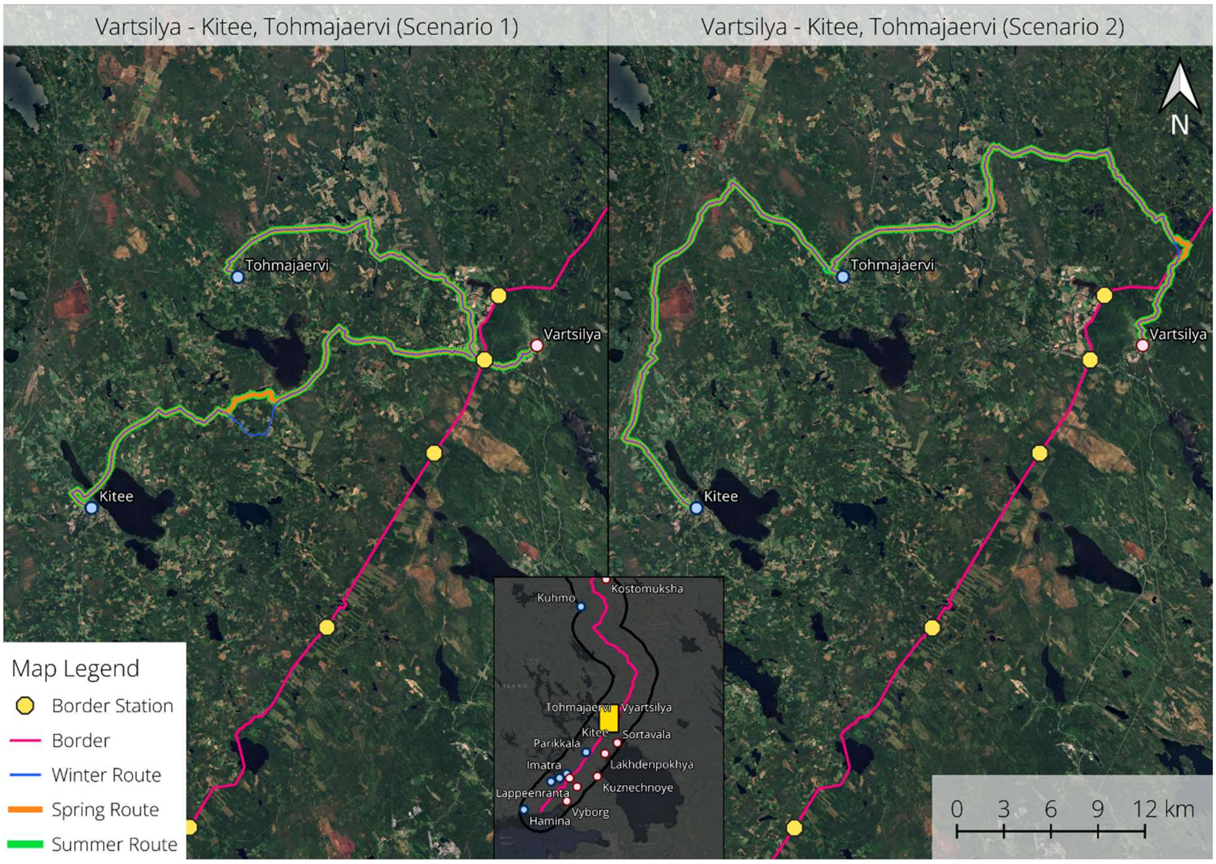

Figure 15. Paths from Vartsilya to Kitee and Tohmajaervi.

Paths further north, again, are not realistic in a scenario with an individual travelling on foot. This is because the distances simply become too great to be traversed by walking, and the rural environment poses a risk in the event of an injury or other types of accidents. However, I still wanted to visualize the results derived from these areas. Here, the spring and winter paths from Kostomuksha to Suomussalmi go the furthest up north, circling a lake on the Finnish side of the border (Figure 16). Another interesting observation is that most of the paths run across a narrow water stream a few hundred meters from the border line (figure 21). In the northern areas, the lack of road networks has an effect to the distances that the paths are forced to travel outside any types of roads near the border area. This means that the "skips" from road to another when moving over the border line become longer, in this case being 500 to 1000 meters, compared to just a few hundred meters in the southern areas.

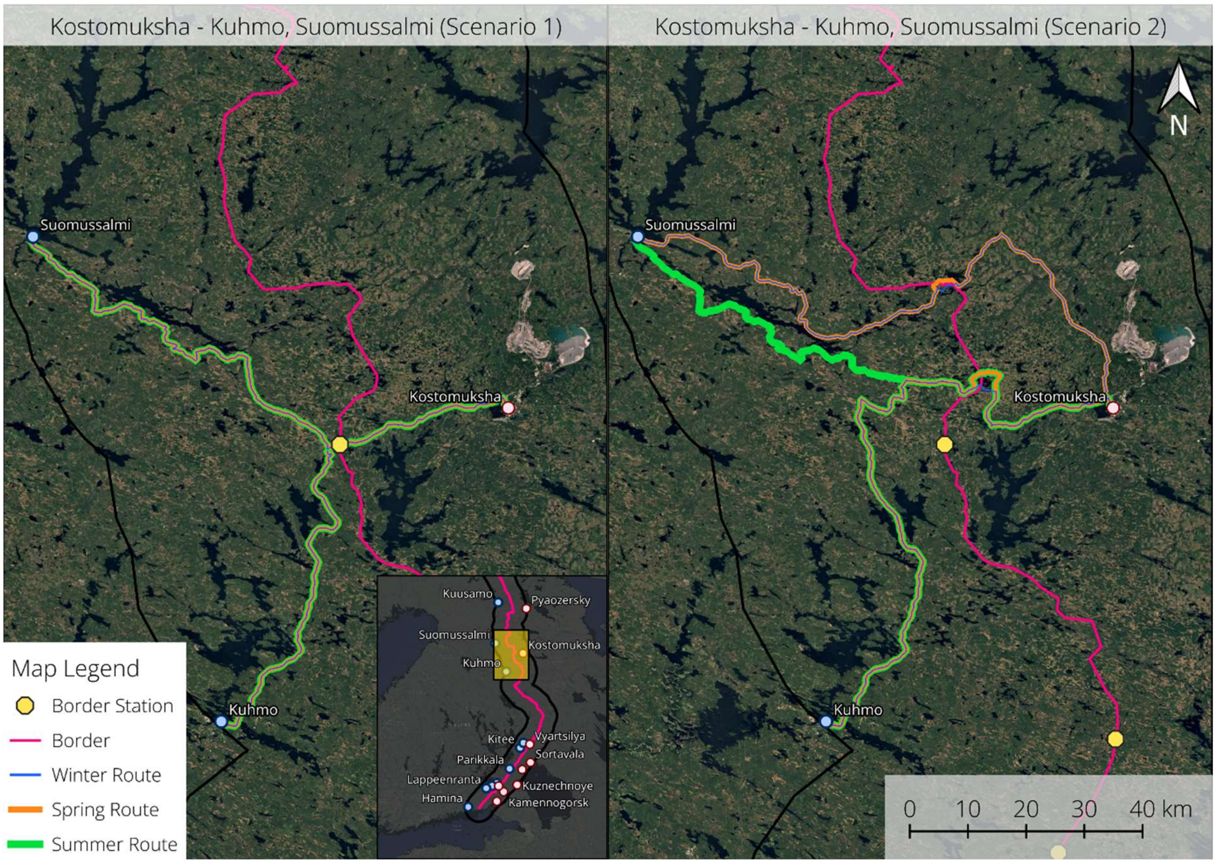

Figure 16. Paths from Kostomuksha to Kuhmo and Suomussalmi.

Paths from towns of Pyaozersky and Kovdor follow the same logic as the paths from Kostomuksha, following a limited number of roads that can be used and moving across larger areas of terrain without roads near the border (Figures 17 and 18). Spring paths from Pyaozersky make long diversions from south, indicating that summer and winter paths are not suitable in spring conditions. A similar diversion of spring path can be observed on a route from Kovdor to Salla.

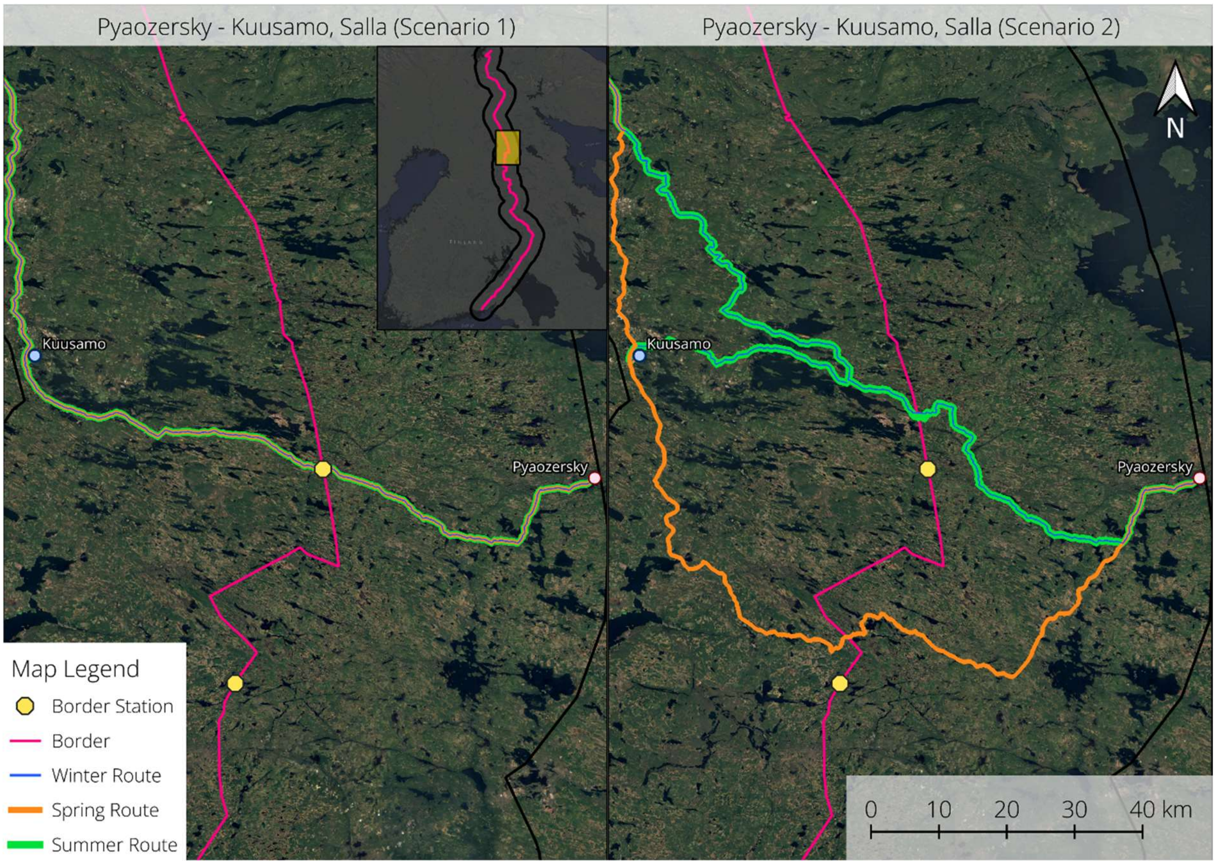

Figure 17. Paths from Pyaozersky to Kuusamo and Salla.

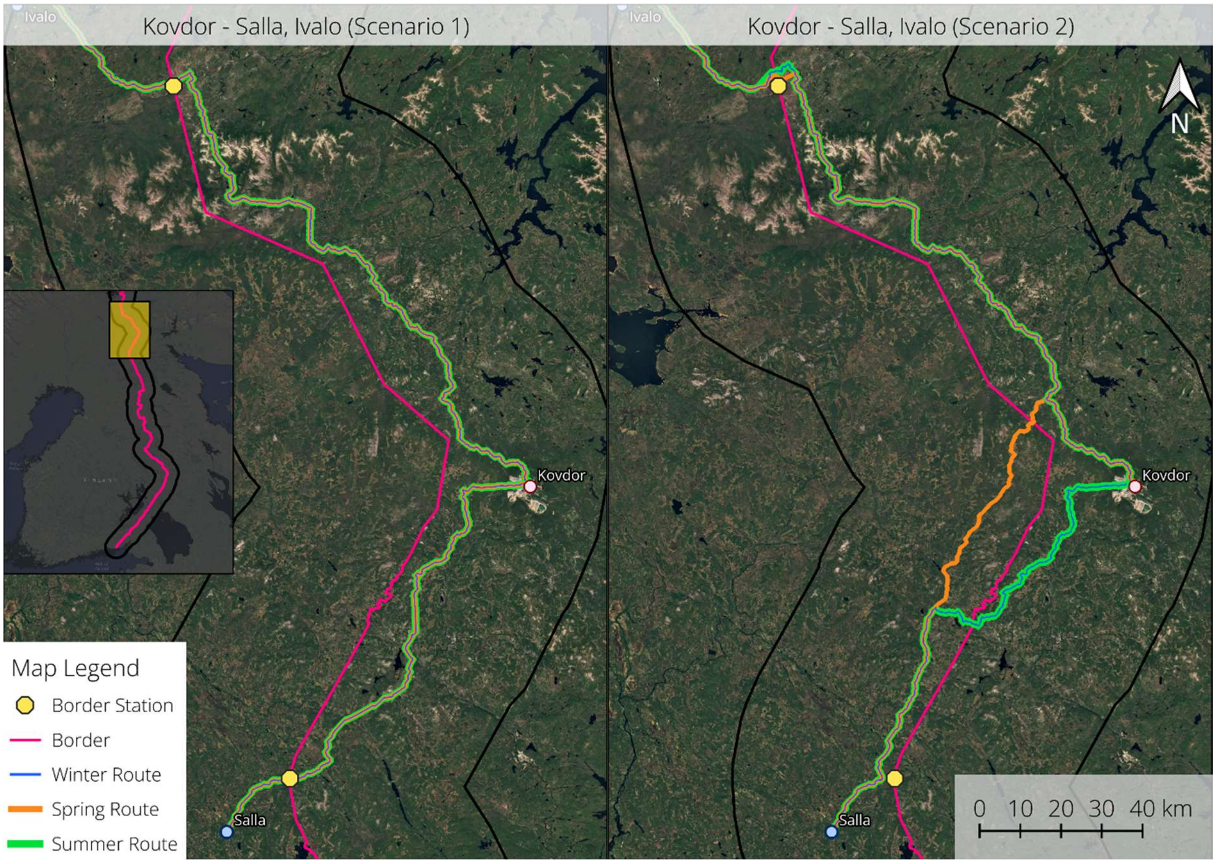

Figure 18. Paths from Kovdor to Salla and Ivalo.

4.3 Path characteristics

Figure 19 shows a typical path in Karelian areas where the path goes across a patch of forest to proceed in the network of roads, which is abundant in the southern parts of the study area. In this example, moving to the border zone is relatively easy because of the various side roads that run along the border line. Figure 20 shows a similar example of paths from Vyborg to Lappeenranta, Joutseno and Imatra. In both cases the distance from a side road to a road on another side of the border is under 100 meters.

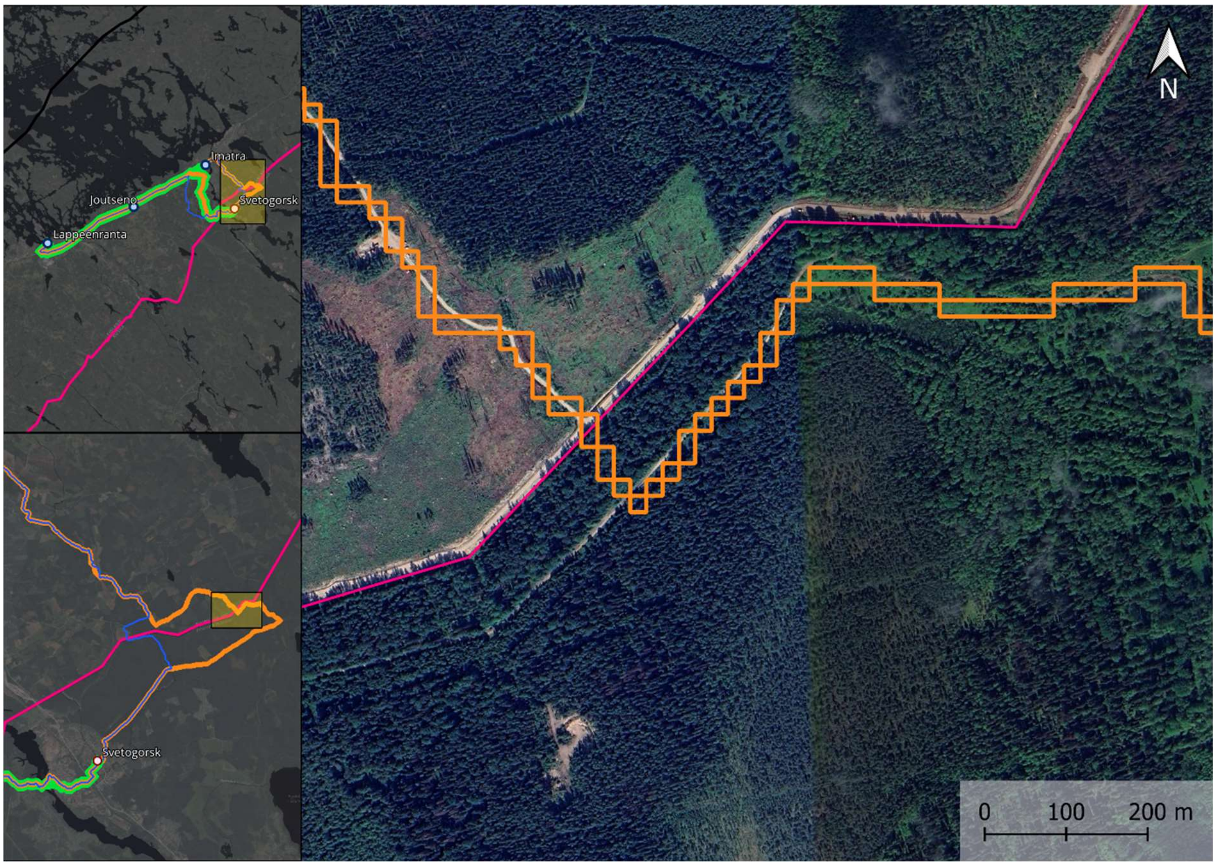

Figure 19. Location where the spring path (scenario 2) from Svetogorsk to Imatra intercepts the border line.

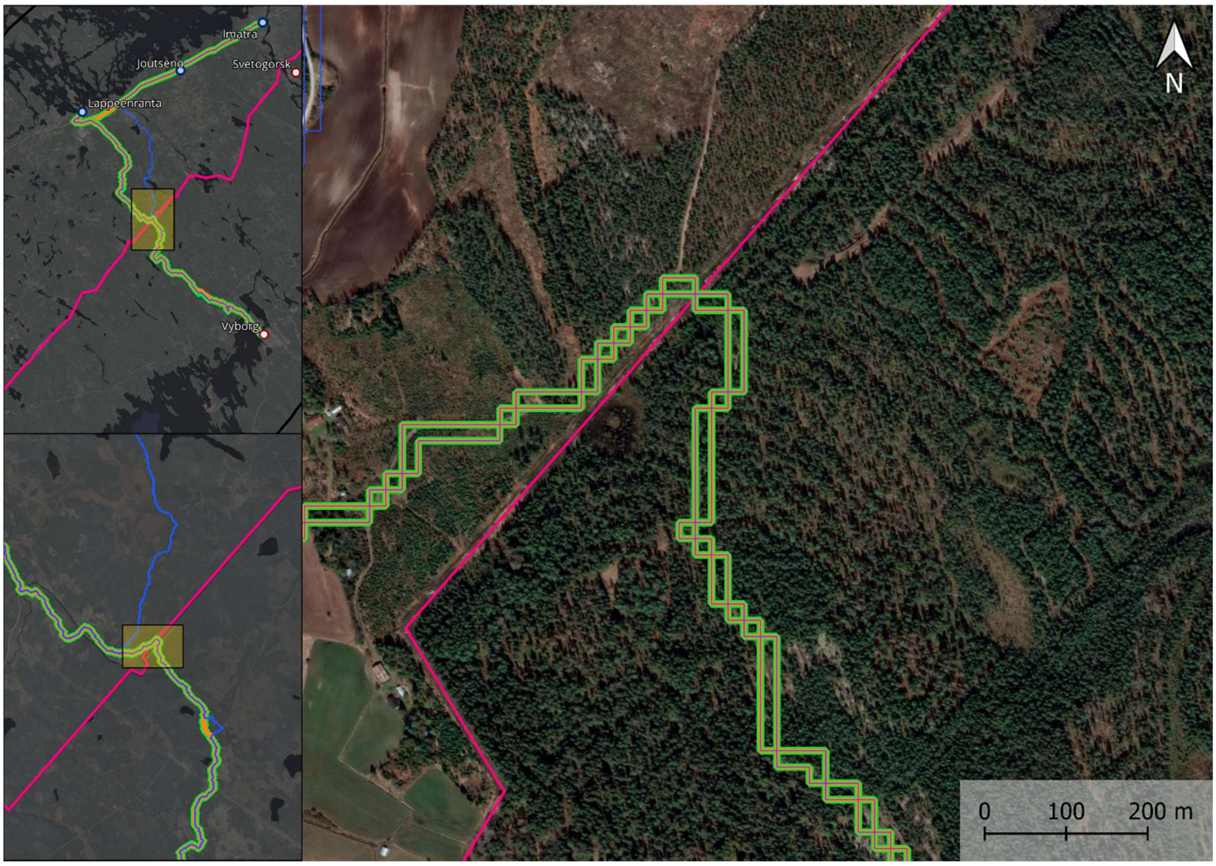

Figure 20. Location where paths from Vyborg to Lappeenranta, Joutseno and Imatra intercept the border line.

Figure 21 shows paths from Svetogorsk to Joutseno and Lappeenranta that go across an agricultural after getting over the border. Regarding individual's ability to cross the border while not being noticed by the border guards of locals, these paths may not be the most realistic, however, in the sense of physical permeability they can be considered viable.

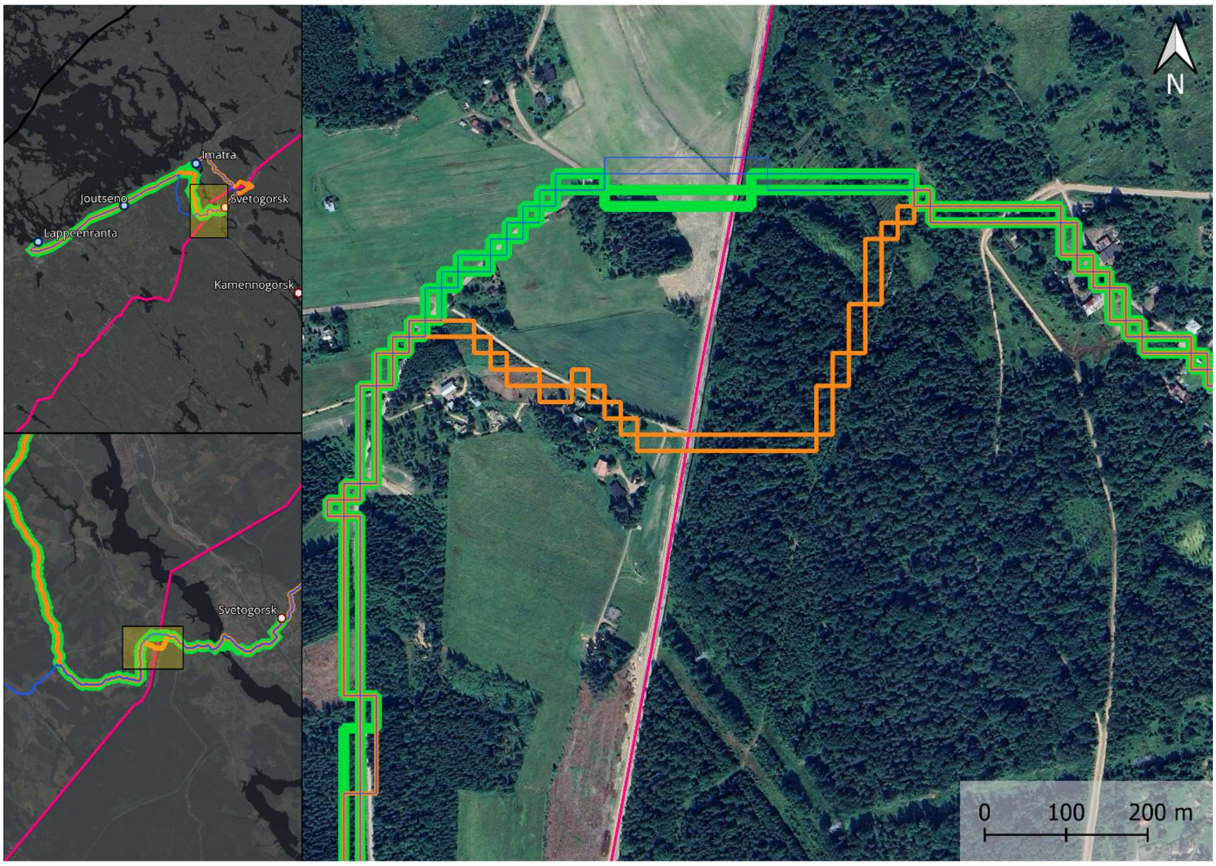

Figure 21. Location where spring, summer and winter paths from Svetogorsk to Joutseno and Lappeenranta intercept the border line.

Figure 22 includes another example of paths that use secondary or tertiary roads to move to the vicinity of the border line and skip over it at the point where the roads on both sides of the border are the closest to each other. Here, the skip from road to another is, again, less than 100 meters.

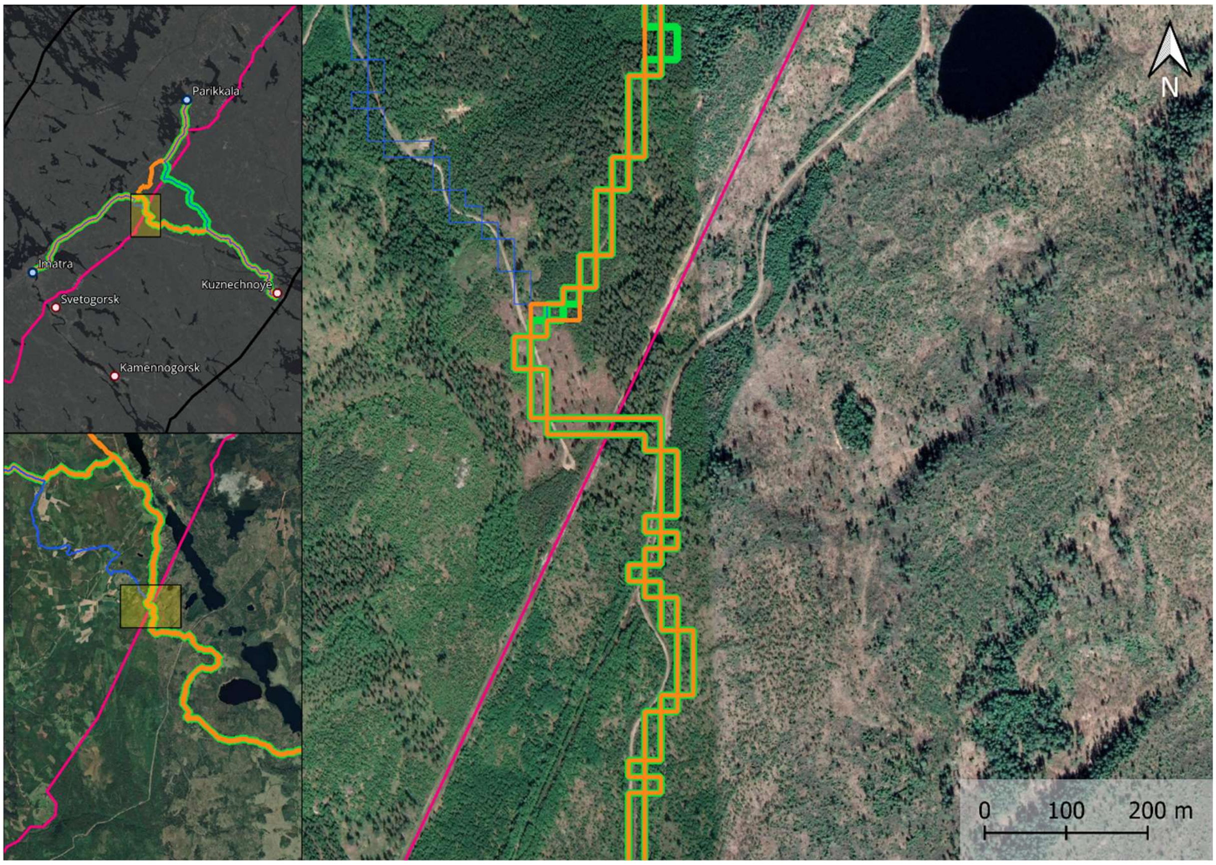

Figure 22. Location where all paths from Kuznechnoye to Imatra, along with the spring path to Parikkala, intercept the border line.

In figure 23, an example of paths that move across a water area is shown. It is interesting to note that while water areas in winter had lesser friction values, spring and summer paths are the ones crossing over a water stream on a route from Kostomuksha to Suomussalmi. While the stream is very narrow (less than 10 meters) it is questionable whether it would be safe to cross, especially in a spring scenario.

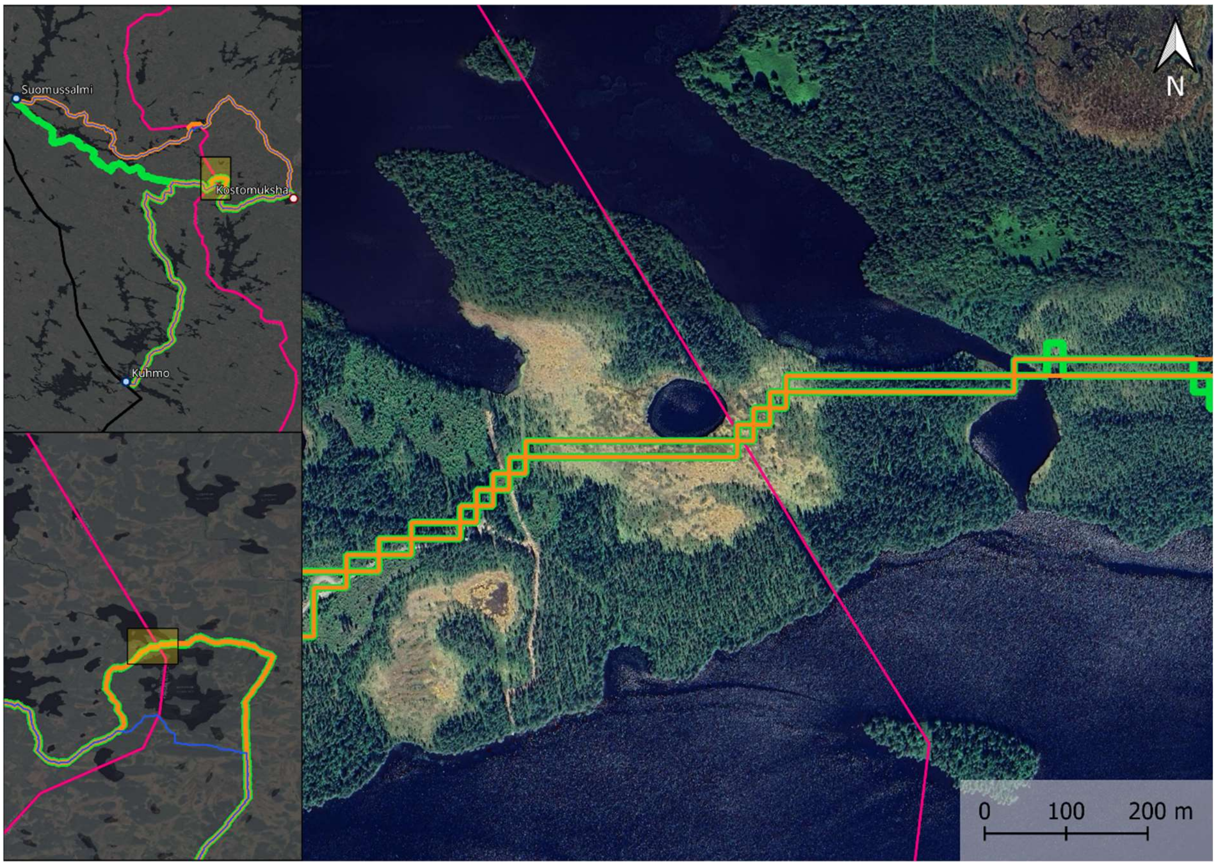

Figure 23. Location where spring and summer paths from Kostomuksha to Suomussalmi intercept the border line.

Paths usually run across the border in locations where roads on both sides of the border are closest to each other. Visual inspection of pathways on a satellite image showed that most of the routes are following mainly secondary or tertiary roads until they get near the border, where they move short distances across forests, croplands or grasslands to get to another secondary or tertiary road on the other side of the border. This visual observation was confirmed by an analysis of paths from different seasons against the land cover data. I grouped the paths from different seasons and compared them with the land cover data in 1- and 3-kilometers buffer areas around the border line to determine which land cover classes were the most used by the paths.

5 Discussion

5.1 Quality of the results and research data

Visual assessment and the comparison of paths with land cover layer and satellite image indicates that paths are relatively realistic. Paths in scenario 1 follow the main roads connecting source and destination towns, as can be expected. In scenario 2, paths follow the alternate routes using mostly secondary roads to get near the border, where they go across the border through short patches of the most permeable land cover types, proceeding on secondary roads on other side of the border. This characteristic is best described in figures 19, 20, 21 and 22. Pathing is seemingly realistic in a way that it crosses the border in places where secondary or tertiary roads on both sides of the border are relatively closest to each other, which is a rational course of action.

As results of the previous chapter have shown, both the friction layers describing border permeability and the paths created based on the cost distance layers indicated that the most effective way of crossing Finnish Russian border is to use secondary or tertiary roads to get as close to the border as possible and then cross short distances on different land cover classes which, in this thesis were mostly forests, grasslands or croplands. I also visually compared the paths with the land cover layer and confirmed these findings. However, a more thorough examination of paths against a google satellite imagery indicated that the paths seemingly ran across the types of land covers that were not considered easily passable in this thesis, i.e. wetlands or water areas. After this observation, I compared the land cover layer with a google satellite imagery in QGIS to find inconsistencies between the two. I was able to determine that there are some flaws in the land cover data used in this thesis, especially regarding wetlands, which are not sufficiently represented in the land cover dataset. While larger wetlands were somewhat visible, smaller wetland areas seem to be systematically misrepresented in the land cover data as grasslands, a flaw that significantly affects how realistic the paths produced in this thesis are in real world applications. This error is probably related to a classification algorithm and how different spectral characteristics have been allocated into land cover classes. ESA WorldCover product validation report has given product an overall accuracy of 76.7% (Zanaga et al. 2021). However, the risk of applying global land cover data on a regional level in a study was well known when I was choosing datasets for this thesis. When making choices with the datasets I wanted to prioritize their consistency and comparability, which would have been more difficult using national datasets from two different countries. Russian national data availability was also uncertain. Therefore, for the purposes of a master’s thesis it was more practical to use global datasets.

I was using OSM national data to refine ESA Worldcover data for the purposes of this thesis by adding the waterway, wetland and settlement data into the original land cover data. While I was satisfied with the waterway addition, it turned out that the OSM data for wetlands in the study area was incomplete in some of the areas. This means that there are visible gaps in the OSM national data for wetlands in certain areas. On the other hand, in areas where the data is complete, it is also very consistent with google satellite imagery. This indicates that the idea of using OSM national data to enhance ESA Worldcover data was rational, but quality of the data limited the results. I was also able to observe that OSM data of Russia was not as sufficient as it was of Finland.

This analysis included a presumed effect of border stations to border permeability in a scenario 2. As described in chapter 3.2.5, border stations affected total friction up to 5 kilometers around each of the stations. Whether this is an actual distance in which the possible surveillance is more intense in a hybrid influencing scenario, remains uncertain. It is also merely an estimation of a possible radius around the border stations that an individual attempting to cross the border illegally would like to avoid. While the effect of border stations regarding illegal border crossing is probable, a magnitude of this effect is unclear and depends on an individual’s perceptions and knowledge of the area, which varies case by case. There are also various types of other border control measures that were not included in this thesis, i.e. border fences and different forms of surveillance.

5.2 Possible issues with the study design

The main issue with the study design in this thesis is the visualization constraint of the results caused by the chosen spatial resolution of the used datasets combined with a large study area. This means that the applied spatial resolution of 20 meters limited possibilities of data visualization in higher map scales. This caused an issue with the analysis of study results, since map scale would have to be smaller so that pixels would be observable, but high enough so the permeability landscape of larger areas could be assessed. This was a challenge especially with the friction layers, since it was not possible to visualize larger areas on a map because many features would not have been visible on larger map scales. Therefore, I had to visualize the results as snapshots from different parts of the study area that supposedly illustrated the variabilities of friction on a larger scale. The same issue was also present when visualizing the results of path analysis. Because of this, it might have been better to limit the study to include only the southern parts of the border.

As mentioned in chapter 3.2, Stephenne and Pesaresi (2006) have previously studied border permeability in a manner that includes an individual’s ability to remain hidden from authorities during the border crossing. While the presumed effect of the border stations was included in this thesis, the aspect of hiding ability was excluded from the analysis. More broad analysis combining both aspects of border permeability would have likely produced significantly different results, given the peripheric nature of most of the regions along the Finnish Russian border, a quality that in previous studies has greatly affected total permeability of studied areas.

Prior to this thesis, I was not familiar with WhiteboxTools analysis platform. While I have experience with other distance tools, I had to get acquainted with distance tools in Whitebox toolkit, especially with the cost-distance and pathway analyses. In WhiteboxTools, the cost-distance analysis produces a cost-distance surface and its backlink raster, which is used for cost-pathway analysis. In contrast with cost-distance surfaces, the backlink raster simply contains directional values that describe the connectivity between pixels. These values are then used to calculate the least cost paths from source points to destinations. To my understanding, this method is appropriate in this type of study, however, I had a few setbacks with cost distance and pathway analyses. I noted that when producing friction layers with certain weight combinations, i.e. higher weight on slope data, the least cost pathway output was either unrealistic or completely flawed. This means that paths were either crossing larger water areas like Gulf of Finland or they very looping in the edges of raster layers. I figured that this might be because in slope data the water areas are simply marked as flat terrain, and therefore slope data does not increase the total friction outside land areas. In resulting total friction layers, land areas consequently have relatively higher friction than water areas, a systematic issue that should be considered. I worked around this issue by limiting the weight of slope data to 0.5, while land cover had a weight of 1. After this adjustment the paths were seemingly more realistic and there were no looping errors present. On second note, this adjustment also limits the realistic effect slope degrees have on individuals’ ability to walk across space.

5.3 Considerations for future studies

This analysis could have benefited from higher temporal resolution, meaning that instead of analyzing seasonal permeability, this analysis could have been made of weekly changes of permeability. This would require integrating the dynamic between weather conditions and different types of terrain into spatial permeability analysis. More dynamic model of spatial permeability in Finnish Russian border seems like a rational step in further analyses of this topic, because of the quickly changing nature of permeability conditions in the study area. Snow cover and flood conditions greatly depend on weather conditions that can change quite radically even on daily levels, and thus temporally more precise analysis is needed to better reflect actual spatial permeability in the border. If this type of analysis can be conducted in a satisfying detail, it could possibly enable use of spatial permeability model in border surveillance. However, interactions between weather conditions and terrain types remain complex in their nature and additional research of the topic is therefore necessary.

It would be relevant to compare optimal paths produced in this thesis to the newly built segments of border fences in Finland to see, whether their effect would render some of the paths unusable. The same comparison could ideally be made with optimal paths in relation to the locations of additional border surveillance methods, like thermal and wildlife cameras deployed by the Finnish Border Guard. This is, however, not possible in public research since operational data of the Finnish Border Guard is not made publicly available.

Acknowledgements

I want to give special thanks to my friend and colleague Iiro Seppä from the department of geography in University of Turku, who's advice and insight through our conversations have helped me a lot to understand the geospatial methods used in this thesis. He has also scrutinized my ideas and given me confidence to move forward with this thesis in times of doubt, for which I am very grateful.

Generative AI has been used in this thesis to produce Python scripts that were used to prepare, modify and analyze geospatial datasets used in this study. The large language model used was LeChat by Mistral AI. After the use of each script, the author has reviewed and confirmed that the scripts have done the desired operations correctly. LeChat was also used as reading assistance when going through the research articles. The author has, again, reviewed the research articles and verified outputs of the LLM.

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