Charlotta Eriksson, Östen Axelsson, Petter Ljungman, Mare Löhmus, Olena Gruzieva, Anna Bergström, Anne-Sophie Merritt, Maria Albin, Kristina Jakobsson, Jenny Selander, Marina Jonsson, Antonios Georgelis, Johnny Lorentzen, Andrei Pyko, Laura Maclachlan, Peter Schantz
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Research Program: Environmental Health Equity in a Sustainable City - The Stockholm Environmental Health Program

Sammanfattning

Forskningsproblem och specifika frågor

Urbana stadsmiljöer utmanar individens möjligheter att upprätthålla en god hälsa genom livet. I Sverige riskerar nuvarande trender i bostads- och närmiljön att ytterligare öka befintliga skillnader i hälsa. Den snabba urbaniseringen och förtätningen av Stockholms län gör Stockholm till en optimal plats att studera hälsoeffekter kopplat till stadsmiljön, exempelvis i relation till luftkvalitet, transportbuller, urban grönska, klimatförändringar och trångboddhet. I det föreliggande programmet ämnar vi utvärdera och utveckla strategier för att bygga en hållbar stad som främjar en god och jämlik folkhälsa bland invånare i urbaniserade områden.

Data och metoder

Programmet kommer att använda ett flertal olika datamaterial och metoder. För att kartlägga miljörisker i Stockholms län kommer ett nytt GIS-baserat verktyg riktat mot regionala intressenter att tas fram. En ny kohort, baserad på den Nationella Miljöhälsoenkäten 2023 i Stockholms län, kommer att ligga till grund för analyser av samband mellan miljö- och hälsa samt skattningar av sjukdomsbördan. Vidare kommer effekterna av trångboddhet på barns utveckling, utbildning och hälsa att undersökas i en rikstäckande kohortstudie och i en interventionsstudie. I en litteraturöversikt kommer vi att sammanfatta kunskapen om olika miljöinsatser som underlag och vägledning för regionala aktörer vid implementering av åtgärder.

Relevans och utnyttjande

Jämlikhetskommissionen listade 7 nyckelområden i livet som avgör ojämlikheter i hälsa. Bland dessa har det tilltänkta programmet fokus på *Boende och närmiljö* men är också av relevans för aspekter av *Det tidig livets villkor*, *Levnadsvanor* och *Kontroll, inflytande och delaktighet*. Genom programmet kommer vi att etablera en stark forskningsinfrastruktur i syfte att följa upp och analysera den byggda miljöns inverkan på folkhälsan och främja en jämlik miljöhälsa. Detta ligger i linje med flera andra aktuella initiativ och styrdokument i Sverige, till exempel Miljömålsrådets initiativ ”Hälsa som drivkraft för miljömålen och hållbar utveckling”.

Plan för programförverkligande

Programmet kommer att genomföras vid Institutet för miljömedicin, Karolinska Institutet, i samarbete med Centrum för arbets- och miljömedicin, Region Stockholm, och bygger på sex olika arbetsgrupper, var och en med sina specifika mål, aktiviteter och leveranser. Forskarna inom programmet representerar ett flertal olika discipliner, från miljömedicin, folkhälsa och epidemiologi till GIS, omvårdnad och mångkulturell psykiatri, och kommer att arbeta i nära samarbete inom de olika arbetsgrupperna. För att säkerställa en god dialog med slutanvändarna av vår forskning kommer vi att arrangera och medverka i en rad aktiviteter under programmets gång, t.ex. via referensgrupper, seminarier, workshops, regionala nätverk och andra tillämpade aktiviteter.

Summary

Research problem and specific questions

Urban living environments challenge the individual's capacity to maintain a good health throughout the course of life. In Sweden, current trends in housing and neighborhood conditions tend to further increase disparities in health. The rapid urbanization and densification of Stockholm County makes it an optimal setting for studying health effects of urban living, for example in relation to air quality, transportation noise, urban greenness, climate change and overcrowded housing. In this program, we aim to assess and develop strategies for building a sustainable city promoting equitable public health among inhabitants of urbanized areas.

Data and methods

The program will use a variety of different data materials and methods. To map environmental hazards in Stockholm County, a new GIS-based tool aimed at regional stakeholders will be developed. A new cohort, based on the National Environmental Health Survey 2023, will form the basis for analyses of environmental health associations and estimates of disease burden. Furthermore, the effects on children's development, education and health from overcrowded housing will be investigated in a nation-wide cohort study and in an intervention setting. In a literature review, we will summarize evidence on environmental interventions which can guide stakeholders in implementing planning and mitigation measures.

Relevance and utilization

The national Commission for Equity in Health listed 7 key areas of life which determine health inequalities. Among these, the intended program has a focus on *Housing and neighborhood conditions but* is also of relevance for aspects of *Early life development*, *Health behavior*, and *Control, influence and participation*. By this program, we aim to establish a strong research infrastructure for monitoring and assessing the impact of the built environment on public health and for the promotion of environmental health equity. This is in line with several other initiatives and governing documents within Sweden, e.g. "Health as a driving force for the environmental goals and sustainable development", initiated by Miljömålsrådet.

Plan for program realization

The program will be carried out at the Institute of Environmental Medicine, Karolinska Institutet, in collaboration with the Center for Occupational and Environmental medicine, Region Stockholm, and builds on six different work packages, each with its specific aims, activities, and deliverables. The researchers of the program represent many different disciplines, spanning from environmental medicine, public health and epidemiology to GIS, nursing and multicultural psychiatry, and will work closely together in the different work-packages. To ensure a good dialogue with end-users of our research, we will host, and take part in, an array of activities throughout the program progression, e.g. via reference groups, seminars, workshops, regional networks and other applied activities.

Background, aims and originality

In Sweden, health is a constitutional right through § 2, Ch. 1 of the 1974 Instrument of Government (1974:152). All Swedish citizens have the right to good health and public institutions shall promote sustainable development leading to a good environment for present and future generations. Consequently, the overarching political objective in Sweden in terms of public health is good and equitable health, and to close the avoidable health gap in a generation.

Current trends in housing and neighborhood conditions in Sweden, especially in cities, tend to further increase disparities in health. Building on current collaborations between disciplines, and between researchers, regional and local authorities, and civil society, we aim to provide data and co-create interventions to address these trends on a regional level. The methods and results can be generalized to and implemented in other cities and towns. Below, we outline the main challenges within environmental health equity in general, and in Stockholm County in particular.

The compact city – Environmental health challenges

At the end of 2020, 88% of Sweden's inhabitants lived in an urban area, corresponding to 9 million of the country's almost 10.4 million people (SCB 2022). In Stockholm County, Sweden's capital and most densely populated region, the number of inhabitants has increased steadily in recent decades, from approximately 1.8 million in 2000 to just over 2.4 million in 2022. Population growth places great demands on new housing and new infrastructure, which leads to increasing urban density. In total, almost 280,000 more dwellings are planned in Stockholm County by 2030. Assuming that all plans are carried out, this corresponds to 26% more housing in Stockholm County in 2030 compared to 2017 (Region Stockholm 2017). At the same time, several major infrastructure projects are underway in the county (Länsstyrelsen 2019). While their effects on nature and cultural heritage is currently considered in the planning process, an agreed approach is urgently needed to also include their impact on the lived environment and health in areas already suffering social and environmental deprivation.

In line with population growth, travel in the Stockholm region increases as does the volume of transported goods to and from the county, which in turn increases the load on the transport system (Region Stockholm 2019). Furthermore, in 2015, Sweden implemented changes in the regulations for traffic noise with more permissive guideline values (SoU 2013:57). With this change, the Swedish guideline values for traffic noise are significantly above the World Health Organization, WHO, recommendations (SFS 2015:216, WHO 2018).The new guideline values for traffic noise entail a risk that more people will be exposed to high noise levels in and near their home, as well as a possible increased risk of a higher population exposure to traffic-related air pollution when the buildings are getting closer to major traffic routes and roads.

With increased urban density, there are also considerable risks that the city's remaining green areas will be substituted with buildings and other infrastructure which means that important opportunities for recreation, social interaction and physical activity will diminish. The negative effects of increased urban density are, however, balanced by positive effects, such as improved walkability and bikeability, by new infrastructure. Additional environmental challenges include climate change, with consequences such as heat waves, floods and fires, as well as effects of increased overcrowding linked to the growing population and housing shortage. Moreover, sociodemographic differences in the population's exposure and vulnerability to urban environmental factors risk leading to an accentuation of already existing gaps in public health, where the weaker socioeconomic groups are at risk of becoming the most vulnerable (EEA 2019).

Air pollution

The primary environmental health problem globally is air pollution (GBD 2015). Calculations of mortality and disease burden linked to air pollution in the external environment 1990-2015 state that air pollution contributes substantially to the total disease burden (Cohen et al. 2017). Exposure to particles with a diameter of up to 2.5 µm ($PM_{2.5}$) was estimated to cause 4.2 million premature deaths and 103.1 million disability-adjusted life-years (DALYs), corresponding to 7.6% of the total number of deaths and 4.2% of the total number of DALYs globally in 2015. The main anthropogenic sources of air pollution in the external environment are road traffic, industries, energy production, heating, shipping and long-range pollution from other European countries (Folkhälsomyndigheten 2017). Even though air quality has improved in Sweden over the past 50 years and that the health effects of air pollution in the Swedish population is declining (Alpfjord Wylde et al. 2023), there are still significant health sequelae. A recent update of the WHO Global Air Quality Guidelines states that there are no safe levels of air pollution, which has resulted in stricter requirements regarding current guidelines (WHO 2021).

For health purposes, airborne particles and nitrogen dioxides are amongst the most important pollutants (Folkhälsomyndigheten 2017). Fine particles ($PM_{2.5}$) are formed when various fuels are burned and are considered particularly dangerous to health as they can be inhaled and reach the respiratory organs. Larger particles (PM_{10}) are mainly formed during mechanical processes such as wear and tear, for example from brakes and degradation of the road surface due to studded tires and are deposited higher up in the airways. Nitrogen oxides (NO and NO_2), are formed during combustion processes and the largest source (40%) is road traffic. The emissions of these particles are projected to increase with the transmission to electric vehicles due to increased tear from their heavier weight.

The main health effects linked to air pollution are diseases in the respiratory tract and the cardiovascular system, but also lung cancer (Vetenskapliga rådet för hållbar utveckling 2020). Studies of short-term exposure to air pollution have shown that particles and nitrogen dioxides can cause hyperreactivity and allergic inflammation in the airways, as well as impaired immune defense. This can give rise to both short- and long-term effects in the form of respiratory tract infections, increased emergency visits and hospital admissions for asthma, chronic bronchitis, and reduced lung function in children. Effects on the cardiovascular system are mainly mediated by systemic inflammation, oxidative stress, effects on blood clotting ability and heart rhythm disturbances (Arias-Péres et al. 2020).

A recent umbrella review found high evidence that air pollution increases the risk of cardiovascular disease, especially mortality, stroke and ischemic heart disease (de Bont et al. 2022). However, for other outcomes, such as arrhythmias, atrial fibrillation and heart failure, lower evidence was identified, mainly because there are few studies of these outcomes. Air pollution has also been shown to increase the risk of lung cancer, for example through carcinogenic substances such as benzene, formaldehyde and butadiene in traffic exhaust gases and wear particles (Hamra et al. 2014). The effects of air pollution can affect people in different ways depending on their state of health and interaction with other risk factors. Children are a particularly sensitive group when it comes to air pollution as their lungs and immune system are still developing and because they cannot choose their environment and usually spend more time outdoors and inhale more pollutants relative to their body weight than adults. Moreover, several chronic conditions with a strong socioeconomic gradient (e.g. COPD, cardiovascular disease, diabetes), are associated with an increased vulnerability to air pollution.

Transport noise

Along with air pollution, ambient noise is an increasing environmental health problem in urban areas. The main source of noise is transport, i.e., road, rail and air traffic, but other sources such as industries, construction activities, cleaning and noise from neighbors also contribute (Folkhälsomyndigheten 2017). In Sweden, it is estimated that about 2 million people, corresponding to about 20% of the population, are exposed to noise from one of the types of traffic outdoors in their home environment that exceeds 55 dB(A) 24-hour equivalent sound pressure level ($L_{Aeq,24h}$) (Naturvårdsverket 2014). A majority of these are exposed to noise from road traffic (1.64 million), followed by rail traffic (232,000) and air traffic (19,000).

Calculations from Stockholm County show that the proportion exposed above the WHO's health-based guidelines (WHO 2018) is significantly higher than the national average of 20%. Based on data for the year 2015, it was estimated that 42% of the county's population is exposed to potentially harmful noise (Eriksson et al. 2020). Calculations have also been made regarding the burden of disease (DALY) linked to traffic noise. At the European level, traffic noise is estimated to cause at least 1 million DALYs annually (WHO 2014). Sleep disorders and general disorders were stated in the report to account for the largest part of the disease burden, but ischemic heart disease also contributed. Calculations for Sweden show that noise from road and rail traffic together gives rise to about 41,000 DALYs, of which road traffic noise accounted for about 90% (Eriksson et al. 2017).

Traffic noise can cause a range of annoyances and health effects in the population. Common complaints are impaired speech perception and communication, reduced concentration and negative impact on performance and learning, general annoyance and sleep disturbance (Folkhälsomyndigheten 2019). Increasing evidence also points to more serious health effects of traffic noise, such as an increased risk of cardiometabolic diseases such as high blood pressure, ischemic heart disease/myocardial infarction, stroke, obesity, abdominal obesity and diabetes (van Kempen et al. 2018, Roswall et al. 2021, Pyko et al. 2017, Sørensen et al. 2014). The strongest evidence exists for road traffic noise and ischemic heart disease, where risk increases of about 8% have been seen per 10 dB(A) from about 53 dB(A) L_{den}.

There are two main hypotheses behind the research on noise and cardiometabolic diseases. Firstly, noise may induce a stress response. Our hearing is an important warning system designed to help us survive dangerous situations; we must react to sound. In the acute stage, loud sounds can activate the sympathetic nervous system and the HPA axis, i.e., connections between the hypothalamus, pituitary gland and adrenal cortex. This in turn leads to a series of haemodynamic, metabolic and immunological changes which in case of prolonged noise exposure can increase the risk of cardiometabolic diseases (Münzel et al. 2014, Münzel et al. 2018, Eriksson et al. 2018). Secondly, noise can also lead to sleep disturbances and an altered sleep profile, which in turn may predict many serious medical conditions, including cardiovascular disease, obesity, diabetes and depression (WHO Night Noise Guidelines 2009, Muzet 2007).

Although the accumulated evidence on health effects of traffic noise is increasing, there are several knowledge gaps that are key to guide physical planning and priorities for environmental remediation measures. Notably, the impact of noise from multiple sources has been little studied but is an increasing problem in growing cities, as well as interaction with air pollution. How the effects of traffic noise are modified by, for example, the sound standard of the home and access to a noise-protected side, and whether the effects differ in different population groups are other key questions that need to be answered.

Green structure and climate

The importance of green structures in urban environments, such as parks and other natural areas, has received increased attention in recent years. The green structure is an essential part of the built environment that fulfills many functions. Among other things, greenery can help to maintain ecosystem services and mitigate the effects of a changing climate but also contribute to improved public health, for example by stimulating social interaction, physical activity and recovery. Greenery can also have compensatory effects on other urban environmental pollutants, such as air pollution and traffic noise. In an increasingly dense city, however, these qualities risk being lost.

A review of the positive health effects of the green structure shows strong evidence for a connection between green environments and higher birth weight, physical activity and lower mortality (Fong et al. 2018). However, these benefits (e.g. increased physical activity) seem to be hampered if the environment is perceived as unsafe. There are also studies that indicate that greenery can counteract depression and reduce depressive symptoms. For cardiovascular disease and respiratory disease (for example, asthma) and allergies, however, the evidence is more contradictory. In a literature review from 2016, the WHO states that green environments have many positive effects on health, especially for several particularly vulnerable groups in the population, including those with low socioeconomic status, children, pregnant women and the elderly (WHO 2016). It is therefore of the utmost importance to secure sufficient access to greenery for all groups in the population.

An increased proportion of green plants in the urban environment has been shown to be able to reduce the temperature locally and thus reduce heat-related mortality (Folkhälsomyndigheten 2017). Since cities are often built of materials that absorb and accumulate heat, the temperature in cities is often higher than outside, especially during the night. Mappings of temperature in Stockholm City indicate large areas of high temperature (>35°C) in the most central urban areas, but also in the Million Programme areas, e.g. Rinkeby-Tensta and Kista (Wiman and Lindeberg 2022). High temperatures during both day and night are especially dangerous for health as the body does not get enough recovery and can lead to increased mortality. Older people are particularly vulnerable to heat as the ability to regulate heat, for example through sweating and changes in the heart and blood vessels, deteriorates with age. Several common diseases with a strong socioeconomic gradient (i.e. cardiovascular disease, diabetes, obesity), and medication with antidepressants or neuroleptics, are also associated with an increased vulnerability to heat stress (Folkhälsomyndigheten 2015).

Greenery can also contribute to better runoff and thus mitigate the effects of climate-related floods, which can affect people's health in various ways, for example through accidents, increased stress, mold infestation and deteriorating indoor air quality as well as infectious diseases (Länsstyrelsen 2012, MSB 2016). How the changing climate will affect the health of Stockholmers is not clear in detail, but these connections will need to be followed up and monitored continuously in the coming decades.

Although associations between green spaces and health have been established, the results are mixed and depend on how green space is measured; through remotely sensed vegetation indices, percentage of land cover or distance to green areas. A limitation in previous studies is that they often only use one measure for green areas and its association with a specific health outcome. This fact complicates literature reviews and contributes to the mixed and sometimes confusing conclusions. As a result, it is unclear how much green space is needed to promote public health. Is there a required lower limit that can serve as a guideline? These issues need to be investigated further for us to be able to map and assess the access to health-promoting greenery at the population level.

Overcrowding

Limited access to affordable housing has been an increasing problem over the last decade in Sweden, especially in cities and for low-income households. While the overall prevalence of overcrowding according to the Eurostat definition and based on SILC data was 16% in 2021, it was higher in cities (22%), and after exclusion of single households on a national overall level remained at 15%, and strongly associated with low income (1st income quintile 46%, 2nd quintile 19%, and 10%, 6% and 3% for the 3rd to 5th quintiles). There are also strong gradients with country of birth (Sweden 10%, EU 27%, Non-EU 35%) and tenure status (tenants 36%, owners 6%) (Eurostat 2023).

An earlier more detailed registry-based study of the 60% living in apartments in the cities of Malmö, Gothenburg and Stockholm in 2014 found that 40-50% of the children in some parishes were living under overcrowded conditions (Swedish overcrowding norm 2) and had disproportionately low income and foreign-born background (Boverket 2016). Furthermore, data from home visits in Malmö indicate that registry data underestimate the problem (Albin et al. 2012).

Household crowding has in many studies been shown to be associated with ill health and connected to poor educational attainment in some studies. While the certainty of the evidence for an increased risk for respiratory infections was assessed by WHO (2016) as moderate to high, evidence for e.g. mental health effects was considered low to moderate, mainly due to difficulties to control for other socioeconomic factors (WHO 2018). Effects are thought to occur both directly through the lack of sufficient space, but also through other aspects of housing quality, e.g. ventilation, dampness, allergens, molds, mites, and infestations (Lorentzen et al. 2022). For instance, the atopic burden in overcrowded housing is high and needs to be further explored in relation to poor housing conditions, particularly in vulnerable populations such as among children and adolescence. Longitudinal data on effects on children's life chances (development, educational attainment and health) from overcrowded housing in a Nordic context are missing (Boverket 2016), and it is important to close this knowledge gap to inform physical planning and mitigation measures.

In this program, we will explore the influence of overcrowded housing regarding neurodevelopment, educational attainment, respiratory and mental health, from early life up to early adulthood in a cohort of all children born in Sweden 1994 to 2014 (Fetal Air Pollution Exposure Cohort, FAIR) (Norlen et al. 2019). Furthermore, opportunities to reduce the burden of asthma and atopy among children in relation to overcrowded housing will be explored in an intervention study focusing on improving the indoor environment in an interactive approach including the families, primary health care and local authorities.

Aims

In support of current policy, the overall aim of the planned program is to prevent environment-related ill-health and to promote a good and equitable public health among residents of Stockholm County. The program also aims to assess and develop strategies for building a sustainable city promoting public health equity among inhabitants of urbanized areas. With its rapid and wide-ranging transformation of the surrounding environment, Stockholm is an optimal setting for such a study.

The program builds on a salutogenic framework and our long-established close collaborations with key stakeholders responsible for physical planning and public health in the county. It will include monitoring of wellbeing and health in relation to environmental exposures associated with changes in the urban form and land use. In particular, the program will assess how the health of the inhabitants in urbanized areas is related to urban density, new infrastructure and increased transports, the introduction of higher guideline values for traffic noise, a changed climate and

overcrowding. The identification of disadvantaged groups will be of particular importance throughout the program.

Primary exposures include *air pollution* (PM_{10}, $PM_{2.5}$ and NO_2) *transport noise* (road, rail and air traffic), *green structure*, *climate-related exposures* (e.g. urban heat islands and indoor temperature), and *overcrowding*. Other related exposures will, however, also be included, for instance allergens and factors in the indoor environment. In addition, synergies between walkability, active mobility and public health will be considered. A particular interest is to elucidate inequities and study the occurrence of multiple environmental disadvantages in the population which may further accentuate health disparities.

Easily accessible and transparent evidence on the distribution of these exposures, and the disease burden, will support consideration and evaluation of environmental equity in the physical planning. We will also explore measures to remediate effects on children of poor and crowded housing.

The more specific aims of the program are:

1. To prospectively assess and analyze population exposure to environmental hazards in the urban population of Stockholm County, for the identification of inequities in environmental burden.
2. To study environmental-health associations in a cohort of approximately 50,000 adults (18–84 years) residing in Stockholm County, and to elucidate environmental-health inequities.
3. To assess the effects on children's development, education and health from overcrowded housing to guide planning and mitigation measures.
4. To assess the burden and distribution of disease in the population in terms of number of cases and DALYs related to the environmental exposures under study.
5. To identify, initiate and evaluate evidence-based environmental interventions in different domains (e.g. physical planning, primary care), targeted on promoting good and equitable public health.
6. To develop guidelines and recommendations on how to promote good and equitable health among inhabitants of urbanized areas in close collaboration with stakeholders and decisionmakers, including both planning and mitigation measures.

Originality

This program is unique in that it takes a holistic approach to environment-related public health and equity in a way that, as far as we know, has not been done before. A continuous and comprehensive survey of the population's exposure and vulnerability to various factors in the ambient environment is a prerequisite for assessment and prevention of environmental-related ill health. The implementation of a support tool for regional stakeholder to visualize the distribution of environmental health hazards within the population is a novel approach bridging research and practice.

The program also provides an excellent opportunity to assess environmental-health inequities as well as exposure-response associations between urban environmental factors and various health outcomes, which is of crucial importance for calculations of disease burden and distribution in the population. The identification of health-hazardous as well as health-promotive environments within Region Stockholm, with its concentration of needs and actions, may set an example also for other regions and cities, both nationally and internationally.

The project's aims to review and summarize evidence-based environmental interventions and to develop guidelines and recommendations for decision making, urban planning and implementation

will create a “good practice guide” for implementation of interventions based on the program findings in dialogue with local authorities and stakeholders. Thus, the program will in an explicit way increase the “know-how” among stakeholders of how to construct urban areas promoting good and equitable health.

Finally, the program entails strengthening of a unique and high performing research infrastructure between a medical university institution on the one hand (IMM, KI), and a regional center formation focused on applied work within environmental medicine on the other (CAMM, Region Stockholm). Within the intended research team, we have a broad spectrum of competence, spanning all disciplines covered within the program, as well as vast experience of administrating large research programs. Moreover, with its far-reaching and already established collaborations and networks at both IMM and CAMM, the program will have leverage on many different levels and will be gainful not only within the research community but, even more importantly, for the general society.

Methods

Population exposure to environmental hazards (Aim 1)

The occurrence of various environmental exposures and their distribution within the county's population will be mapped using geographic information systems (GIS) and through the collection and analysis of data on concentrations or levels of respective exposure in relation to demographic and socioeconomic data for Stockholm County. This part of the program is linked to CAMM's recently initiated project *Environmental health on the map*, which aims to develop a new support tool for monitoring and analyzing the environment-related public health in Stockholm County.

Currently, the project focuses on mapping of three prioritized environmental exposures: Air pollution – including particles ($PM_{2.5}$, PM_{10}) and nitrogen dioxide (NO_2) – transport noise (i.e., noise from road, rail and air traffic), as well as green structure. The present program will contribute to develop the tool further, including also heat islands, overcrowding and walkability/bikeability. Collection and management of exposure data takes place in close collaboration with IMM at KI, which has many years of experience in this area. An effort is currently being made at IMM to develop an *exposome database*, intended to provide data and methods for individual-based estimates of various environmental and occupational exposures. The database will primarily be used for research purposes, mainly for correlation analyzes between the environmental exposures and health.

CAMM's project Environmental health on the map is an example where data on central environmental exposures can be more practically applied and disseminated to regional stakeholders. An infrastructure for data collection is under construction at CAMM and IMM and involves contacts with several different regional as well as national data providers, including *the Land Survey* (terrain data, building layers, etc.), *SLB Analysis* (regional road network, traffic flows, air pollution level maps), the *Swedish Transport Administration* (heavier rail traffic and commuter trains), the *Traffic Administration in Stockholm* (light rail traffic, e.g., subway and light rail), *Swedavia* (air traffic) and the *Geographical Information Agency* (remotely sensed green structure).

There are several current, or already completed, research projects within which exposure data is available or is being collected, for example *Scapis Miljö* (FORTE Dnr. 2019-00108 ; PI Petter Ljungman, KI). Possible sources of climate-related exposure data are, for example the *Swedish Geotechnical Institute (SGI)*, *the Swedish Meteorological and Hydrological Institute (SMHI)*, and the *Swedish Civil Contingencies Agency (MSB)*. The national FAIR-cohort (FORTE Dnr. XXX; PI Jenny Selander, KI) already has extensive data on child and maternal health and socioeconomic factors, early development and school grades. This will be supplemented with housing and residential area information.

In addition, we will also collect population data, including demographic and socio-economic variables such as age, sex, marital status, ethnicity, education level, occupation and income at the individual level, and average income, unemployment rate and education at the area level (DeSO). Access to this data is obtained via *the Regional Database* that *Statistics Sweden* provides through its platform for microdata*, MONA*. Land cover data will also be collected, for example National Land Cover Data from the *Swedish Environmental Protection Agency (EPA)*, which contains detailed spatial information on, for example, buildings, roads, hard surfaces and various types of green areas (e.g., forests, wetland, grass areas and fields).

The technical platform for visualization and making data available to the public is under construction and will be based on map services and applications available via Region Stockholm's geodata *portal Geonavet* and Esri's web-based mapping software *ArcGIS Online*. All other statistical processing is conducted with the aid of the programming language *R.*

The results will be reported on *CAMM 's website* (camm.regionstockholm.se), and will also be accessible via *Folkhälsoguiden* (folkhalsoguiden.se)**,** a website for public health issues in Region Stockholm. Some central environmental health indicators for the region will also be made available via the Center for Epidemiology and Community Medicine's (CES) tool *Folkhälsokollen* (folkhalsokollen.se).

Environmental-health associations (Aim 2)

Study design and population

To analyze environmental-health associations and inequities within an urban population, we intend to establish a new cohort, the Stockholm Environmental Health Cohort. The cohort will be established in connection with the distribution of the National Environmental Health Survey 2023 (NMHE23), administered by Statistics Sweden (SCB) on behalf of the Public Health Agency of Sweden (Folkhälsomyndigheten). NMHE23 will be sent to roughly 230,000 randomly selected Swedish citizens, aged 18–84 years. Through extra funding from the Health and Medical Administration (HSF) and CAMM at Region Stockholm, the County Administrative Board (Länsstyrelsen) in Stockholm County and Uppland's Väsby Municipality, the survey will be distributed to approximately 125,000 residents in Stockholm County. With an estimated response rate of around 40%, approximately 50,000 responses are expected and hence become the base of the cohort. Through a follow-up survey in 2028, longitudinal information will be obtained which can form the basis for evaluations of the development over time.

The environmental health surveys are recurring surveys that aim to show the population's exposure to various environmental factors and related problems (Folkhälsomyndigheten 2023). NMHE23 contains about 60 different questions relating to the respondents' health, housing and living conditions, symptoms and complaints from various environmental exposures, tobacco, means of transportation to work, leisure and outdoor activities, and climate change. In order to minimize the number of questions in the survey, supplemental information about the individual is obtained from registers, including age, sex, education, marital status, income, country of birth, citizenship, municipality, county, area of residence, housing type, year of construction of the residence, living space, form of ownership and number of rooms, as well as address coordinates. Information on specialist care and medicine use is retrieved from the National Board of Health and Welfare's register.

All personal data is processed in accordance with the Helsinki declaration and the EU data protection regulation. Informed consent is obtained in connection with answering the questionnaire. To enable

follow-ups with register data and a new survey, SCB creates serial numbers that are linked to social security numbers for those who participate in the survey. The link (code key) is saved separately from survey responses and register data and is delivered to the Public Health Agency after completion of processing at SCB.

Outcome assessment

When the study is established (2023), self-reported information will be obtained from the NMHE23. Central questions that are included in the questionnaire are for example:

- *General health*
- *Height and weight*
- *Self-reported diseases (e.g., asthma, allergic complaints, type 2 diabetes, stroke, heart attack, bronchitis and COPD)*
- *Respiratory symptoms*
- *Annoyance from traffic emissions and wood burning*
- *Noise annoyance*
- *Perceived air quality in and nearby the home*
- *Means of transport to work and time spent in traffic*
- *Access to patio or balcony*
- *Frequency of stay in green areas*
- *Concern about climate change*
- *Visible moisture damage in the home.*

In addition, information on diagnoses and drug use is obtained from the National Board of Health and Welfare's register (Patient Register, Medicines Register) or via administrative healthcare databases within Region Stockholm (the so called “VAL” databases). We will monitor the following outcomes:

- *Hypertensive diseases (subdivided by ICD-10-SE codes I10 and I11)*
- *Ischemic heart diseases (I20, I21, I22, I24, I25)*
- *Arrhythmias (I48)*
- *Disease conditions within the pulmonary circulation (I26)*
- *Diseases of the vessels of the brain (I60-I64)*
- *Diseases of arteries, arterioles and capillaries (I70, I74)*
- *Kidney disease (N17-N18)*
- *Other acute infections of the lower respiratory tract (J20)*
- *Other diseases of the upper respiratory tract (J30, J31)*
- *Chronic diseases of the lower respiratory tract (J40-J42, J44-J46)*
- *Diabetes (E10-E14)*
- *Obesity and other overnutrition conditions (E66)*
- *Respiratory and thoracic cavity organs tumors (C34.9)*

Exposure assessment

The assessment of the study participants' exposure to various environmental factors will be based on the address coordinates obtained via linking to SCB’s register in connection with the establishment of the study. The address coordinate is used to identify the geographic location of the participant's residence and for linking to GIS-based data layers with concentrations/levels of exposure near the residence. In this way, both the participants present and historic exposure can be assessed.

Total levels of air pollution (PM_{10}, $PM_{2.5}$ and NO_2) for different years are calculated by SLB Analys (www.slb.nu) using dispersion and street space models in combination with measurements of air pollution levels (Segersson 2017). The calculations include both local sources, such as road traffic, wood burning, shipping, industrial processes and energy plants, as well as long-range transport. The concentrations of the pollutants are commonly estimated at two meters above the ground or street.

Noise from road traffic is modeled using the Nordic calculation method (Naturvårdsverket 1996) two meters above ground at the building's most exposed facade and is expressed as A-weighted 24-hour equivalent sound level (dB $L_{Aeq,24h}$) and as day-evening-night level (dB L_{den}) where noise events that occur in the evening and at night are weighted up by 5 and 10 dB(A), respectively. The model is based on input data such as terrain (3D laser scan), buildings, road network, traffic flows, speeds and distribution of vehicle type (light/heavy traffic). Via MHE23 it is also possible to identify whether the home faces a side exposed to noise or not.

For rail traffic, information on noise from light rail (e.g., subway and light rail) is obtained from the Transport Administration (Trafikförvaltningen) within Stockholm Region, which models the noise at its facilities in accordance with the European Noise Directive (2002/49/EC) and the Swedish regulation on ambient noise (2004:675). In a similar way, information on heavier rail traffic (intercity trains, commuter trains and freight traffic) is obtained from the Swedish Transport Administration.

Noise from air traffic in Stockholm County (at Arlanda and Bromma) is also modeled within the framework of the EU directive, but only from sound levels of 55 dB(A) L_{den} and above.

Exposure to green structure will be mapped in two ways; partly via remotely sensed Normalized Difference Vegetation Index (NDVI; Ekkel et al. 2017), partly via National Land Cover Data (NMD). NDVI quantifies vegetation by calculating the difference between near-infrared (NIR), which vegetation strongly reflects, and red light (RED), which vegetation absorbs; $NDVI = (NIR - RED)/(NIR + RED)$. NDVI varies between -1 and 1 where higher values are associated with more greenery, values close to 0 indicate urban areas and negative values indicate water. Data on NDVI is obtained from the Geographical Information Agency (Geografiska informationsbyrån 2023-01-23).

Exposure to greenery will be calculated within buffer zones around the participants' address points. NMD is an up-to-date and comprehensive mapping of Sweden's land cover that has been produced by the Swedish EPA in collaboration with several other Swedish authorities and organizations (Naturvårdsverket NMD). NMD provides information on how the landscape looks and changes over time regarding what covers the land surface, including forest, buildings, water, agricultural land, parks and more. Data from NMD will be used to assess percentage of green space as well as individuals' distance to public green spaces from the home.

Information about the study participants' exposure to climate-related effects is obtained from authorities specialized in monitoring these phenomena, for example SMHI and MSB. For instance, data on maximum outdoor temperatures, covering all of Sweden, is available through a map service at MSB (Värmebölja (msb.se)). In addition, we aim to collaborate with an adjacent research initiative to develop methods for assessment of indoor temperatures; *Building vulnerability in a changing climate: Indoor heat exposure and public health* (PI M. Lõhmus).

With regards to walkability, the aim is to investigate the relationship between the probability that people will choose to walk to daily activities, such as work, and urban features relevant to urban planning, such as street layout, access to footpaths and local services. This knowledge may then be used to create a walkability index for mapping walkability in the county. The challenge is to identify which urban features are the best predictors of the probability that residents of Stockholm County

will choose to walk. This information is relevant, because daily physical activity is important for public health.

Finally, overcrowding will be assessed from the national registries of the population (RTB) and the registries of apartments and houses (Lägenhets- och fastighetsregistret). Updates of the exposure data will be made on a regular basis and account will be taken of how the participants move through follow-up in the Population Register.

Statistical analyses

Because of social and geographical interactions across space, it is necessary to beware of the risk for spatial autocorrelations in data that pertains to interconnected locations. This notion is captured in Tobler's first law of geography, stating that "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970, p. 236). Consequently, the plan is to use spatial regression models developed in social science that may control for autocorrelations in the observations (e.g., Anselin, 1988; LeSage & Kelley Pace, 2009; Elhorst, 2014). Methods are available for both cross-sectional and longitudinal (panel) data, and for various forms of dependent variables. Many such models are implemented in the programming language R.

To be useful in urban planning and predictive mapping for policy assessment, associations with health will be sought, not only for the environmental exposures, as outlined above, but also for their underlying determinants, related to urban form and land use. As an example, for air pollution and environmental noise, determinants include traffic flows and distance to roads. From this point of view, the environmental exposures may be thought of as mediating factors between their determinants and health. The rational of this approach is that to improve public health it is necessary to alter the exposures, and to alter the exposures we must change their determinants. Ultimately, urban planning manages the determinants, not the exposures per se.

When dealing with spatial data, it is important to understand that the cross-sectional observations are a single realization of a stochastic field, frozen at a moment in time. The aim of the statistical analyzes is to begin unveiling the nature of the stochastic process underlying public health in Stockholm County that resulted in the cross-sectional observations.

The long-term objective is to develop a prediction model that will make it possible to identify risk areas in Stockholm County where housing must not be constructed, or areas that are especially beneficial for housing. It must also be possible to use the model for testing future scenarios and the impact they may have on public health. In this way, the model may be useful for detailed planning of future urban developments, a feature that is on the wish-list of the regional planning department.

The Stockholm Environmental Health Program will be a first step on this journey towards a prediction model. The plan is to use the 2023 data set for developing a preliminary model. It will then be possible to investigate how well this model predicts the outcome of the 2028 survey, keeping in mind that these two sets of data only represent two observations, or snapshots, of the underlying stochastic process that we are trying to understand.

Overcrowded housing and children´s development and health (Aim 3)

We will use the national birth cohort FAIR including all children born in Sweden 1994-2014 (n=2,113,336) and their parents to explore the effect of overcrowded housing from early life (e.g. birth outcomes, early development indicators, diagnoses from specialized care, prescribed drugs, educational attainment), and up to the recently (2017) reestablished conscription. Observational data will be used to emulate a target trial to evaluate the effect of "treatment" (i.e. moving from overcrowded to non-crowded housing and vice versa), in order to reduce the risk of uncontrolled

confounding and reversed causality. We will further use data from the Stockholm Regional Environmental Health Survey 2019 to explore children's (8 month, 12 years) health and wellbeing (e.g. asthma and atopy) in relation to over crowded housing according to symptoms scores, severity, general health, while accounting for socioeconomic factors.

To assist the interpretation of the findings and discuss needs and suggestions for mitigation measures, we will form focus groups with parents from selected highly segregated disadvantaged areas in Stockholm (same as described for collaboration with primary health care).

In an intervention part of the program, we will study the possibility to reduce the burden of atopy and asthma among children in areas with a high prevalence of crowded and poorly maintained housing. We will consecutively recruit children in the ages 6 months to 15 years (n≈300) seeking care for respiratory symptoms, asthma or atopy in a subset of 16 primary health care centers who have designated responsibility and funding for extended health promotion in the catchment area from Region Stockholm. The intervention will be developed and tested in collaboration with 1-2 primary health care centers, before extension to in total 6-8 centers. A specialist allergy nurse who currently carries out home-visits will collaborate with the primary health care centers to recruit the children. Following approval from the family, the allergy nurse will then carry out a home visit to perform an interview-based survey about the child's health, e.g. atopy/asthma development, and for older children also schooling and experienced impact of the indoor environment. Through the interviews, the study will also include a qualitative approach, assessing and exploring the needs of parents living in overcrowded homes in relation to health, development, and schooling of their children. This will give us knowledge about physical, physiological and social needs so that their experience can be integrated in further implementation activities.

With support from an environmental hygienist, the nurse will also perform an inventory and mapping of the indoor environment according to a structured checklist (inspection of visible moisture, mould and odour) currently used on home-visits to identify deficiencies in overcrowded housing. This may also include some testing and sampling (i.e. mite analysis/allergy test). To support the family in improving the children's health, the nurse will give advice based on the earlier Asthma and Allergy Prevention project for recent Immigrants (ALPIN; initiated by K Jakobsson) on potential indoor environmental interventions adapted to the family's needs. After four weeks and four to six months, follow-up visits will be carried out by the nurse to assess changes in the children's health and environment. We will additionally monitor change in absence from school/day-care center due to illness, and specialized and primary care visits from register data (VAL). The result of the intervention will form a basis for possible extended care programs (home-visits) for children with asthma/atopy in these areas, and for a more formalized interventions study including both the full investigation, and a minimal intervention (advice only). For the latter, we will apply for extra funding rom Region Stockholm and external funding agencies.

During the study, the results will continuously be shared and discussed with the municipalities Environmental Health Protection Offices, as a basis for potential housing inspections directed towards specific housing estates within the area. We will also throughout the program consult with the local community, and tenants' association, on how vulnerable tenants suffering from poorly maintained flats can best be advised to claim action.

Estimations of disease burden (Aim 4)

The burden of disease will be estimated quantitatively by calculating the number of cases of different types of problems, disorders and cases of disease that can be linked to the environmental factors being studied. For traffic noise, a recently developed methodology is available, prepared by the

project's principal investigator on behalf of the Swedish EPA (Eriksson and Pershagen 2022). The estimates should be based on population-based calculations of the number exposed and current evidence-based knowledge about the relationship between exposure and health.

Based on known exposure-response relationships, the number of cases of various problems/diseases at different exposure levels is calculated and summed at the population level. As an example, the number of cases of highly annoyed, the number of cases of severe sleep disturbance and the number of cases of ischemic heart disease are calculated for road traffic noise; disease outcomes assessed by the WHO as having moderate or high evidence (WHO 2018). In a similar way, estimates can also be made for other exposures and outcomes. Furthermore, there are good opportunities to also calculate disease burden in the form of DALY (Disability Adjusted Life Years) based on proven methodology (WHO 2020).

Identification of disease preventive and health promotive interventions (Aim 5)

Current scientific evidence of various disease prevention and health promotion interventions aimed at preventing environment-related ill-health and/or promotion of an equitable public health will be assessed and summarized in a narrative review. The compilation will be exposure-specific and will include air pollution as well as traffic noise, green structure, climate-related effects and overcrowding. The compilation will have a broad approach where efforts at different levels are assessed, from a structural level to measures in the physical environment.

On a structural level, this implies, for example, evaluation of the effects on the population's health of current laws, regulations and benchmarks linked to the respective environmental exposure. It can also be about evaluating local measures in the physical environment, such as dust sealing, studded tire bans, speed reductions, reducing physical barriers for easier access to green areas, and more. The various measures will also be ranked in relation to their respective benefit, estimated based on the number of individuals affected by the measure as well as on the measure's expected effects and costs.

Development of guidelines and recommendations (Aim 6)

To develop guidelines and recommendations for decision making, regional priorities and implementation, the main findings and conclusions of the program will be presented to and discussed with key stakeholders within the region. Regional needs and whishes will be considered and cared for. The results of the dialogue will be summarized in a comprehensive report along with an overall picture of the population's exposure to environmental hazards and its health consequences, including estimates of the burden and distribution of disease. Furthermore, we will provide a summary of effective interventions to prevent and/or mitigate the public health consequences of environmental exposure.

A particular focus of the report will be to elucidate and describe characteristics of geographical areas where the burden of multiple environmental exposures is high, as well as to identify groups in the population which are of extra high risk of environmental illness. This will enable more accurate and cost-effective opportunities for prevention of environmental-related ill health through targeted interventions which, in turn, may aid to close the health gaps within the population. Of equal importance is to describe characteristics of health promotive environments, thereby setting examples ahead for an urban planning promoting good and equal health in urbanized areas.

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