The quest for sustainable Reykjavik Capital Region: lifestyles, attitudes, transport habits, well-being and climate impact of young adults (SuReCaRe)

Report for a project funded by Skipulagstofnun
Rannsóknar- og þróunarsjóður

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2018

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Summary

The report contains the results and description of methods used in the Tasks 1 and 2 of the project. The results of Task 1: *Quantitative description of urban form characteristics in the Reykjavik Capital Region* are a series of maps and GIS layers that describe urban form characteristics relevant for daily travel patterns and well-being of the residents. These include access to green, blue and open spaces, population density, access to public transportation, distance to the city center, street network characteristics, and travel-related urban zones. The report is accompanied by a GIS database that contains the measures calculated in a 100 m grid. The results of Task 2: *Quantitative description of the residents' climate impacts from transport* include an estimation of greenhouse gas (GHG) emissions of the study participants Capital Region residents aged 25 to 40. The estimations are then analyzed geographically to highlight the differences in the region and the relationships with residential location and the urban form.

Quantitative description of urban form characteristics in the Reykjavik Capital Region

The Capital Region was divided into 6 zones based on population density, the floor area density of commercial and office buildings and bus departure frequency from stops within a 5-minute walk. The method was based on a similar classification used in Finland and Sweden. The zones are the central pedestrian zone, the fringe of the central pedestrian zone, pedestrian zones of the sub-centers, intensive public transportation zone, basic public transportation zone, and car-oriented zone.

The urban form characteristics are presented on maps in section 4, and as GIS layers in the accompanying database. The results highlight the differences between the areas in the region in terms of supporting the use of different travel modes and participation in outdoor activities.

The results show that the vast majority of the Capital Region has access to a bus stop within a 5-minute walk, but with varying frequency of departure and route diversity. The zone with the best access (Zone 1) is located around the main bus stops of Reykjavik city center, along with the main roads of Reykjavík and around other major stops. This zone is inhabited by 19.4% of residents in the region. It is surrounded by zone 2, in which buses depart less frequently, albeit not evenly. The zone houses 34.1% of residents in the region. Most notably, almost no areas in Garðabær and Mosfellsbær belong to this zone. The largest zone is zone 3, in which there are buses within a 5-minute walk, but the frequency of departures is less than 4 per hour. It houses 43.4% of residents. Areas with no access to a bus stop within walkable distance are rare but do exist.

The urban region is stretched for long distances from the city center, which is a major factor in choosing travel modes in daily travel. In 2017, around 40 thousand people lived within 3 km from the center, and another 40 thousand in 3-6 km distance band. More than 50 thousand people lived in the distance bands 6-9 km and 9-12 km from the center. About 25 thousand people lived further than 12 km from the main city center.

The highest population densities are observed in central and near-central Reykjavík, more peripheral locations, such as Breiðholt and Háaleiti, and at the very central parts of

Hafnarfjörður, Kópavogur, and Grafarvogur. The lowest population densities are observed in Garðabær, Mosfellsbær, Álftanes, Árbær, and Vatnsendi. The highest street connectivity, which is related to good conditions for walking, is observed in downtown Reykjavík, the old part of Vesturbær, Hlíðar, Breiðholt, and some centrally located parts of Grafarvogur and Hafnarfjörður. Lower values are observed in more suburban and coastal areas.

The access to green spaces and the amount of vegetation around residential locations are the lowest in built-up areas surrounded by water or sparsely-vegetated land, most of them centrally located. The index has the highest values in areas close to a thicker vegetation, such as forests or river valleys, most of them peripherally located.

Residents' climate impacts from transport

The calculated annual emissions from local, domestic and international travel vary depending on the residential location of respondents. Residents of the more centrally located areas have on average relatively low emissions from local travel, averaging at about 500 kg CO2e per year per person in the *central pedestrian zone*. Residents of the suburban neighborhoods have relatively high emissions from local travel, averaging at about 1400 kg CO2e per year per person in the *car-oriented zone*. At the same time, the highest emissions from international travel are observed in centrally located areas, including Vesturbær and Miðbær. The residents of the most central areas cause higher emissions (ca. 3600 kg CO2e per year per person in the *central pedestrian zone*) than the residents of more suburban areas (ca. 2400 kg CO2e per year per person in the *car-oriented zone*). No significant differences between geographic areas were found in terms of average emissions from domestic travel. The emissions from all travel combined do not differ significantly across the region, despite a clear geographic trend in the emissions from local travel, and average at about 4000 to 4500 kg CO2e per year per person.

Samantekt

Skýrslan inniheldur niðurstöður og lýsingu á aðferðum sem notaðar eru í hluta 1 og 2 verkefnisins (e. Tasks 1 and 2). Niðurstöður hluta 1: Lýsing á byggðareinkennum höfuðborgarsvæðisins eru kort og GIS-lög sem lýsa byggðareinkennum sem skipta máli fyrir daglegar ferðavenjur og vellíðan íbúa. Þar á meðal eru kort sem sýna aðgengi að grænum, bláum og opnum svæðum, íbúaþéttleika, aðgengi að almenningssamgöngum, fjarlægð frá miðborginni, einkennum gatnaneta og einnig kort af ferðatengdum borgarsvæðum. Skýrslunni fylgir GIS gagnagrunnur sem inniheldur mælieiningar sem reiknaðar eru í 100 m rist. Niðurstöður hluta 2: Lýsing á loftslagsáhrifum af ferðum íbúa innihalda áætlaða losun gróðurhúsalofttegunda frá þátttakendum rannsóknarinnar, íbúar höfuðborgarsvæðisins á aldrinum 25 til 40 ára. Áætlaða losunin er síðan greind landfræðilega til að varpa ljósi á muninn milli svæði og tengsl við staðsetningu búsetu og byggðarmynstur.

Lýsing á byggðareinkennum höfuðborgarsvæðisins

Höfuðborgarsvæðinu var skipt upp í 6 svæði út frá íbúaþéttleika, þéttleika verslunar- og skifstofuhúsnæðis og tíðni brottfara frá strætó stoppistöðvum sem eru í innan við 5 mínútna göngufjarlægðar. Flokkunaraðferðin byggðist á svipaðri aðferð sem notuð var í Finnlandi og Svíþjóð. Svæðin eru; göngusvæði miðsvæðis (e. central pedestrian zone), jaðar göngusvæðis miðsvæðis (e. the fringe of the central pedestrian zone), gönguvænir kjarnar (e. pedestrian zones of the sub-centers), öflugt almenningssamgöngusvæði (e. intensive public transportation zone), almenningssamgöngusvæði (e. basic public transportation zone) og bílasvæði (e. car-oriented zone).

Byggðareinkenni eru sett fram á kortum í kafla 4 og sem GIS-lög í gagnagrunninum sem fylgir skýrslunni. Niðurstöðurnar vekja athygli á hversu ólík svæði borgarinnar eru hvað varðar stuðning við notkun mismunandi ferðamáta og þátttöku í ýmisskonar útivist.

Niðurstöðurnar sýna að mikill meirihluti höfuðborgarsvæðisins hefur aðgang að strætóskýli í innan 5 mínútna göngufjarlægð (400 m), en tíðni brottfara er breytileg. Svæðið með besta aðgengið (Svæði 1) er staðsett í kringum aðal stoppistöðvar miðborgarinnar, stofnbrautir höfuðborgarsvæðisins og aðrar helstu stoppistöðvar. Á þessu svæði búa 19,4% íbúa og 21,9% heimila höfuðborgarsvæðisins. Það er umkringt svæði 2, þar sem strætó fer sjaldnar, þó ekki jafnt. Á því svæði búa 34,1% íbúa og 34,4% heimila. Eftirtektavert er að nánast engin svæði í Garðabæ eða Mosfellsbær tilheyra þessu svæði. Stærsta svæðið er svæði 3, þar sem það eru strætó stoppisvöðvar í innan við 400 m, en tíðni brottfara er minni en 4 á klukkustund. 43,4% íbúa og 40,9% heimila búa á svæðinu. Svæði sem hafa ekki aðgang að strætóskýli innan 400 m eru sjaldgæf en finnast þó.

Borgin teygir sig langar vegalengdir frá miðbænum, sem er stór þáttur í vali á ferðamátum í daglegum ferðum borgarbúa. Árið 2017 bjuggu um 40 þúsund manns innan 3 km frá miðbænum og 40 þúsund í 3-6 km fjarlægð. Meira en 50 þúsund manns bjuggu í fjarlægðarflokkunum 6-9 km og 9-12 km frá miðbænum. Um 25 þúsund manns bjuggu í lengra en 12 km fjarlægð frá miðbænum.

Mesti íbúaþéttleikinn er að finna í miðbænum og í nálægð við miðbæinn, í jaðarsvæðum eins og Breiðholti og Háaleiti, og í miðkjörnum Hafnarfjarðar, Kópavogs og Grafarvogs. Lægsti íbúaþéttleiki finnst í Garðabæ, Mosfellsbæ, Álftanesi, Árbæ og Vatnsenda. Hæstu gildin fyrir götutengsl, sem er gildi sem tengist góðum aðstæðum til að ganga, sjást í miðbæ Reykjavíkur, gamla Vesturbænum, Hlíðum, Breiðholti og í miðlægum hlutum Grafarvogs og Hafnarfjarðar. Lægri gildi koma fram í úthverfum og strandsvæðum.

Aðgengi að grænum svæðum og magn gróðurs í kring um íbúðarsvæði er lægst í byggðarsvæðum sem umkringd eru vatni eða lítt-grónu landi, sem flest eru staðsett miðsvæðis. Vísitalan er hæst á svæðum nálægt þykkum gróðri, svo sem skógum eða dölum, flest þeirra staðsett á jöðrum borgarinnar.

Lýsing á loftslagsáhrifum frá ferðum íbúa

Reiknuð árleg losun frá daglegum ferðum innan borgarinnar, út á land og til annarra landa er mjög misjöfn eftir því hvar þátttakendur eru búsettir innan borgarinnar. Íbúar sem búsettir eru nálægt miðbænum hafa að meðaltali tiltölulega litla losun frá daglegum ferðum innan borgarinnar, þeir sem búa á *göngusvæðinu miðsvæðis* losa að meðaltali um 500 kg af koltvísýringsígildum á ári á mann. Íbúar úthverfanna losa tiltölulega mikið frá daglegum ferðum, en íbúar *bílasvæðis* losa að meðaltali um 1400 kg á ári á mann. Á sama tíma sést mesta losunin frá utanlandsferðum á miðlægum svæðum, þar á meðal í Vesturbæ og Miðbæ. Íbúar á flestum miðlægum svæðum valda meiri losun frá utanlandsferðum en íbúar úthverfa (íbúar *göngusvæðis miðsvæðis* losa að meðaltali um 3600 kg af koltvísýringsígildum á ári á mann á meðan íbúar bílasvæðis um 2400 kg). Við höfum ekki fundið marktækan mun á svæðunum hvað varðar meðallosun frá ferðum út á land. Þrátt fyrir að skýr landfræðilegur munur sé á losun frá daglegum ferðum innan borgarinnar, er munur milli svæða borgarinnar á heildarlosun frá öllum ferðum ekki marktækur, og er að meðaltali um 4000 til 4500 kg af koltvísýringsígildum á ári á mann.

Background

Knowledge of actual mobility patterns and relationships between urban form and mobility behavior is necessary to guide sustainable mobility planning in cities. Previous research on such relationships points to the significant role of urban structure that is nevertheless modified by psychological, social and cultural factors. Existing evidence is based on studies conducted predominantly in the USA (e.g. Ewing and Cervero, 2010) and Nordic countries (Naess, 2012). Still, there have been few studies conducted on this topic in Iceland. The proposed project would strengthen the evidence basis for changes in urban structure aimed at increasing access to services while lowering environmental impacts of travel. SoftGIS methodology proposed for the project has been successfully used in numerous studies on environmental and psychological factors of everyday mobility in Finland (Salonen et al. 2014; Haybatollahi et al. 2015; Broberg & Sarjala, 2015) and other countries (Czepkiewicz et al. 2016).

Despite the relatively low environmental impact of domestic production, residents in Nordic countries cause relatively high levels of emissions, when indirect sources are taken into account. It is largely due to increased outsourcing and high level of consumption power (Heinonen et al. 2013ab; Wiedmann et al. 2015; Ivanova et al. 2016). This is also true for Iceland, which has a low level of climate impact associated with local energy production, but indirectly causes high level of emissions due to the import of goods produced elsewhere, and an important role of private car and aviation in individual travel – resulting in emissions as high as in e.g. Australia or the UK according to a recently published first-ever study of the carbon footprints of Icelandic consumers (Clarke et al. 2017). More detailed calculations of indirect emissions associated with lifestyles of Icelanders are still rare and researchers have only recently started to apply life-cycle analysis (LCA) methods to Icelandic economy (Clarke et al. 2017; Heinonen 2017).

Project goals and outcomes

SuReCaRe is set to improve our understanding of the premises of creating sustainable urban settlements, with the focus on Reykjavik Capital Region. The project approaches the issue in a novel way never used in Iceland before. Data about the lifestyles, transport habits, feelings, and attitudes are collected with a SoftGIS survey combining map and traditional survey tasks. Climate impact of individual behavior is estimated using a life-cycle analysis (LCA) methodology that takes into account indirect sources of greenhouse gas emissions. The combination of methods enables new analytical possibilities that will improve understanding of individual lifestyles and premises of sustainable urban development of the Capital Region.

Project goals

The project poses research goals and questions in three themes closely related to the Landsskipulagsstefna 2015–2026:

- Everyday mobility and use of services: in relation to part 3.2 of the policy (Sjálfbært skipulag þéttbýlis) the project investigates mobility patterns (e.g. distances, directions, frequencies, and travel modes) of young adults living in the Capital Region, the climate impact of the mobility patterns, and the extent to which settlement structure influences these patterns at local and regional scales.

- Well-being and residential satisfaction: in relation to part 3.3 of the policy (Gæði hins byggða umhverfis) the project investigates how the urban structure of Capital Region contributes to a good life and flourishing of its inhabitants, and whether the built environment provides well for the residential needs and preferences expressed by young adults in the region.

- Climate impact: in relation to part 3.7 of the policy (Náttúruvá og loftslagsbreytingar) the project investigates climate impact (i.e. direct and indirect greenhouse gas emissions of service use and mobility) of individual behaviors of young adults of the Capital Region, and the degree to which the climate-relevant behaviors are influenced by settlement structure in local and regional scales. The chapter shows examples of Figures and Tables and their references to them.

Project outcomes

The research goals and questions of the project area realized and answered by performing the following tasks:

Task 1. Quantitative description of urban form characteristics in the Reykjavik Capital Region. The measures of the urban form was based on external GIS data sources obtained from SSH (http://ssh.is/), GMES Urban Atlas, OpenStreetMap, and Landsat. The measures were calculated in GIS-based buffers related to the residential location of study participants. The content of urban form measures was chosen based on their relevance for well-being and sustainability, including such aspects as service and job accessibility, population density, access to green and open spaces, street layout, and access to public transportation. The task resulted in GIS layers and digital maps that can be shared with other institutions for use in planning and research.

Task 2. Quantitative description of the residents' climate impacts from transport. The internal structure of individual climate impacts was based on behavioral data reported in the survey and life cycle assessment (LCA) approach, that includes both direct (fuel combustion) and indirect (fuel and energy production, infrastructure construction, vehicle manufacturing) emissions. The LCA data and calculation methods were taken from previous studies (e.g. Chester & Horvath, 2009; Aamaas et al., 2013; Czepkiewicz et al., 2018).

Task 3. Quantitative analysis of relationships between individual traits of respondents, urban form measures, climate impacts, and well-being. Urban form characteristics and individual climate impacts were calculated in tasks 1 and 2 described above. Individual traits were elicited with an online survey that included socioeconomic and demographic characteristics, and psychological and cultural attitudes. Well-being and residential satisfaction was derived from answers to a series of Likert-like statements included in the survey. The data allowed for testing relationships between urban form and individual characteristics on one side, and well-being and climate impacts on the other side.

The report includes the results of Task 1 and 2. The results of task 3 are included in forthcoming academic publications. The following sections refer to each of the tasks by presenting the methods and materials used to perform each task, its results, and conclusions.

Urban form characteristics in the Reykjavik Capital Region

Density- and transport-related measures

Population density

Materials and methods

Measures based on population data provided by Samtök sveitarfélaga á höfuðborgarsvæðinu (SSH) were calculated in 100 m grid. As spatial units, 1km buffers were used, both simple and street network-based. To assign population data to each buffer, the statistics of the grid cell centroids that were contained or intersected by each buffer were summarized. The statistics included the number of residents within buffers (figure 1) and population density per hectare (figure 2).

Population density is one of the most commonly used measures of urban density. It approximates the social opportunities related to meeting other people and is often related to the availability of various services. The measures calculated in street network buffers may be interpreted as the number of people that can be reached within a 10-15 minute walk from home. The measures in simple buffers are the more conventional way of measuring population density, which does not consider characteristics of the street network.

Results

The highest population densities are observed in central and near-central Reykjavík (Austurbær, Hlíðar, Vesturbær), and more peripheral locations, such as Breiðholt and Háaleiti. High population densities are also observed at the very central parts of Hafnarfjörður, Kópavogur, and Grafarvogur. The lowest population densities are observed in Garðabær, Mosfellsbær, Álftanes, Árbær, and Vatnsendi.

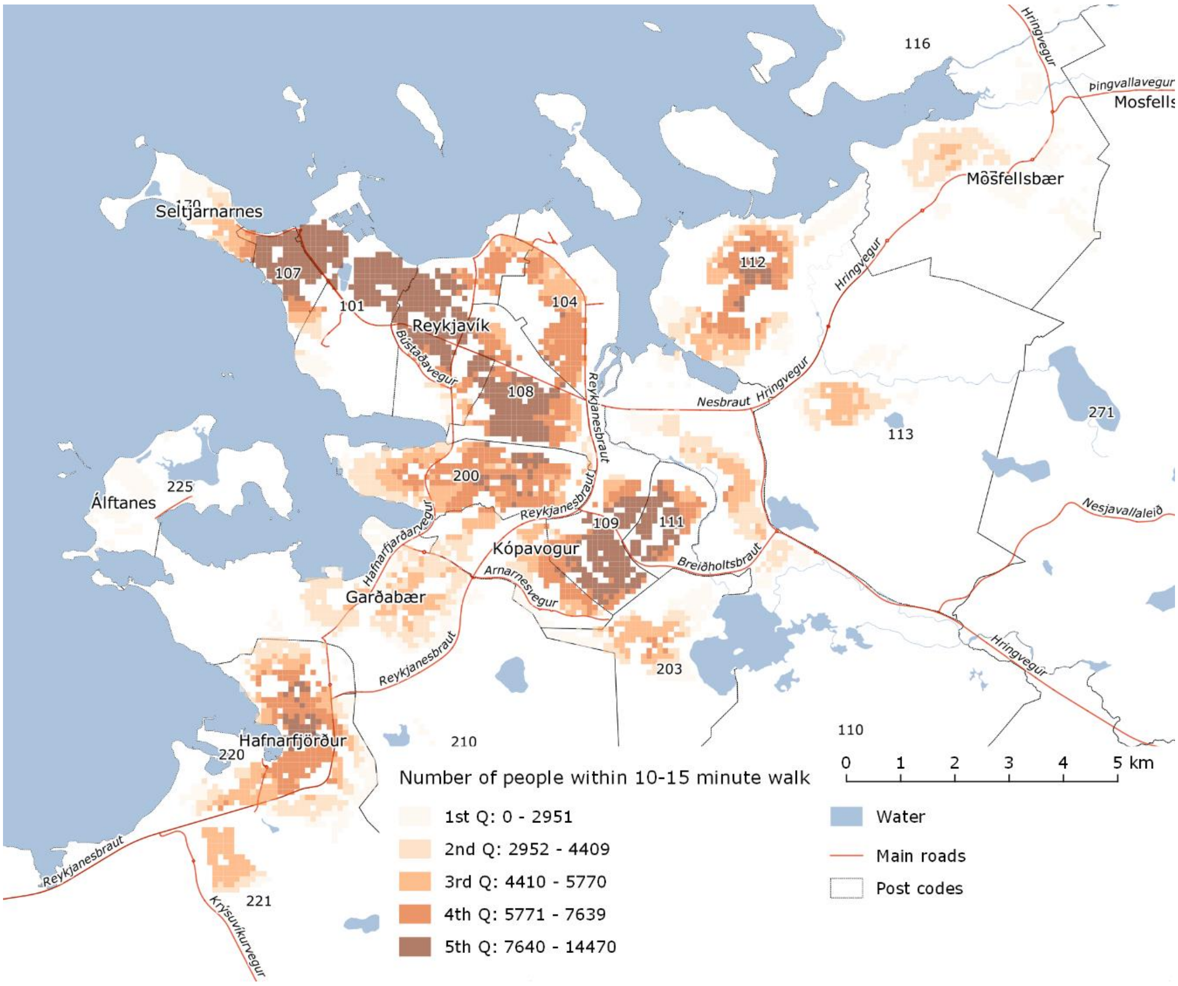

Figure 1. Spatial distribution of population density in the Capital Region measured as the number of residents within 1km street network buffer (approximately 10-15 minutes walk)

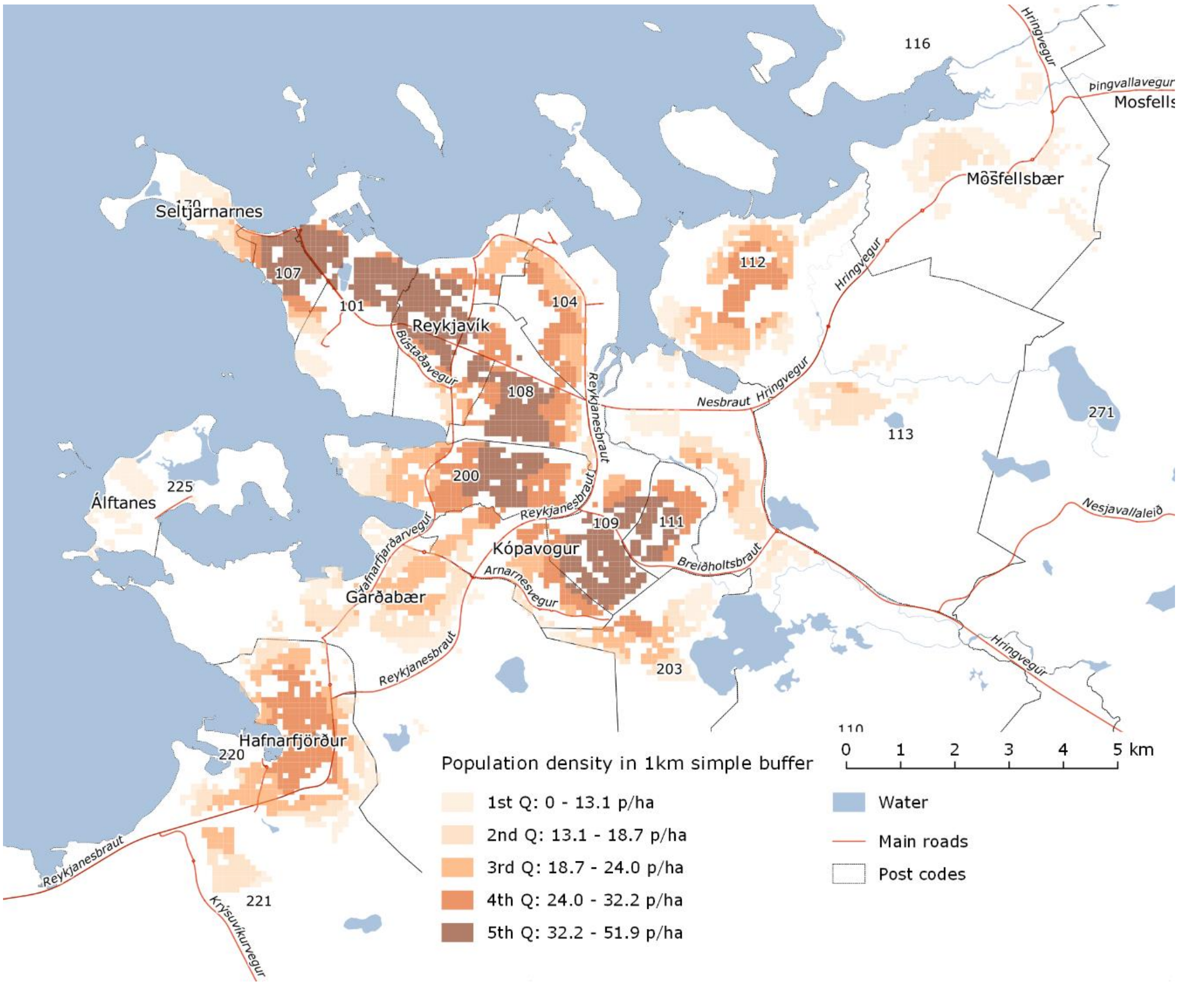

Figure 2. Spatial distribution of population density in the Capital Region measured as the number of residents per hectare within 1km simple buffers around residential locations

Street connectivity

Materials and methods

Street connectivity is one of the measures of walkability (i.e. propensity of urban environments to support walking for transportation). It is defined as "the directness and availability of alternative routes from one point to another within a street network" (Handy et al., 2002). Usually calculated in administrative units, it can also be calculated in areas related to residential location. Following Hirsch et al. (2014), it is calculated here as the ratio between the area covered by 1km simple buffer and area covered by 1km street network buffer.

The measure assumes values between 0 and 1, but due to polygon generalization, it may slightly exceed 1. High values mean that the street network around the location is dense and well connected, there are many pedestrian paths, there are few closed areas or they are small and that a large area can be covered on foot. Low values mean that the street network is fragmented and sparse (e.g. there are many cul-de-sacs and few pedestrian paths), there are large areas that do not allow passage (e.g. airports, factories, water bodies) and that only a small area can be covered on foot. Areas with good street connectivity potentially offer better access to services and other destinations, but the measure does not directly cover this aspect of walkability.

Results

The highest connectivity is observed in downtown Reykjavík, the old part of Vesturbær, Hlíðar, Breiðholt, and some centrally located parts of Grafarvogur and Hafnarfjörður. Lower values are observed in more suburban and coastal areas (Figure 3).

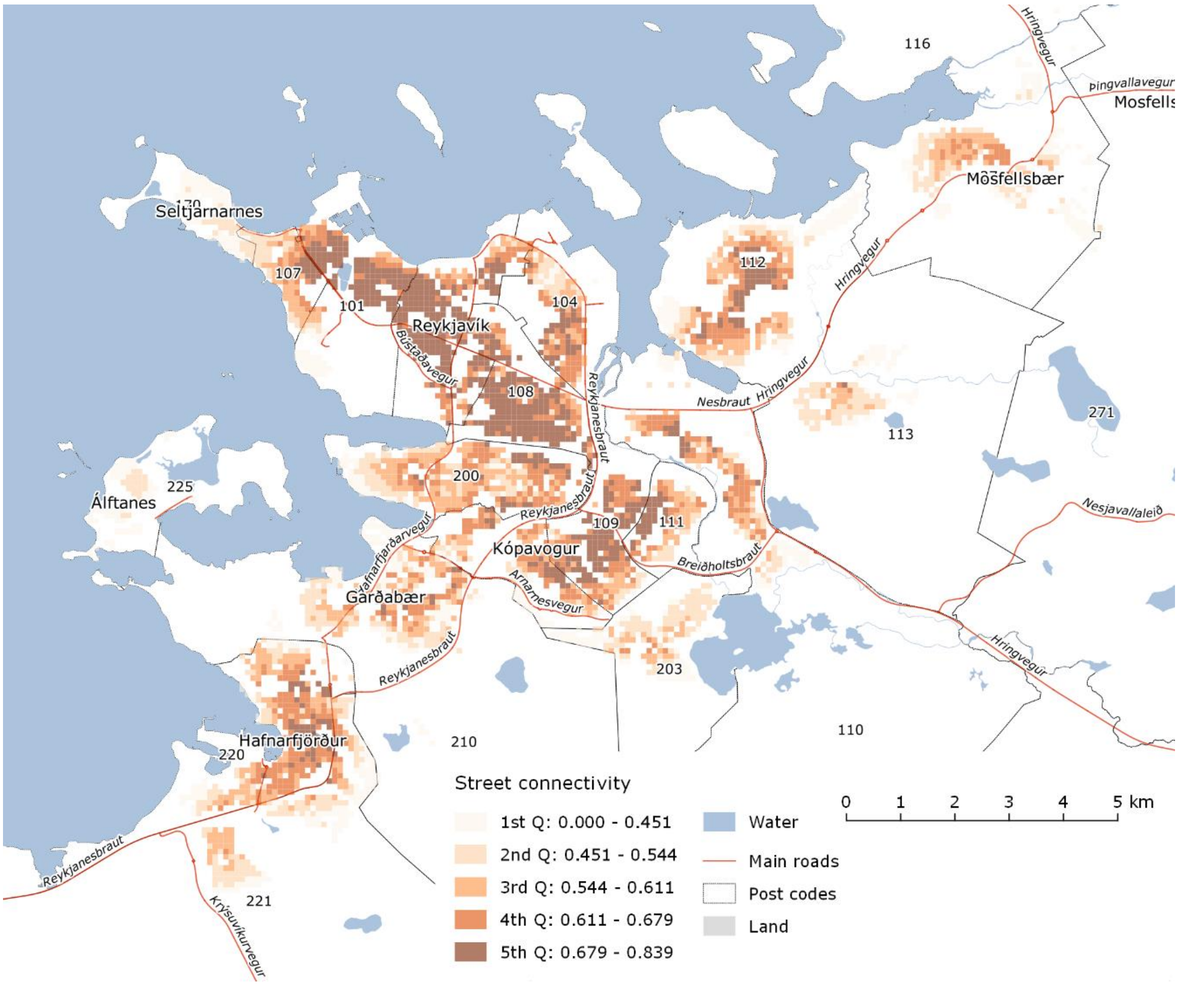

Figure 3. Spatial distribution of street connectivity around places of residence measured as a ratio between a 1km simple buffer and 1km street network buffer.

Access to public transportation

Materials and methods

Access to public transportation is one of the key variables related to everyday travel in cities. It can be measured in a variety of ways and in this case, it is based on distance to bus stops and average frequency of departures from the stops. The data on bus stop location and attributes was downloaded from SSH website. The bus stops were divided into three classes, similarly as in SSH materials: stops that have at least 10 departures per hour on average (waiting time about 6 minutes), stops that have at least 4 departures per hour on average (waiting time about 15 minutes) but less than 10 departures, and stops that have less than 4 departures per hour on average. Then, areas located within walking distance to the stops of each category were delineated using Service Area tool in Network Analyst in ArcGIS 10.5. The threshold distance was 400 meters, which roughly represents a distance that can be covered in 5 minutes by an average person. Then, the residential areas were assigned to the zones with access to bus stops of varying departure frequency. An alternative version of the measure in which the threshold distance equals 332 meters was also calculated. The zones are similar to those used by the SSH, but in our measures, the distances are measured along the street network and not as straight lines, and as such are more realistic.

Results

The results show that the vast majority of the Capital Region has access to a bus stop within a 5-minute walk, but with varying frequency of departure. The zone with the best access (Zone 1) is located in Reykjavik city center, around bus stops and stations such as Lækjatorg and Hlemmur, along the main roads of Reykjavík, such as Bústaðavegur and Hringbraut, and around major stops, such as Mjódd, Ártún, Spöngin, Ásgarður in Garðabær, Hamraborg in Kópavogur, Fjörður in Hafnarfjörður, and the main stop in Mosfellsbær. This zone is inhabited by 19.4% of residents in the region. It is surrounded by zone 2, in which buses depart less frequently, albeit not evenly. Most notably, almost no areas in Garðabær and Mosfellsbær belong to this zone. The zone houses 34.1% of residents in the region. Almost all remaining areas of the Capital Region belong to the zone 3, in which there are buses within a 5-minute walk, but the frequency of departures is less than 4 per hour (average waiting time is longer than 15 minutes). It's the largest zone, and it houses 43.4% of residents. Areas with no access to a bus stop within walkable distance are rare but do exist, mostly in fringe areas of Mosfellsbær, Garðabær, and Kópavogur. Only 3.1% of the residents live in this zone.

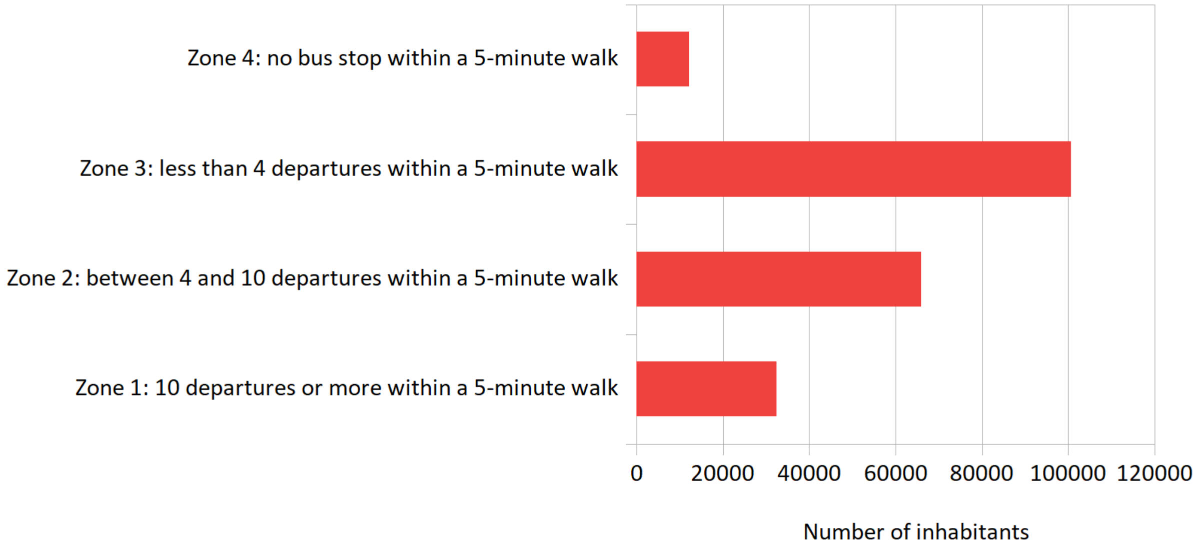

Figure 4. The number of inhabitants with different levels of access to public transportations based on distance to bus stops and departure frequency (bus stop and population data source: SSH.is).

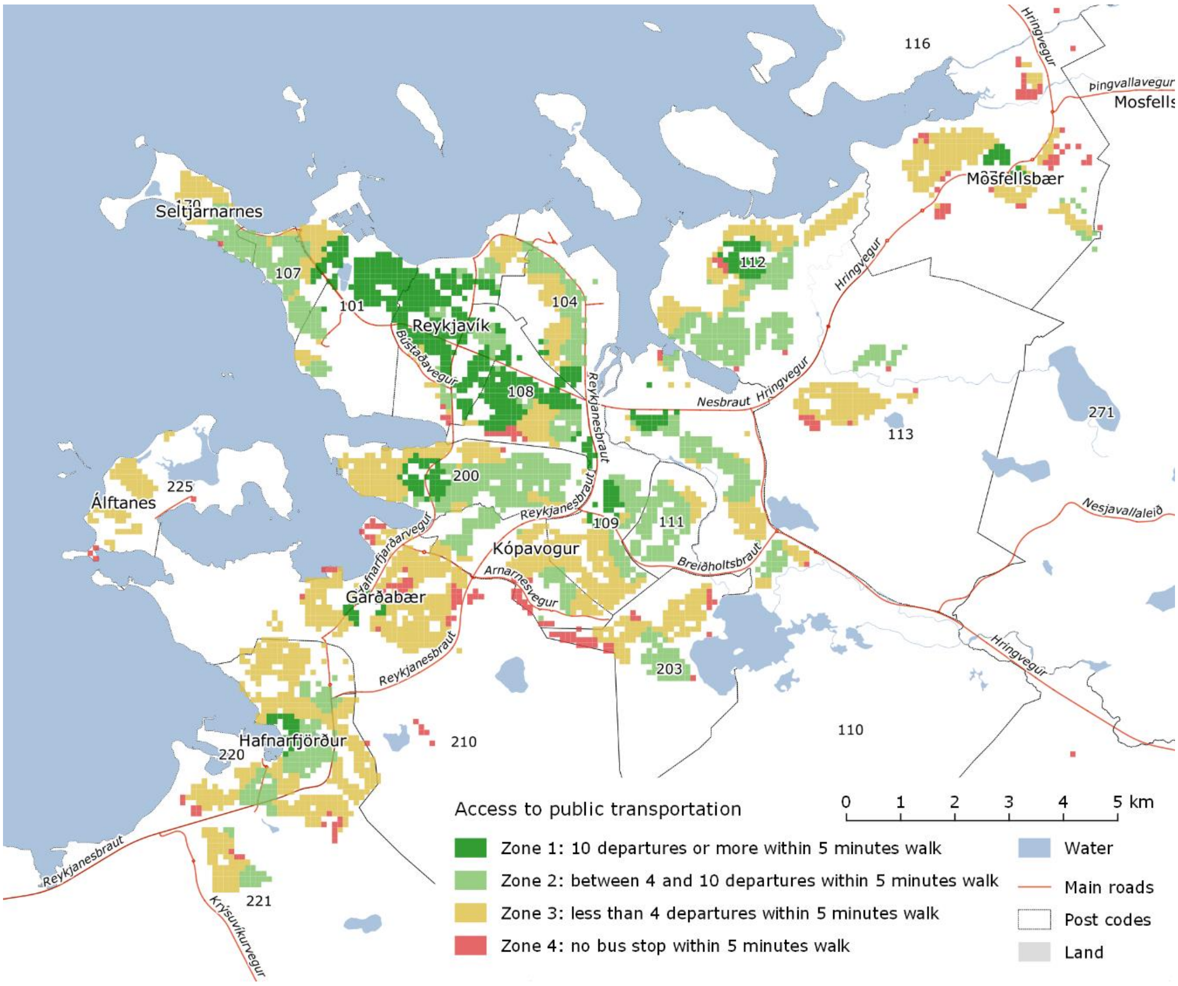

Figure 5. Spatial distribution of different levels of access to public transportation based on distance to bus stops and departure frequency (bus stop data source: SSH.is).

Distance to the city center

Materials and methods

Distance to the city center was calculated as the shortest driving route between each grid cell and the point chosen to represent the center. The point was located at the corner of Laugavegur, Bankastræti, and Skólavörðustígur, after consultation with an expert (Harpa Stefansdóttir). The driving distances were determined with Route algorithm in Network Analyst toolset in ArcGIS 10.5. The street network was based on roads layer (samgöngur) from the i50v topographic map. The variable was calculated in two versions, in meters and kilometers. The distances were also grouped into 3 km bands such as 0-3, 3-6, 6-9, 9-12 and so on.

The measure is a crude representation of the centrality of residential locations. It is thought to represent the location on the urban-suburban continuum and can be used as a proxy for access to jobs and services in mono-centric cities. Despite its rather simple character it has been employed in many studies, in which it has been significantly related to longer traveling distances, longer commuting times, higher energy use for transport, and more frequent use of motorized travel modes, especially private car (Holden & Norland, 2005; Næss et al., 2010; Næss, 2012).

Results

Four neighborhoods are located within 3 kilometers driving from the city center: Austurbær, Vesturbær, Hlíðar, and Tún, roughly corresponding to the postcodes 101, 107, and 105. The next distance band, between 3 and 6 kilometers includes Seltjarnarnes, central parts of Kópavogur, and postcodes 104 and 108 in Reykjavík. Garðabær, the southern part of Kópavogur, Breiðholt (postcodes 109, 111 in Reykjavík), and Árbær mostly belong to the band between 6 and 9 kilometers from the city center. Other areas, including Hafnarfjörður, Álftanes, Grafarvogur, and Mosfellsbær are located farther away. In 2017, around 40 thousand people lived in bands 0-3 km and 3-6 km, and more than 50 thousand people lived in bands 6-9 km and 9-12 km.

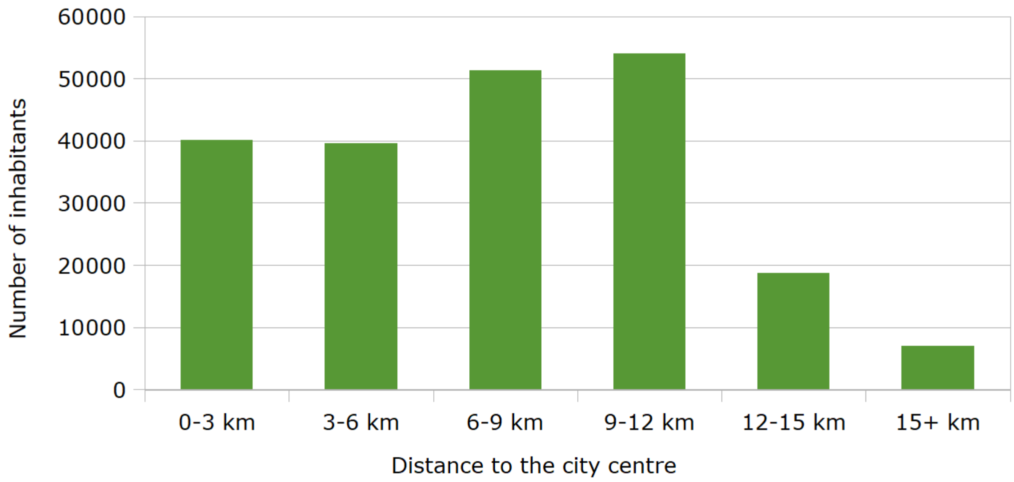

Figure 6. The number of inhabitants living in different distance bands to the city center (population data from January 2017, source: SSH.is)

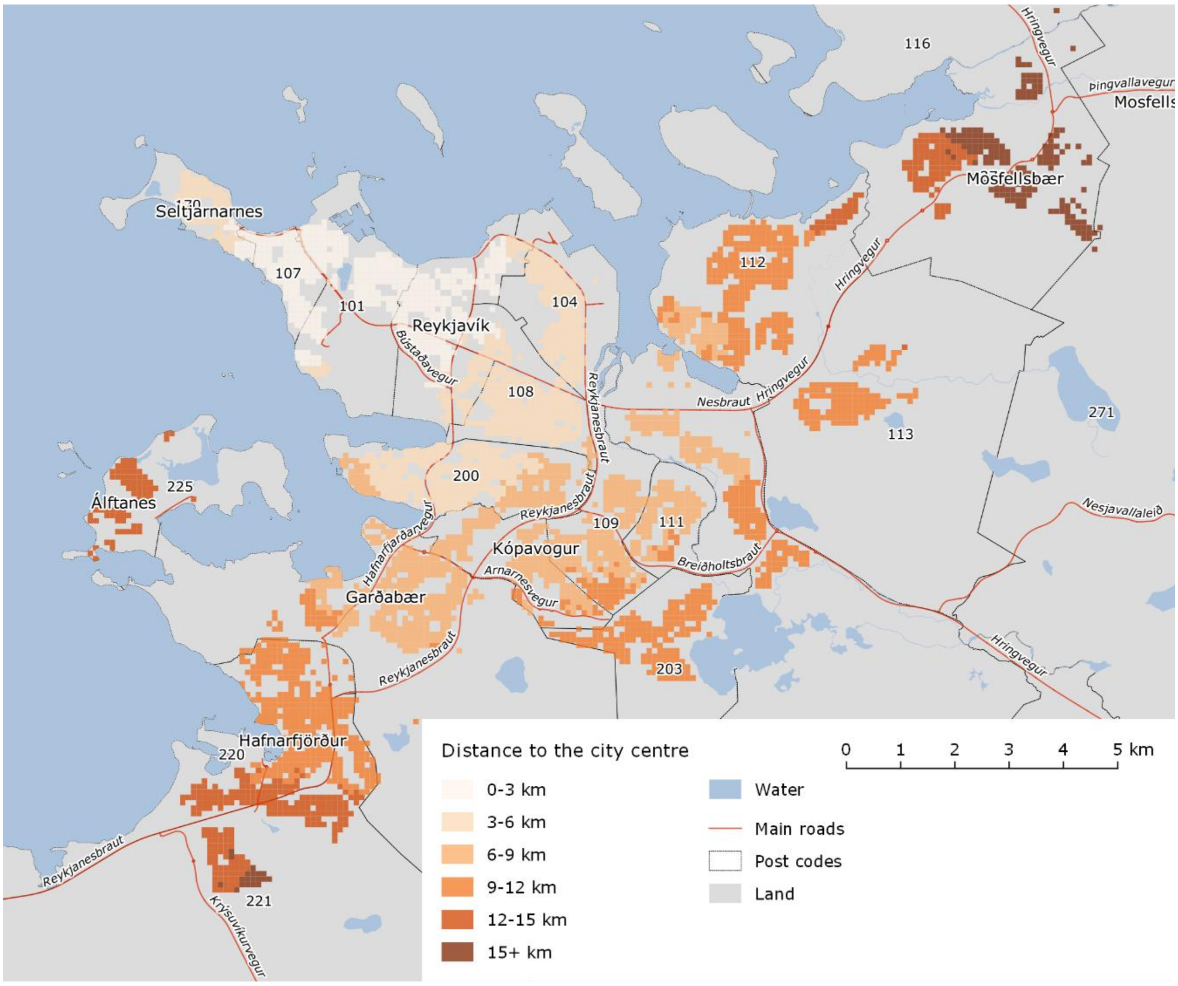

Figure 7. Driving distances to the city center from residential locations in the Capital Region

Travel-related urban zones

Materials and methods

The classification was based on a similar one calculated in Helsinki and Stockholm. The method is based on the theory of three urban fabrics: a walking city, a transit city, a and car city, proposed by Newman et al. (2016). The calculation methods applied in Helsinki and Stockholm are described in detail by Ristimäki et al. (2011) and Söderström et al. (2015). The definitions, datasets and calculation methods used in developing the urban zones for the Capital Region are presented in table 1. Four steps were involved in delineating the zones:

1. *Delineation of densely built and populated areas:* for each 100 m grid cell, the population density was calculated in circular buffers with 500 m radius (calculations in Helsinki used 8 cells neighboring a 250 m cell – approximately 375-530 meter radius). The cells were divided into 4 ordered groups based on Jenks Natural Breaks methods, each getting score between 1 (the lowest) and 4 (the highest) (Figure 8).

2. *Delineation of commercial centers:* for each 100 m grid cell, floor area density of commercial and office class was calculated in circular buffers with 500 m radius (in Helsinki it was 8 cells neighboring a 250 m cell – approximately 375-530 meter

radius). In Helsinki, job data in retail and total jobs were used, but such data was unavailable in the Capital Region. The cells were divided into 4 ordered groups based on Jenks Natural Breaks methods, each getting score between 1 (the lowest) and 4 (the highest) (figure 9).

3. *The central point of the main commercial center* was identified as a centroid of a contiguous area with a summary score of the centrality of at least 11, which was at the intersection of Vitastigur and Laugavegur streets in downtown Reykjavík (figure 11).

4. *Delineation of areas with different levels of access to public transportation.* First, the bus stops were divided into three classes: stops that have at least 10 departures per hour on average (waiting time about 6 minutes), stops that have at least 4 departures per hour on average (waiting time about 15 minutes) but less than 10 departures, and stops that have less than 4 departures per hour on average. Then, areas located within walking distance to the stops of each category were delineated using Service Area tool in Network Analyst in ArcGIS 10.5. The threshold distance was 332 meters, which roughly represents a distance that can be covered in 5 minutes by an average person, and is used in similar calculations published by SSH. Then, each grid cell was assigned to the zones with access to bus stops of varying departure frequency. Cells with access to a stop with at least 10 departures were assigned score 4, those with access to a stop with between 4 and 10 departures were assigned score 3, with access to a stop with less than 4 departures – score 2, and the remaining cells were assigned score 1 (figure 10).

5. Delineating zones was done by assigning zone numbers to grid zones according to criteria described in table 1. The final result is presented in figure 12.

In the methods applied in Helsinki and Stockholm pedestrian zones of sub-centers were delineated as one of the zones. Besides being concentrations of population and retail jobs, and major public transportation hubs, these areas are characterized by having a mix of functions and land uses, and a walkable urban structure (Ristimäki et al., 2011). Even though seven commercial sub-centers were identified (figure 12), none of them is surrounded by a pedestrian zone, and thus pedestrian zones of sub-centers could not have been defined in our classification.

Table 1. The criteria used to delineate the travel-related urban zones

Zone name	***Definition***	***GIS calculations***
The central pedestrian zone	Densely built and populated, located within a walkable distance from the main commercial center (up to 1500 meters), contains a high number and diversity of jobs and services, and has a good access to public transport.	The contiguous area within 1500 m network distance from the main commercial center.
The fringe of the central pedestrian zone	Densely built and populated, located within a bikeable distance from the main commercial center (up to 3000 meters) from the main commercial center, contains a high number and diversity of jobs and services, and has a good access to public transport.	The contiguous area between 1500 and 3000 m distance from the main commercial center
Intensive public transportation zone	Area in which the public transport frequency is at least 10 departures per hour, and walking distance to a bus stop is less than 5 minutes (332 meters)	Not included in the above zones AND bus stop with at least 10 departures per hour within a 5-minute walk (332 m street network distance).
Basic public transportation zone	Area in which the public transport frequency is at least 4 departures per hour, and walking distance to a bus stop is less than 5 minutes (332 meters)	Not included in the above zones, bus stop with at least 4 departures per hour within walk (332 m street network distance).
Car-oriented zone	Area in which the public transport frequency is less than 4 departures per hour or there is no bus stop within walking distance of 5 minutes (332 meters)	Not included in the above zones

Results

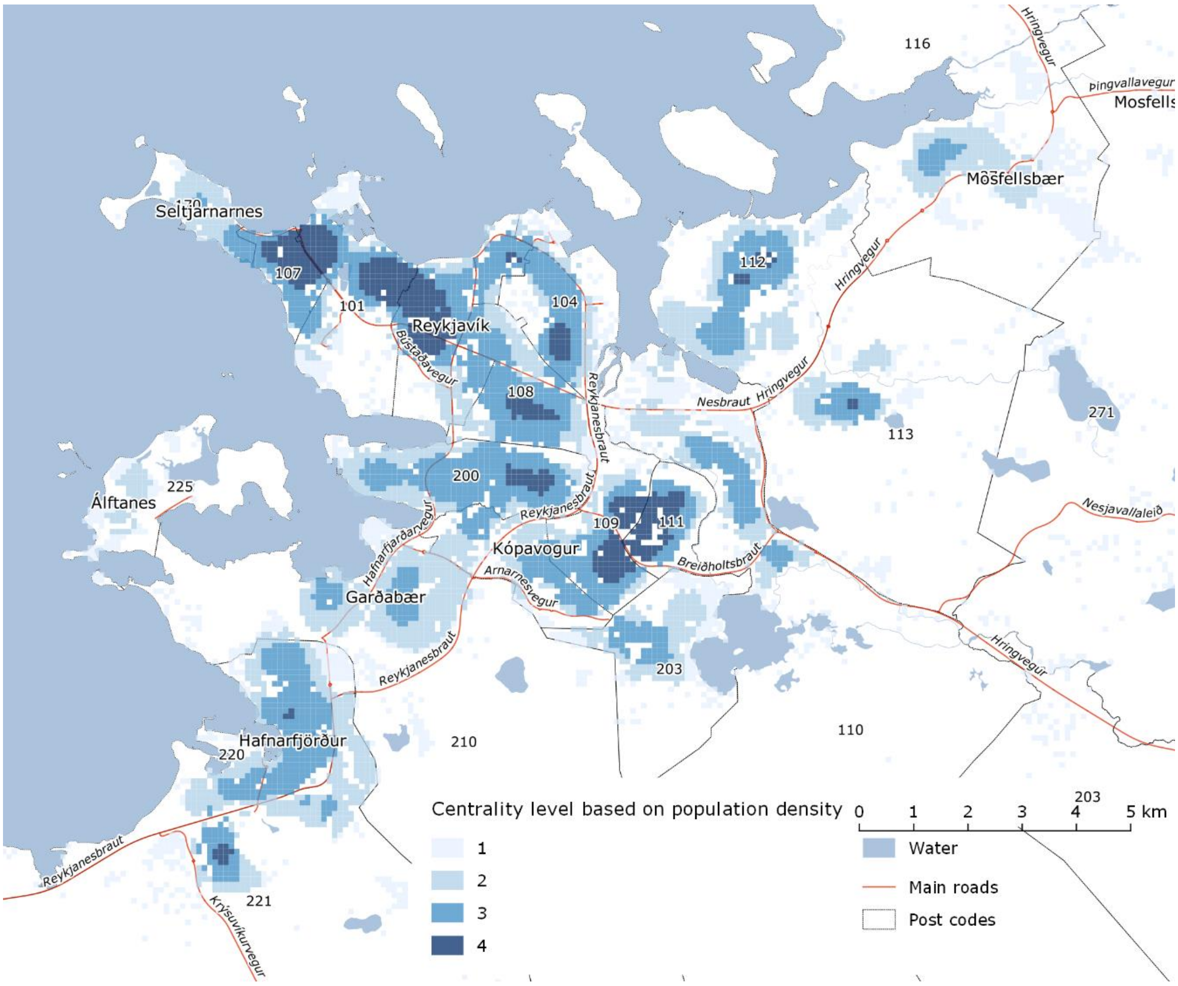

Figure 8. Levels of centrality based on population density in 500m simple buffers around grid cells

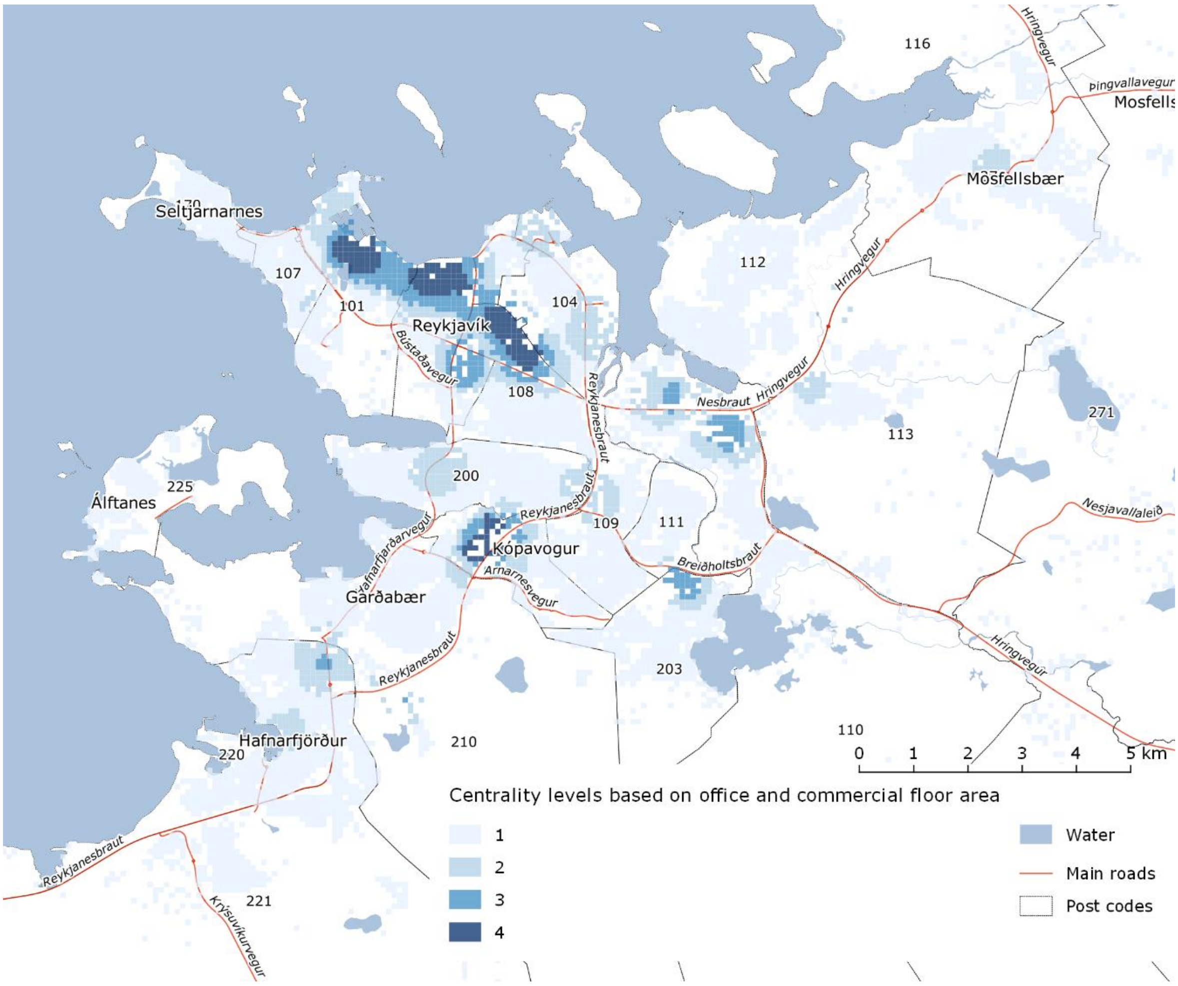

Figure 9. Levels of centrality based on floor areas of commercial and office functions in buildings in 500m simple buffers around grid cells

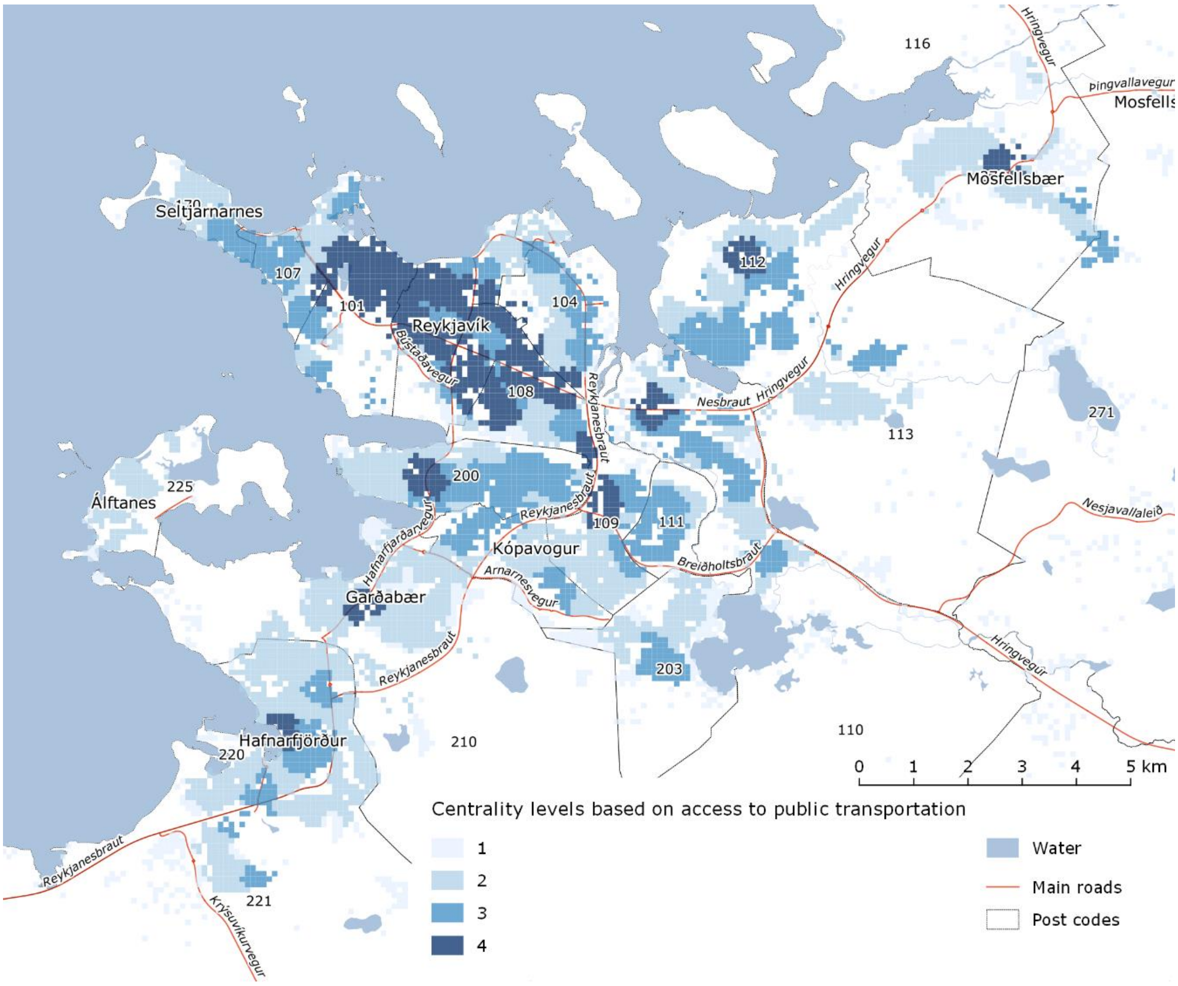

Figure 10. Levels of centrality based on access to public transportation based on the number of departures from bus stops located within a 5-minute walk (332 m) from grid cells.

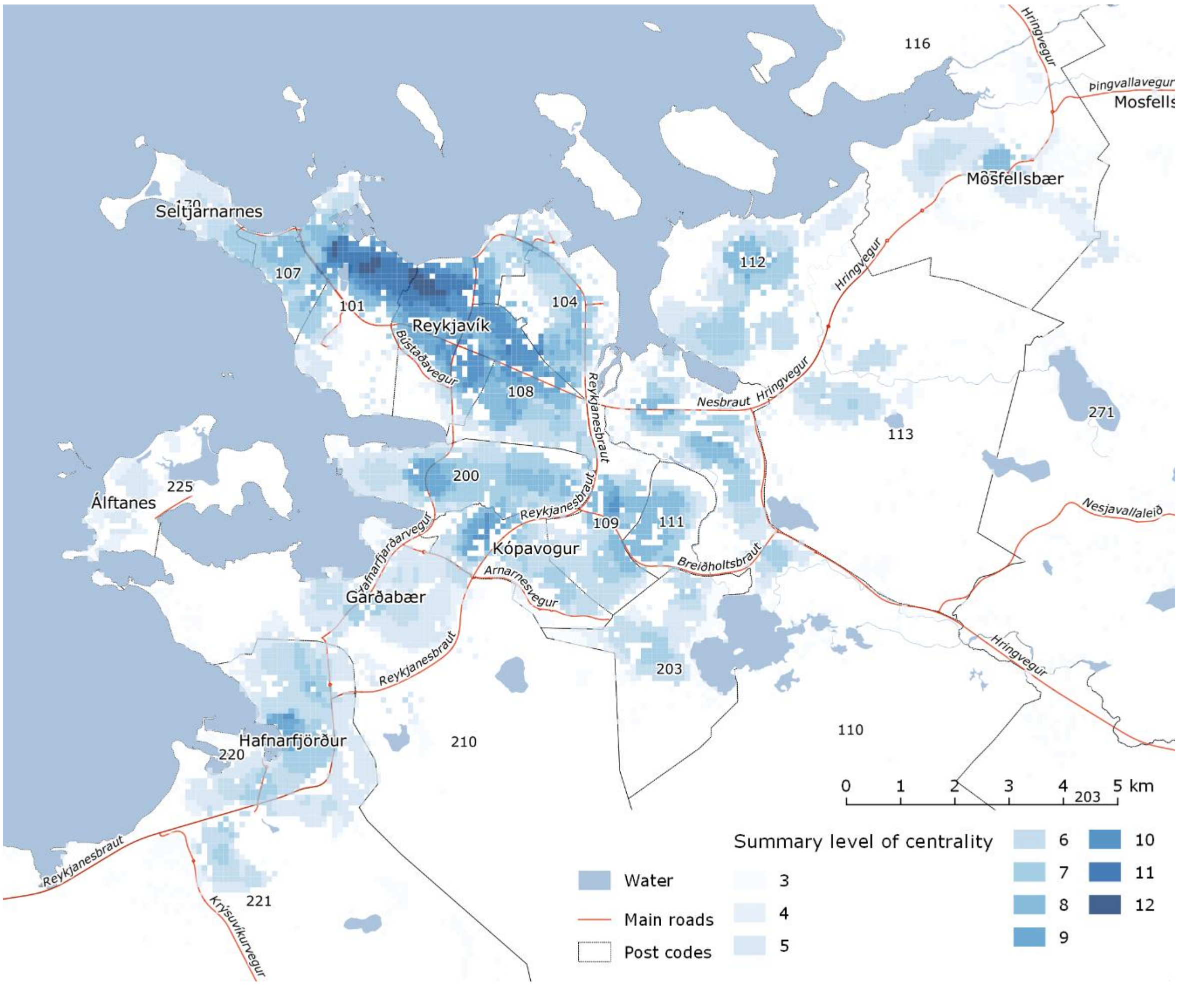

Figure 11. Summary levels of centrality based on population density, office, and commercial floor area, and access to public transportation.

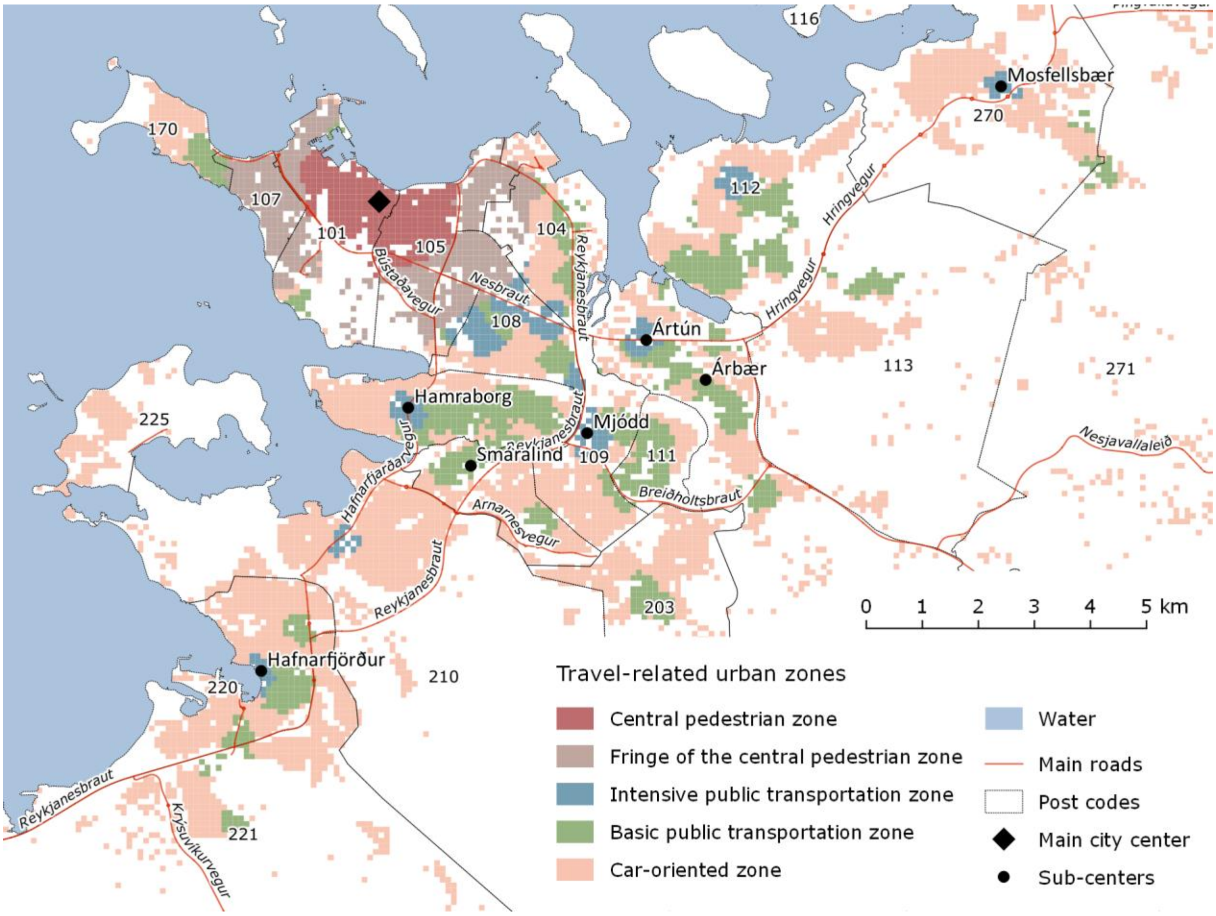

Figure 12. Travel-related urban zones of the Capital Region.

Access to green, blue and open spaces

Percentage of area covered with green, blue, and open spaces

Materials and methods

The measure was calculated as a percentage of land use classes within the spatial units. The land use classes were taken from the GMES Urban Atlas data set provided for Reykjavik urban region by the European Environmental Agency (EEA, 2016). The data set is based on the classification of remote sensing images and field audits conducted in 2012 in all European urban regions of at least 100,000 inhabitants. Thus, the measures based on the Urban Atlas can be and has been applied to all major cities in Europe (e.g. Kabisch et al. 2016). The dataset's spatial resolution corresponds to 1:10 000 topographic maps. The map does not capture small and dispersed green spaces, such as street greenery or private yards. Three measures based on different land use classes were calculated (Table X). Ocean water, that is not included in the Urban Atlas data set was added.

Table 2. Urban Atlas land use classes used in calculations

Name	Definition	Urban Atlas land use classes included
Open spaces	All not-built-up areas that include natural features and are publicly accessible	Green urban areas Sports and leisure facilities Pastures Forests Herbaceous vegetation associations (natural grassland, moors…) Open space with little or no vegetation (beaches, dunes, bare rocks, glaciers) Wetlands Water + Ocean water
Green spaces	Areas covered by vegetation that are publicly accessible	Green urban areas Pastures Forests Herbaceous vegetation associations (natural grassland, moors…) Wetlands
Blue spaces	Areas covered by water bodies, such as rivers, lakes, and the ocean	Water + Ocean water

Results

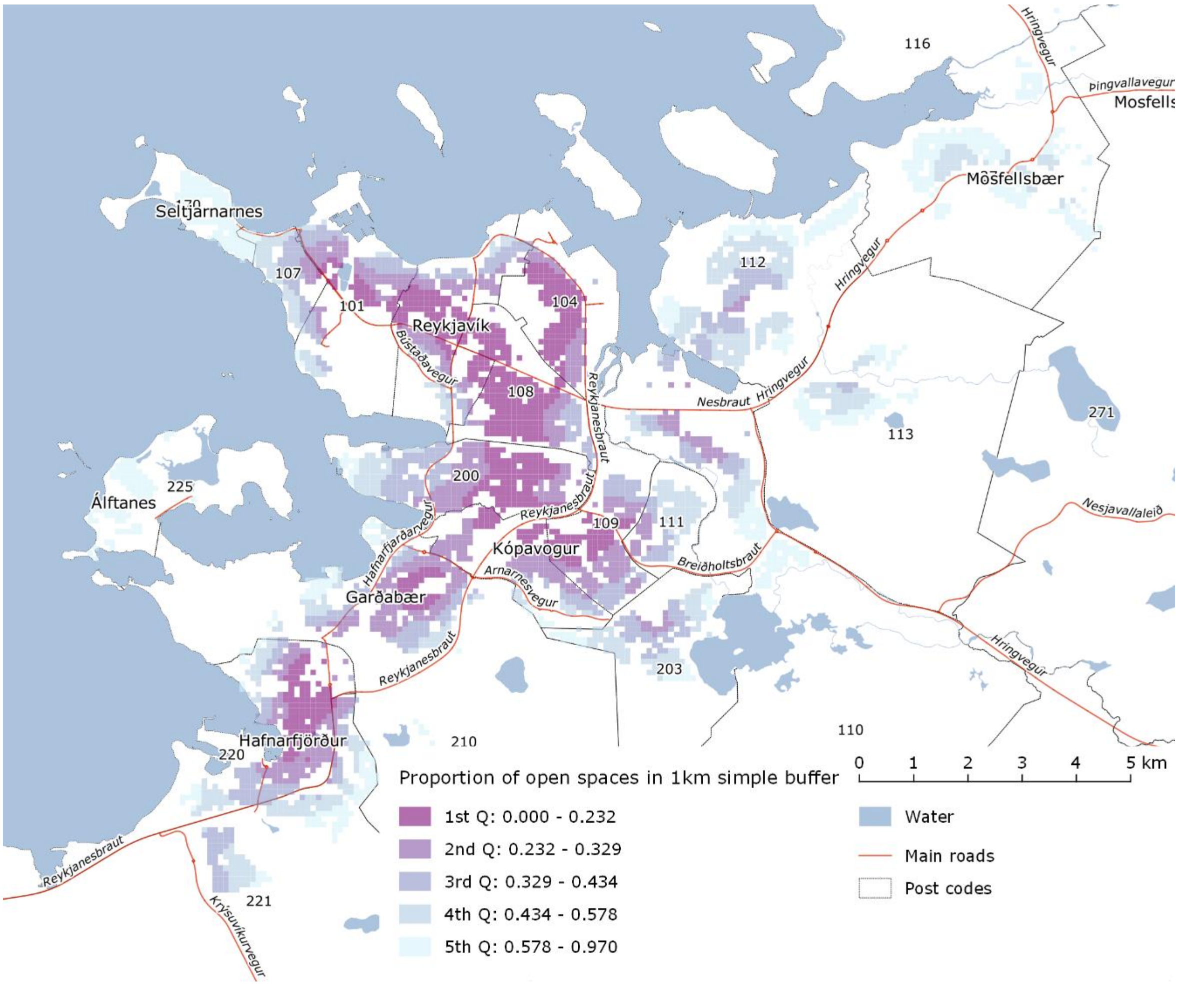

Figure 13. The proportion of open spaces in the 1km simple buffer

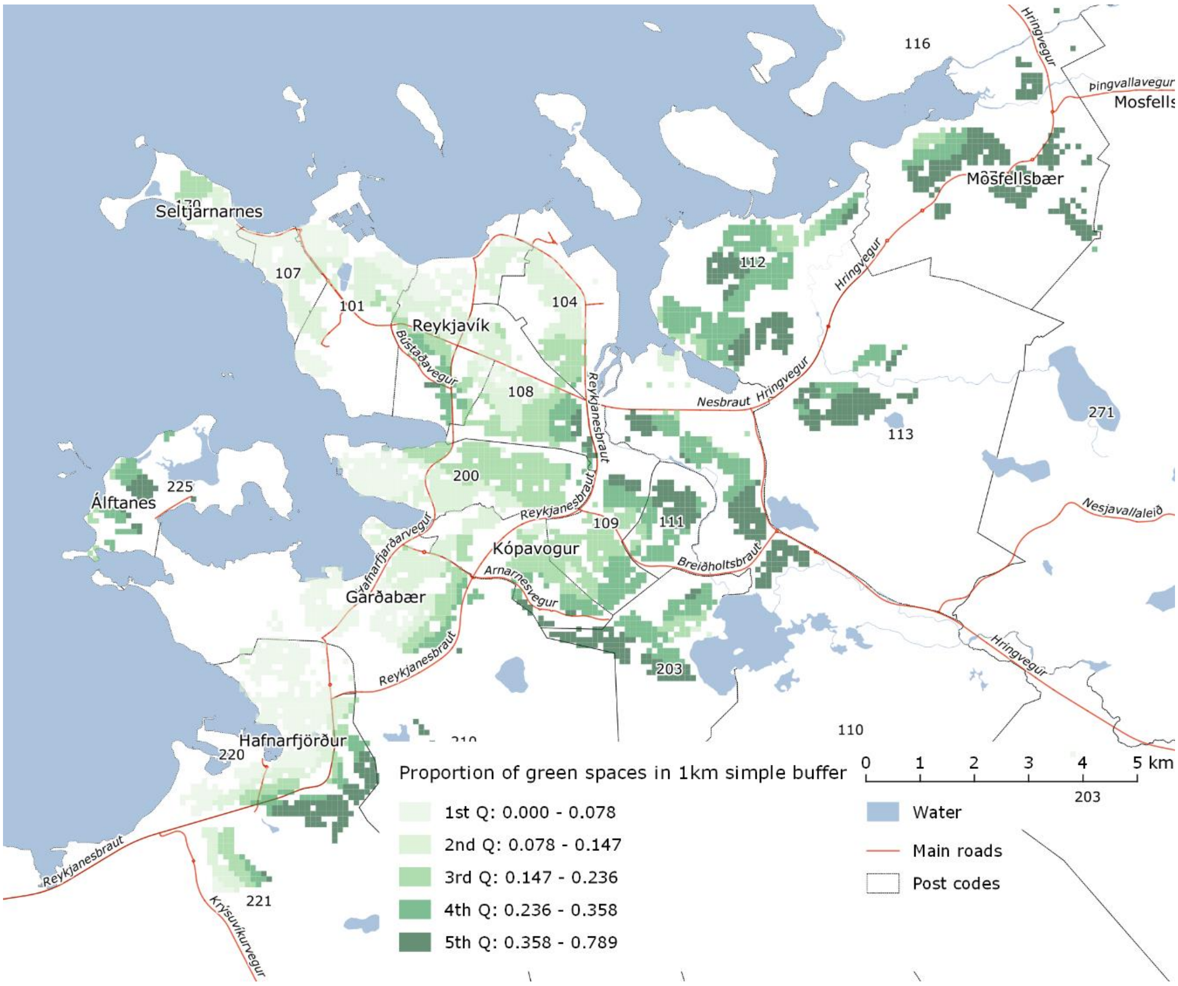

Figure 14. The proportion of green spaces within 1 km simple buffer

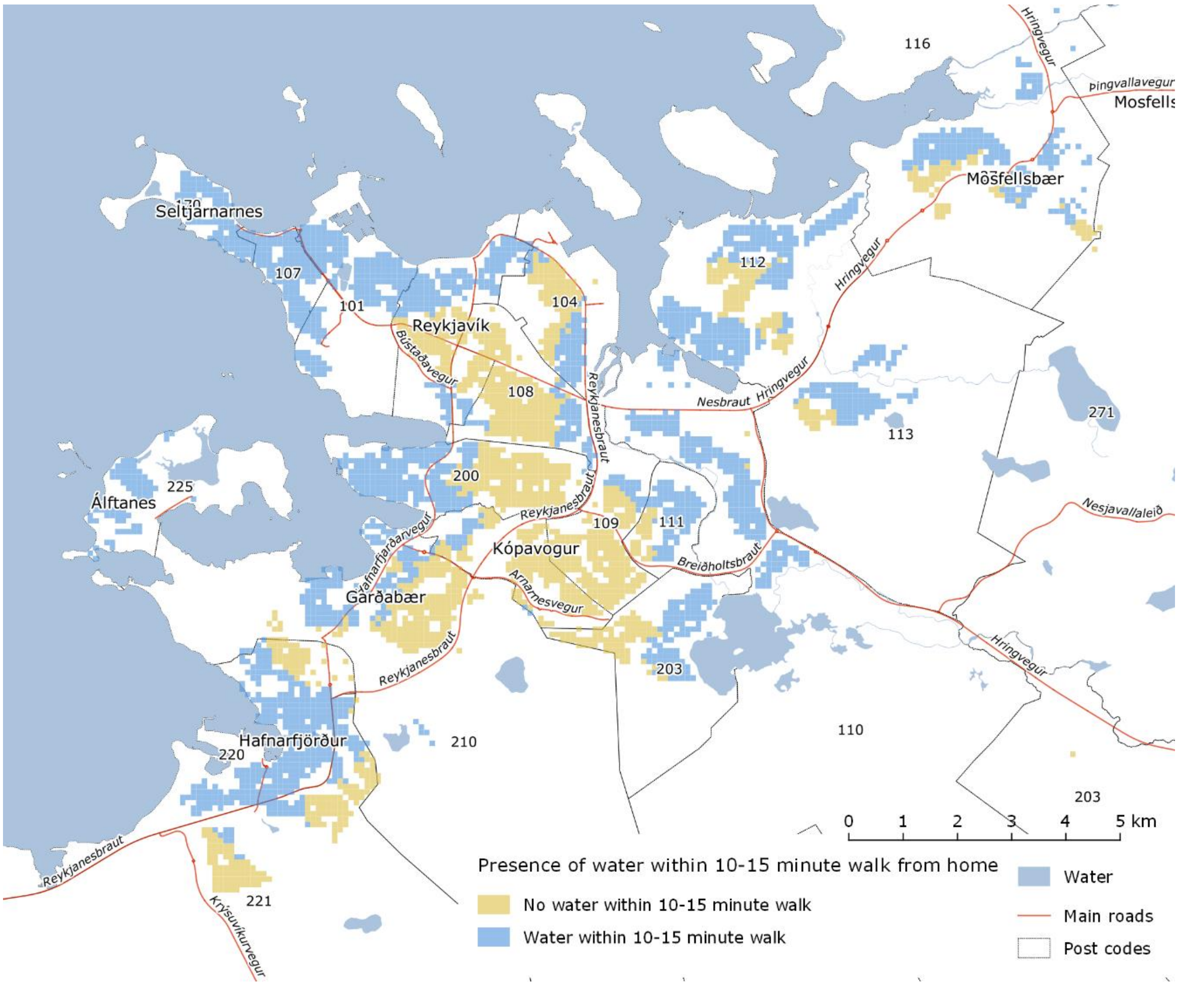

Figure 15. Presence of water within 10-15 minute walk from a residential location (i.e. 1 km street network buffer)

Mean NDVI values

Materials and methods

Normalized Difference Vegetation Index (NDVI) was calculated in 1 km buffers around grid cells. The index was calculated with Landsat 8 imagery downloaded from EOS Land Viewer. The image was taken on 30th July 2016. Its spatial resolution is 30 m. The index values were calculated in Raster Calculator in QGIS using the general formula: NDVI = (NIR – RED) / (NIR + RED). The specific formula for Landsat 8 is NDVI = (Band 5 – Band 4) / (Band 5 + Band 4). Mean values of the index in each buffer were then calculated using “Raster statistics for polygons” tool in SAGA GIS.

The NDVI captures areas covered by vegetation and productivity of the vegetation by utilizing difference of how photosynthesizing plants reflect and absorb light in the red and near-infrared spectrum. Similar measures have been used in studies on the influence of neighborhood greenness on health and well-being (Tilt et al., 2007; Rhew et al., 2011). Advantages of this measure include capturing all green spaces, vegetated land, and dispersed individual plants that are visible from above, regardless of their size or classification in topographic or land use maps. This allows capturing private gardens, street trees and other types of vegetation that are relevant for aesthetics and human health but are often not featured on maps. The main disadvantage of this measure is that it excludes water bodies from the calculation, even though they are important for recreation in coastal cities such as Reykjavik.

Results

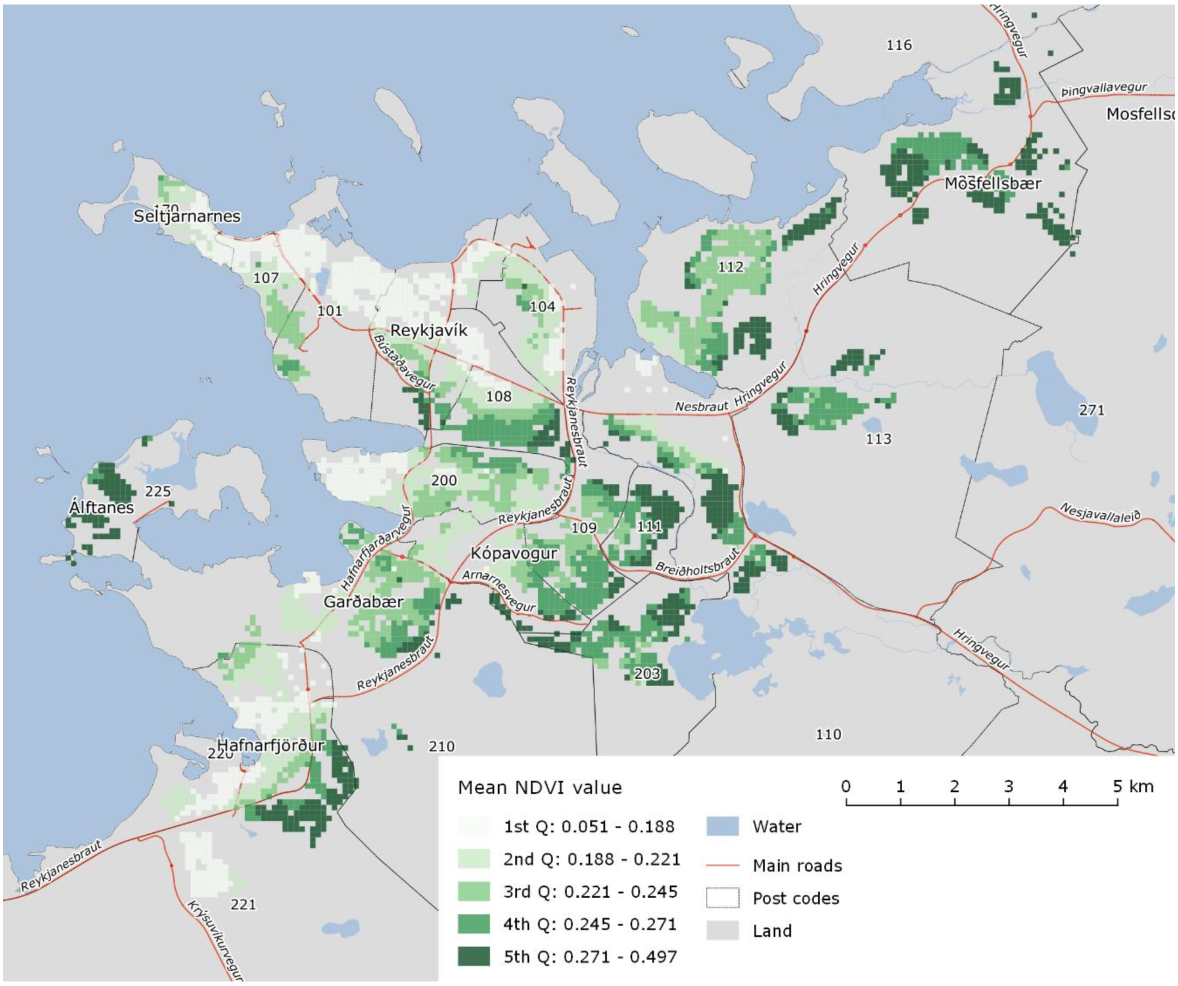

Figure 16. Distribution of mean NDVI values in Reykjavik Capital Region calculated in 1km street network buffers around grid cells.

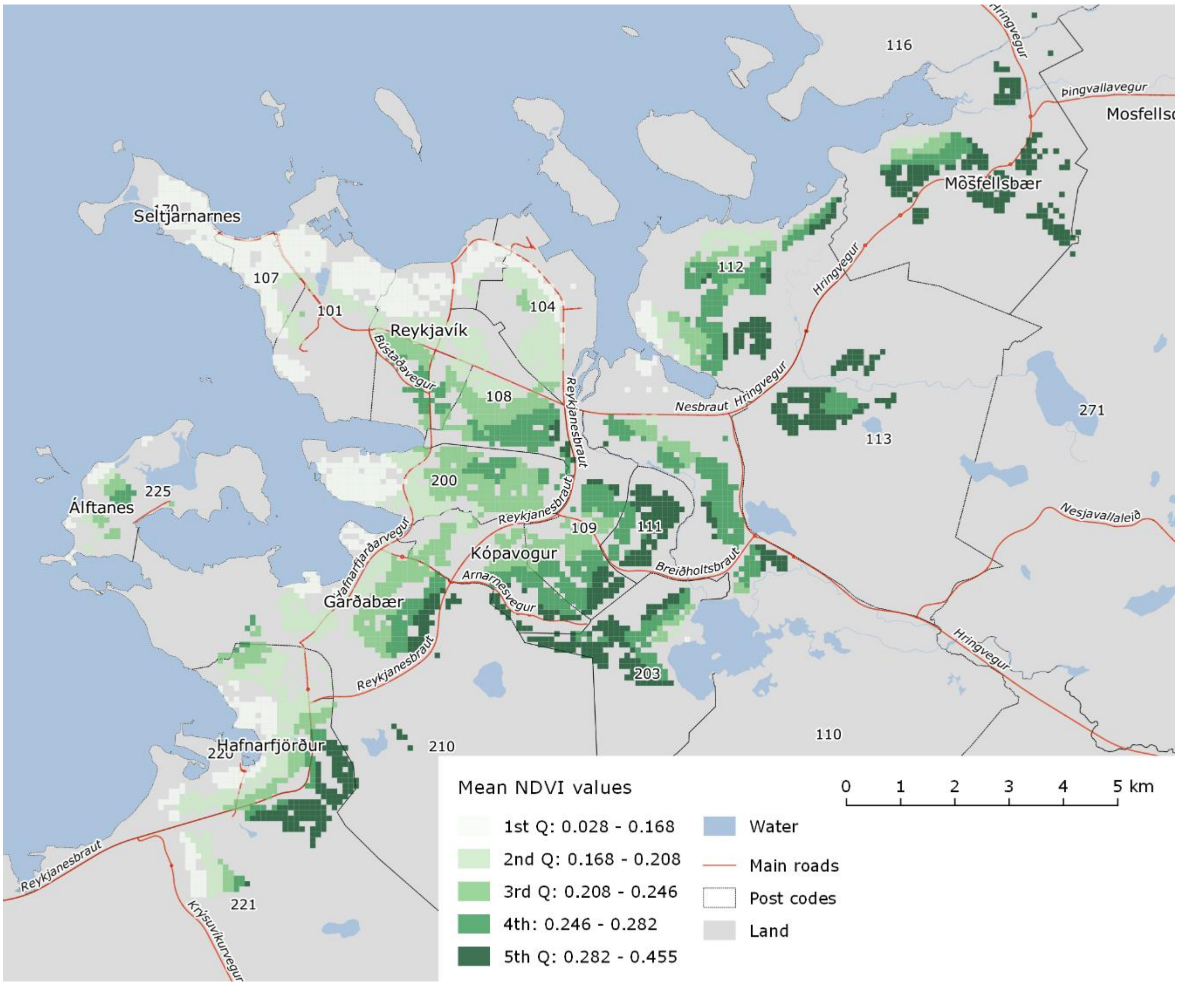

Figure 17. Distribution of mean NDVI values in Reykjavik Capital Region calculated in 1km simple buffers around grid cells.

Interpretation

The mean NDVI has the lowest values in built-up areas surrounded by water or sparsely-vegetated land. Some of them centrally located. Including downtown Reykjavík, Vesturbær, Seltjarnarnes and the eastern part of Kópavogur (Kársnes). The index has the highest values in areas surrounded by a thicker vegetation, such as forests. Most of them peripherally located, including suburban parts of Reykjavík (Grafarvogur, Grafarholt, Breiðholt, Árbær), Mosfellsbær, Álftanes, and eastern parts of Garðabær, Kópavogur (Vatnsendi), and Hafnarfjörður. The regions with low values do not have good access to thick and vast vegetation such as forests, river valleys, and shrubs, even if they may have access to coastal areas. The regions with high values do have good access to forests, river values, and other areas with thick and vast vegetation.

Residents’ climate impacts from transport

Materials and methods

Data collection and sampling

The climate impacts were associated based on the travel patterns reported by individuals who took part in an online survey administered between 12th of September and 7th of November 2017 in three languages: Icelandic, English, and Polish. The survey employed a softGIS method, which combines traditional questionnaires with Internet maps and allows participants to mark locations on a map and answer questions pertaining to these locations (Brown and Kyttä, 2014). The questionnaire is available online at https://app.maptionnaire.com/en/2294/.

The target population of the survey were **registered residents of the Reykjavík Capital Region** (the municipalities of Reykjavík, Kópavogur, Hafnarfjörður, Garðabær, Mosfellsbær, Seltjarnarnes, and Kjósarhreppur), **aged between 25 and 40** as of 1st of August 2017.

Sampling was done by randomly drawing **6000** target group members from Registers Iceland, (Þjóðskrá Íslands) using a geographically stratified sampling method, in which the proportion of residents of each municipality is the same in the sample as it is in the target population. About **5184** invitations have been properly delivered and resulted in **735** answers (response rate 14.2%), of which **588** were completed (response rate 11.3%).

The questionnaire consisted of 12 thematic pages, of which four were relevant for this report:

1. **Page 4** contained questions related to the location and characteristics of a place of residence, workplaces, and study places.
2. **Page 5** consisted questions related to location and characteristics of places visited within the Capital Region (i.e. local trips). The respondents were asked to mark between 5 and 15 locations that they have been frequently visiting. The time frame was not specified, to capture habitual travel patterns. Participants marked locations in six categories: services and errands; shopping; leisure and going out; culture and sports events; daycare, kindergarten or school; sports and active recreation. Each marked location was associated with additional questions about travel mode, the frequency of visits, and direction of travel (i.e. whether it is visited from home, work or study place, or on the way between home and work/study place).
3. **Pages 6 and 7** consisted questions related to destinations visited within Iceland but away from the Capital Region (i.e. domestic trips), and destinations visited away from Finland (i.e. international tips). On both pages, the participants were asked to mark all trips made during 12 months previous to the survey. Domestic trips were grouped into four categories by travel mode: car, bus, plane, and boat. International trips originating in Iceland were grouped into two categories: plane, and boat. The international trips not originating in Iceland were in three categories: car, train, and bus. Each marked location was associated with questions regarding the number of trips made to the location during the last 12 months, trip purpose, main motivation to take the trip, and the trip origin. For trips made by plane, there was a question on the number of

interchanges, and for trips made by car, a question on the number of passengers, and a question about hitchhiking trips.

Trip distances and frequencies

The calculation of distances differed between geographical scopes and travel modes:

1. Distances to international and domestic destinations visited by plane and international locations visited by ferries were calculated as geodesic shortest distances between home and the destination in a Spatialite database using The World Geodetic System 1984 (WGS84) coordinate system to take into account the curvature of the Earth. Every regional and international destination was treated as a two-way trip. The distance estimation was corrected by multiplying by 1.2 per interchange to account for the deviations from the shortest distances that result from the interchanges.
2. Distances to international destinations not originating in Iceland and visited by car, bus, or train, were calculated as geodesic shortest distances and multiplied by a "detour factor" of 1.417 to account for the deviations from the shortest distances that result from the street and rail network layouts.
3. Distances to domestic destinations visited by car, bus or ferry, were calculated along the road network data obtained from the i50v topographic map, and the ferry network data obtained from EuroGlobalMap and OpenStreetMap and checked with ferry operators' websites. The distances between home locations and destinations were then calculated using Route tool in the Network Analyst toolbox in ArcMap 10.
4. Distances to local destinations were calculated along the street network data obtained from OpenStreetMap for walking and cycling, and i50v topographic map for car and bus. The distances between home locations and destinations were then calculated using Route tool in the Network Analyst toolbox in ArcMap 10.

The frequencies of local trips were measured in categories related to weekly or monthly periods (e.g. "five to seven times a week" or "once or twice a month") and coded numerically to estimate the number of trips made during 12 months. The reported number of trips in regional and international travel was also coded numerically and used to estimate the number of trips in 12 months. The yearly distance traveled to each of the marked destinations was then estimated by multiplying distances and frequencies. The yearly distances were then multiplied by GHG emission coefficients described below.

Greenhouse gas emissions

The GHG assessment was conducted with a life cycle assessment (LCA) approach, which considers both the direct and indirect emissions from travel. The sources of indirect emissions include fuel and electricity production (for electric vehicles), vehicle manufacturing, and infrastructure construction, which are the major contributors to the GHG emissions from transport (Chester and Horvath, 2009). The measures of global warming potential over 100 years (GWP100) was employed. In addition to the long-lived GHGs (LLGHG) typically included in GWP calculations, such as carbon dioxide or nitrous oxide, the short-lived climate forcers (SLCFs) were included, such as black carbon, organic carbon, volatile organic compounds, contrails, and aircraft-induced cirrus. The SLCFs are highly relevant for estimating the climate impacts of air travel and less relevant for those from ground transport (Aamaas et al., 2013).

Following emission data sources were utilized:

1. Due to the absence of data sources from Iceland, the direct combustion emissions of buses were taken from the LIPASTO database produced by the VTT Technical Research Centre of Finland Ltd (VTT 2016).
2. For air travel, the combustion phase emissions were taken from Aamaas et al. (2013), and the split into short (<800 km) and long (>800 km) flights follow the source. The values are considerably higher than values without SLCFs provided by VTT (2016), where emissions are estimated at 0.26 CO_2e kg/PKT for flights shorter than 463 km, and at 0.11 CO_2e kg/PKT for flights above 3000 km. Therefore, the inclusion of SLCFs emphasizes the importance of emissions caused by air travel, and long-haul flights in particular.
3. The indirect emissions coefficients were taken from Chester and Horvath (2009), including roadways, tracks, stations, runways and other infrastructure, vehicle production and maintenance and fuel production. The uncertainty of the measures lies in the assumptions that the emissions are compatible between the U.S. and Iceland.
4. For trips with private cars, the fuel efficiencies and occupancy rates reported by the survey respondents were used. The fuel efficiency was asked with a five-category question with options from below 4 liters per 100 km (l/100km) up to over 10 l/100km with two-liter intervals and separate options for electric vehicles. For those who did not answer the question on fuel efficiency, the average if 7.6 l/100km was assumed. For the trips without data on car occupancy, the average occupancy rates of 1.3 for local trips and 1.9 for all other trips were assumed, following the LIPASTO database.
5. The estimated fuel consumption was turned into GHG emissions with a multiplier of 2.36 kg CO_2e/liter (US EPA 2008).

Table 3. GHG emission coefficients per travel mode in CO2e kilograms per person kilometer traveled [kg/PKT]

Travel scope	**Travel mode**	**Explanation and sources**	**Direct emissions: combustion**	**Indirect emissions**		**Total emissions**
				Fuel production	**Life cycle**	
Local	Car	Reported fuel efficiency (liters per km, survey data) times 2.36 kg CO2e/liter (US EPA, 2008), divided by 1.3 car occupancy (VTT, 2008). Indirect emissions for San Francisco Muni (Chester & Horvath, 2009).	0.138 (average)	0.026	0.074	0.238
	Bus	Natural gas bus, the average occupancy rate in local traffic, 18/50 passengers (VTT, 2008).	0.069	0.031	0.050	0.150
Domestic and international	Plane <800 km	LLGHGs and SLCFs included (Aamaas et al., 2013), indirect emissions for a midsize aircraft (Chester & Horvath, 2009).	0.300	Included in combustion factor	0.020	0.320
	Plane >800 km		0.240	Included in combustion factor	0.020	0.260
	Ferry	Helsinki-Stockholm, average occupancy (VTT, 2008), indirect emissions for a midsize aircraft (Chester & Horvath, 2009).	0.223	0.015	0.020	0.258
	Bus	Diesel bus, average occupancy rate on long distance trips, 12/50 passengers (VTT, 2008)	0.049	0.037	0.058	0.144
	Train	Pendolino and intercity trains, average occupancy (VTT, 2008). Indirect emissions for an SFBA Caltrain (Chester & Horvath, 2009).	0.022	Included in combustion factor	0.062	0.084

Spatial analysis

The emissions were calculated per each study participant, aggregated to spatial units, and analyzed with spatial statistics. To create the chart in figure 19, the participants were aggregated into four equal distance bands from the city center (described in section 4.1.a). To create the chart in figure 18, the participants were aggregated into travel-related urban zones, whose calculation is described in section 4.1.5. Figures 20-22 were calculated using a Getis Ord Gi* method in Hot Spot Analysis tool in ArcMap 10, in which local averages of analyzed values are compared to regional averages. When the local average is higher or lower than the expected value, and the difference is too large to be the result of random chance, the area is highlighted as a "hot spot" or a "cold spot", respectively. The method is described in more detailed in the ArcMap documentation.

Results

There is a clear geographical trend in emissions from local travel, regardless if the aggregation is based on the travel-related urban zones (Figure 18), or distance from the city center (Figure 19). The residents of areas close to the city center cause much lower emissions (ca. 500 kg CO2e per year per person in the *central pedestrian zone*) than the residents of more peripheral areas (ca. 1400 kg CO2e per year per person in the *car-oriented zone*). The emissions lower than the average cluster in Reykjavík postcodes 101, 105, 103, and 104, and appear to be correlated with distances to the city center and to major concentrations of workplaces (Figure 20). The emissions higher than the average cluster in areas most distanced from the city center, and most reliant on car traffic: Grafarholt, Mosfellsbær, and Hafnarfjörður (Figure 20). The observed trend is thus mostly due to differences in the use of private cars for daily travel. The results are in line with previous studies, which point out to distance to the main city center as the primary factor of car use, and emissions from daily travel (e.g. Naess, 2012).

The trend is almost reversed in international travel. The residents of the most central areas cause higher emissions (ca. 3600 kg CO2e per year per person in the *central pedestrian zone*) than the residents of more suburban areas (ca. 2400 kg CO2e per year per person in the *car-oriented zone*). The emissions higher than the average cluster in Vesturbær and Miðbær (Reykjavík postcodes 101 and 107). The trend is similar to that found in previous studies conducted in Helsinki (Ottelin et al., 2014; Czepkiewicz et al., 2018a) and in other locations, as summarized in a recent literature review (Czepkiewicz et al., 2018b). Preliminary results of Task 3 of the project (in a forthcoming article) point out to the role of income, language skills, and cosmopolitan attitudes and lifestyles in predicting the number of international trips per years and the associated emissions.

No significant differences between geographic areas in terms of average emissions from domestic travel were found (Figure 21). The total travel-related emissions are similar across the region, and range between 4000 and 4500 kg CO2e per year per person).

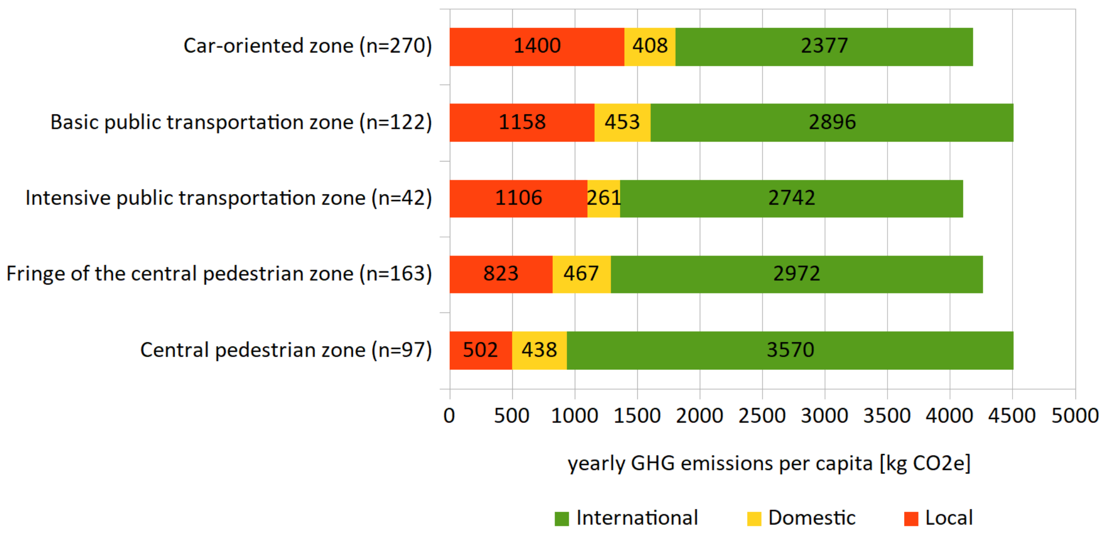

Figure 18. Average GHG emissions from international, domestic, and local travel per resident of the travel-related urban zones in Reykjavik Capital Region.

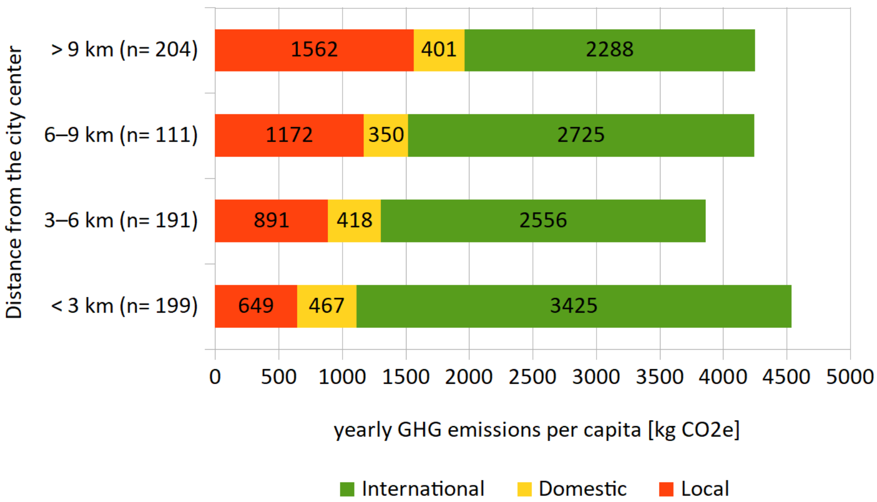

Figure 19. Average GHG emissions from international, domestic, and local travel per resident of the distance bands from the city center in Reykjavik Capital Region.

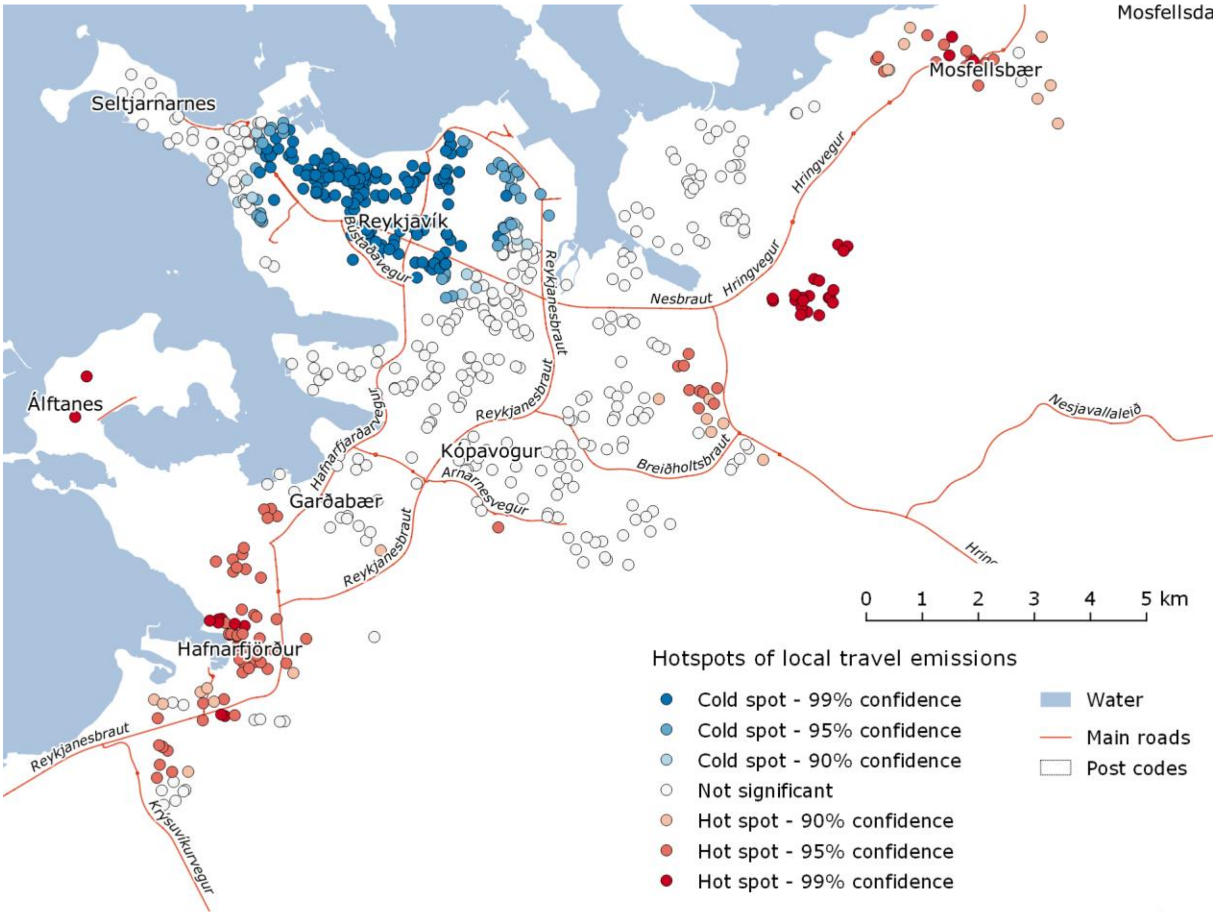

Figure 20. Hotspot map of average GHG emissions from local travel calculated with Getis-Ord Gi method. Blue areas ("cold spots") have emissions lower than the average, and red areas ("hot spots") have emissions higher than the average.*

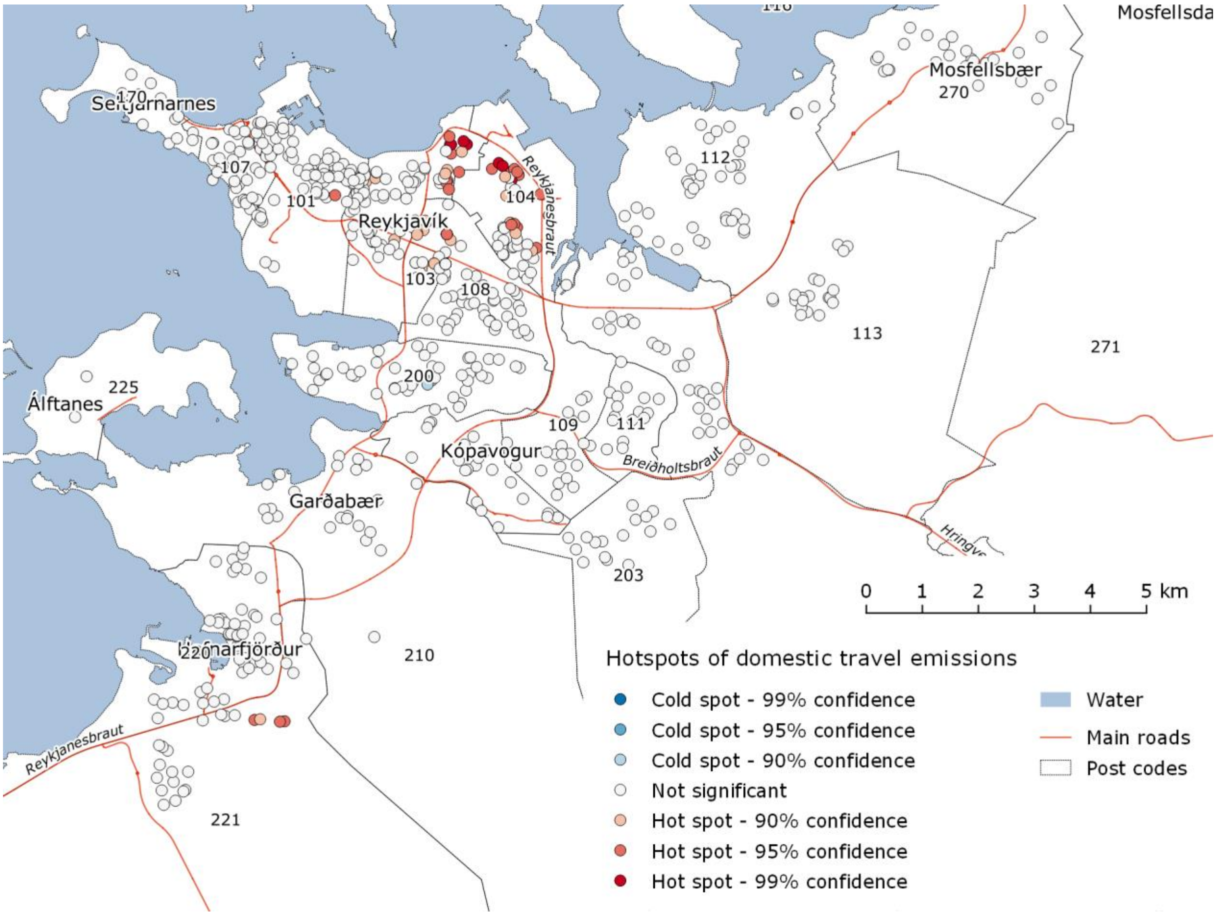

Figure 21. Hotspot map of average GHG emissions from domestic travel calculated with Getis-Ord Gi method. Blue areas ("cold spots") have emissions lower than the average, and red areas ("hot spots") have emissions higher than the average.*

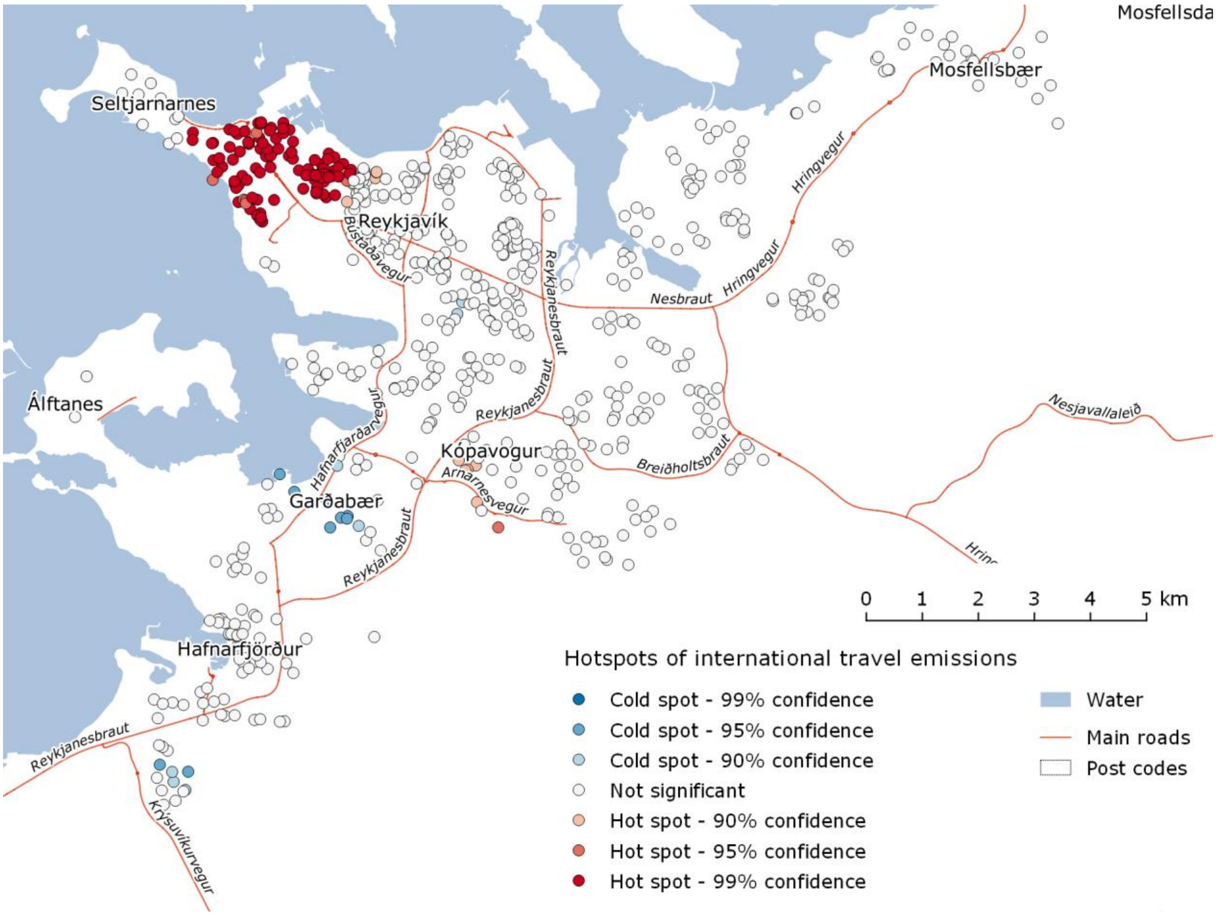

Figure 22. Hotspot map of average GHG emissions from international travel calculated with Getis-Ord Gi method. Blue areas ("cold spots") have emissions lower than the average, and red areas ("hot spots") have emissions higher than the average.*

References

Aamaas, B., Borken-Kleefeld, J., & Peters, G. P. (2013). The climate impact of travel behavior: A German case study with illustrative mitigation options. *Environmental Science and Policy*, 33, 273–282. https://doi.org/10.1016/j.envsci.2013.06.009

Chester, M. V., & Horvath, A. (2009). Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letters*, 4(2). https://doi.org/10.1088/1748-9326/4/2/024008

Czepkiewicz, M., Ottelin, J., Ala-Mantila, S., Heinonen, J., Hasanzadeh, K., & Kyttä, M. (2018a). Urban structural and socioeconomic effects on local, national and international travel patterns and greenhouse gas emissions of young adults. *Journal of Transport Geography*, 68. https://doi.org/10.1016/j.jtrangeo.2018.02.008

Czepkiewicz, M., Heinonen, J., & Ottelin, J. (2018). Why do urbanites travel more than do others? A review of associations between urban form and long-distance leisure travel. *Environmental Research Letters*, 13(7). https://doi.org/https://doi.org/10.1088/1748-9326/aac9d2

Holden, E., & Norland, I. T. (2005). Three challenges for the compact city as a sustainable urban form: household consumption of energy and transport in eight residential areas in the Greater Oslo Region. *Urban Studies*, *42*(12), 2145–2166.

Naess, P. (2010). Residential location, travel, and energy use in the Hangzhou Metropolitan Area. *Journal of Transport and Land Use*, *3*(3), 1–11. https://doi.org/10.5198/jtlu.v3i3.98

Naess, P. (2012). Urban form and travel behavior: experience from a Nordic context. *Journal of Transport and Land Use*, *5*, 21–45. https://doi.org/10.5198/jtlu.v5i2.314

Newman, P., Kosonen, L., & Kenworthy, J. (2016). Theory of urban fabrics: planning the walking, transit/public transport and automobile/motor car cities for reduced car dependency. *Town Planning Review*, *87*(4), 429–458. https://doi.org/10.3828/tpr.2016.28

Ottelin, J., Heinonen, J., & Junnila, S. (2014). Greenhouse gas emissions from flying can offset the gain from reduced driving in dense urban areas. *Journal of Transport Geography*, 41, 1–9. https://doi.org/10.1016/j.jtrangeo.2014.08.004

Rhew, I. C., Vander Stoep, A., Kearney, A., Smith, N. L., & Dunbar, M. D. (2011). Validation of the Normalized Difference Vegetation Index as a Measure of Neighborhood Greenness. *Annals of Epidemiology*, *21*(12), 946–952. https://doi.org/10.1016/j.annepidem.2011.09.001

Ristimäki, Mika, Hanna Kalenoja & Maija Tiitu (2011). Yhdyskuntarakenteen vyöhykkeet: Vyöhykkeide kriteerit, alueprofiilit ja liikkumistottumukset. Publications of the Ministry of Transport and Communications 2011: 15. 97 pp. Ministry of Transport and Communications, Helsinki.

Ristimäki, Mika, Maija Tiitu, Hanna Kalenoja, Ville Helminen & Panu Söderström (2013). Yhdyskuntarakenteen vyöhykkeet Suomessa: Jalankulku-, joukkoliikenne- ja autovyöhykkeiden kehitys vuosina 1985–2010. Syke reports 2013: 32. 141 pp. Finnish Environment Institute, Helsinki.

Söderström, P., Schulman, H., & Ristimäki, M. (2015). *Urban Form in the Helsinki and Stockholm City Regions*: *Development of Pedestrian, Public Transport and Car Zones.* Reports of the Finnish Environmental Institute, 16/2015.

Tilt, J. H., Unfried, T. M., & Roca, B. (2007). Using objective and subjective measures of neighborhood greenness and accessible destinations for understanding walking trips and BMI in Seattle, Washington. *American Journal of Health Promotion*, *21*(4 SUPPL.), 371–379. https://doi.org/10.4278/0890-1171-21.4s.371