Marjo Seppänen is a health geographer who completed her PhD at the Geography Research Unit and at the Research Unit of Population Health at the University of Oulu and at the Department of Sports and Exercise Medicine at the Oulu Deaconess Institute Foundation. Her dissertation focuses on the associations between residential environment, physical activity behaviour and depressive symptoms. She investigates these associations at three geographical levels: global, regional and local. Her work provides a multidisciplinary understanding of the environmental and behavioural factors associated with depressive symptoms at the population level.

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Residential environment, physical activity and depressive symptoms in adults

Marjo Seppänen

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Contents

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Abstract

Depression is, at its worst, a fatal disease and a significant factor threatening work ability. Recent studies have suggested physical activity as an effective treatment for depression. Scientific evidence on the beneficial association between physical activity and depressive symptoms is strong. Recently, studies have also highlighted the residential environment's importance for both mental health and physical activity. Due to accelerating urbanisation, it is increasingly important to understand how our living environment affects our physical movement behaviour and mental health.

This study's aims were to I) compare the prevalence of depression symptoms in different countries, II) investigate how characteristics of the residential environment and physical activity are associated with depressive symptoms, and III) study how 24-hour movement behaviours (physical activity, sedentary time and sleep) are associated with depressive symptoms in urban and rural residents. The main data for the study were collected from individuals born in Northern Finland in 1966 when they were 46 years old (n=5,860). In addition, the first substudy utilised previously published research articles to compare the prevalence of depressive symptoms between different countries. The characteristics of the residential environment, based on the participants' home coordinates, were examined using geographic information system methods. Physical activity was measured using both a questionnaire and accelerometer-based activity monitors that the participants wore for 2 weeks. Depressive symptoms were assessed in all studies based on the second version of the Beck Depression Inventory.

The results indicated that depression symptoms vary between countries. Higher urbanicity and population density of the residential environment were associated with a higher odds of more severe depressive symptoms, while higher greenness was associated with a lower odds of severe depressive symptoms. More time spent in moderate to vigorous physical activity or sleep at the expense of light activity or sedentary behaviour within a 24-hour day was associated with lower depressive symptoms in those living in rural areas. Among urban residents, reallocating time from sedentary behaviour to any other behaviour was associated with lower depressive symptoms. According to this study's results, preserving and increasing green spaces in urban planning and taking into account all the movement behaviours of the 24-hour day, for example in health care and physical activity recommendations, could be ways to decrease depressive symptoms at the population level. It is also important to consider the differences in movement behaviours between those living in urban and rural areas. Future research in longitudinal settings is needed to confirm causal relationships, in particular, between residential environment and depressive symptoms.

Keywords: depressive symptoms, residential environment, GIS, physical activity, sedentary behaviour, sleep, midlife

Tiivistelmä (abstract in Finnish)

Masennus on pahimmillaan kuolemaan johtava sairaus ja merkittävä työkykyä uhkaava tekijä. Viimeaikaisten tutkimusten mukaan fyysinen aktiivisuus on tehokas masennuksen hoitokeino. Tieteellinen näyttö fyysisen aktiivisuuden suotuisasta yhteydestä masennusoireiluun on vahvaa. Viimeaikaisissa tutkimuksissa on korostettu myös asuinympäristön merkitystä niin mielenterveyden kuin fyysisen aktiivisuudenkin näkökulmasta. Kiihtyvän kaupungistumisen takia on entistä tärkeämpää ymmärtää, miten asuinympäristömme vaikuttaa liikkumiskäyttäytymiseemme ja mielenterveyteemme.

Tämän tutkimuksen tarkoituksena oli I) verrata masennuksen oireiden esiintyvyyttä eri maissa, II) selvittää, miten asuinympäristön piirteet ja fyysinen aktiivisuus ovat yhteydessä masennusoireiluun ja III) tutkia, miten vuorokauden aikaiset aktiviteetit (fyysinen aktiivisuus, paikallaanolo ja uni) ovat yhteydessä masennusoireiluun kaupungissa ja maaseudulla asuvilla. Pääasiallisena aineistona väitöskirjassa käytettiin aineistoa, joka kerättiin Pohjois-Suomessa vuonna 1966 syntyneistä heidän ollessaan 46-vuotiaita (n=5860). Lisäksi ensimmäisessä osatyössä hyödynnettiin jo julkaistuja tutkimusartikkeleita masennusoireilun vertailussa eri maiden välillä. Asuinympäristön piirteitä tarkasteltiin tutkittavien asuinkoordinaattien pohjalta paikkatietomenetelmin. Tieto tutkittavien fyysisestä aktiivisuudesta perustui sekä kyselyyn että kiihtyvyysanturipohjaisiin aktiivisuusmittareihin, joita tutkittavat käyttivät kahden viikon ajan. Masennusoireilua tarkasteltiin kaikissa osatöissä Beckin depressioasteikon toisen version perusteella.

Tulosten perusteella masennuksen oireet vaihtelevat eri maiden välillä. Kaupunkimaisempi asuinympäristö ja suurempi väestöntiheys olivat yhteydessä korkeampaan vakavampien masennusoireiden todennäköisyyteen, ja asuinympäristön vihreys puolestaan oli yhteydessä pienempään vakavampien masennusoireiden todennäköisyyteen. Suurempi määrä päivittäistä keskiraskasta tai raskasta fyysistä aktiivisuutta tai unta kevyen fyysisen aktiivisuuden tai paikallaanolon kustannuksella oli yhteydessä vähäisempään masennusoireiluun maaseudulla asuvilla. Kaupungissa asuvilla paikallaanolon korvaaminen millä tahansa muulla vuorokauden aikaisella aktiviteetilla oli yhteydessä vähäisempään masennusoireiluun. Viheralueiden säilyttäminen ja lisääminen kaupunkisuunnittelussa sekä kaikkien vuorokauden aikaisten aktiviteettien huomioiminen esimerkiksi terveydenhuollossa ja liikuntasuosituksissa ovat tutkimuksen tulosten perusteella mahdollisia keinoja vähentää masennusoireilua väestötasolla. Kaupungissa ja maaseudulla asuvien erot liikkumiskäyttäytymisessä tulisi myös huomioida. Etenkin asuinympäristön ja masennusoireilun kausaalisuhteiden varmistamiseksi tarvitaan tulevaisuudessa pitkittäistutkimuksia.

Asiasanat: masennusoireilu, asuinympäristö, GIS, fyysinen aktiivisuus, paikallaanolo, uni, keski-ikä

List of original publications

This thesis is based on the following publications, which are referred to throughout the text by their Roman numerals (* equal contribution):

Study I Seppänen M, Lankila T, Auvinen J, Miettunen J, Korpelainen R & Timonen M (2022) Cross-cultural comparison of depressive symptoms on the Beck Depression Inventory-II, across six population samples. *BJPsych Open* 8(2): e46. https://doi.org/10.1192/bjo.2022.13

Study II Rautio N*, Seppänen M*, Timonen M, Puhakka S, Kärmeniemi M, Miettunen J, Lankila T, Farrahi V, Niemelä M & Korpelainen R (2023) Associations between neighbourhood characteristics, physical activity and depressive symptoms: The NFBC 1966. *European Journal of Public Health* 2023: ckad215. https://doi.org/10.1093/eurpub/ckad215

Study III Seppänen M, Lankila T, Niemelä M, Rautio N, Korpisaari M, Timonen M, Korpelainen R & Farrahi V (2025) Compositional associations of 24-h physical activities, sedentary time and sleep with depressive symptoms in urban and rural residents: a cross-sectional study. *BMC Medicine* (23): 219. https://doi.org/10.1186/s12916-025-04051-9

Original publications are available in the appendices of the printed version of this thesis. Publication I is reprinted with the permission from Cambridge University Press. Publications II and III are reprinted under CC BY 4.0 Creative Commons licence.

Author's contributions

I participated in the planning and designing of the studies as well as formulating the research questions and selecting methods in all studies (I–III). In Study I, I was responsible for the literature search, screening the articles and extracting the data from the included studies; I calculated the relative means used in the meta-analysis and meta-regression and interpreted the results together with JM, who conducted the analyses; and I wrote the first draft of the manuscript. In Study II, I had an equally shared responsibility (with NR) for analysing the previously collected data, interpreting the results, and writing the draft as well as the final version of the manuscript. In Study III, I was responsible for analysing the previously collected and pre-processed data (with help from VF and MN), interpreting results and writing the manuscript. All manuscripts were finalised based on co-authors' and reviewers' comments.

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Oulu, May 2025

Abbreviations

BDI-II	Beck Depression Inventory-II
CI	Confidence interval
DSM	Diagnostic and Statistical Manual of Mental Disorders
EE	Energy expenditure
GIS	Geographic information system
GPS	Global Positioning System
ICD	International Classification of Diseases
LPA	Light-intensity physical activity
MAD	Mean amplitude deviation
MET	Metabolic equivalent
MPA	Moderate-intensity physical activity
MVPA	Moderate- to vigorous-intensity physical activity
NDVI	Normalised Difference Vegetation Index
NFBC1966	Northern Finland Birth Cohort 1966
OR	Odds ratio
PA	Physical activity
PPGIS	Public participation geographic information system
SB	Sedentary behaviour
SD	Standard deviation
SES	Socio-economic status
ST	Sedentary time
VPA	Vigorous-intensity physical activity
WHO	World Health Organization

1 Introduction

Depression is the leading cause of disability worldwide and can lead to suicide in severe cases (Kessler & Bromet 2013; World Health Organization, WHO 2017). Over time, the prevalence of depression has increased worldwide (Robinson *et al.* 2022) and in Finland (Miettunen *et al.* 2024). Several risk factors for depression are known, including genetic (Wray *et al.* 2018), psychological (Klein *et al.* 2011) and social factors (Kessler & Bromet 2013; Lorant *et al.* 2003). In addition, several environmental and lifestyle factors have been associated with a higher risk of depression, such as lack of green space exposure (Liu *et al.* 2023), living in urban areas (Sampson *et al.* 2020) and low physical activity levels (Schuch *et al.* 2018).

Physical activity (PA) has been shown to be effective to both prevent (Schuch *et al.* 2018) and treat depression, with an effect size similar to that of medication or cognitive behavioural therapy (Noetel *et al.* 2024). In particular, higher-intensity PA has been shown to be effective in treating depression (Noetel *et al.* 2024), whereas mentally passive sedentary behaviour (Huang *et al.* 2020) and insufficient or excessive sleep (Zhai *et al.* 2015) are associated with a higher risk of depression.

Several studies have found that living in urban areas is associated with a higher risk of depression, while some studies have found the opposite or no association between urbanicity and depression (Rautio *et al.* 2018; Sampson *et al.* 2020). In addition, the characteristics of urban areas, such as low socio-economic status (SES), traffic noise and unsafe neighbourhoods, have been associated with the presence and severity of depression (Generaal *et al.* 2019). On the other hand, green space exposure (Liu *et al.* 2023) has been associated with a lower risk of depression. In a broader context, the country in which the individual lives, together with the cultural context, may also play a role in depressive symptoms. For example, the prevalence of specific symptoms of depression has been found to vary between countries (Nuevo *et al.* 2008).

The residential environment has also been associated with the level of PA, with beneficial associations found, for example, between better accessibility, active transport infrastructure, neighbourhood density and higher PA level (Kärmeniemi *et al.* 2018, 2019). Green spaces have also been beneficially associated with PA. Moreover, the context of PA has been found to differ between urban and rural residents, with higher recreational PA associated with living in urban areas (Boakye *et al.* 2023).

Considering accelerating urbanisation (United Nations 2018), the increasing prevalence of depression (Robinson *et al.* 2022) and the decreasing number of people meeting PA recommendations (Bull *et al.* 2024), there is a need to better understand the associations between residential environment, depressive symptoms and PA. This study addresses this research gap by comparing the prevalence of depressive symptoms among six populations from different countries and utilising population-based Finnish birth cohort data.

2 Review of the literature

2.1 Depression

In everyday life, the word depressed can be used to describe a feeling or temporary state of mind, or an individual may experience symptoms of depression that are associated with primary organic diseases or other psychiatric disorders, such as schizophrenia (Beck & Alford 2009). The diagnosis of depression is mostly based on the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) (American Psychiatric Association 2013) or the International Classification of Diseases, with the most recent revision being the 11th revision (ICD-11) (WHO 2024). In Finland, the 10th revision of the ICD is still in use, as the transition to the 11th revision has not yet been completed. According to the Psychiatric Classification Manual for the Finnish version of ICD-10 (Komulainen *et al.* 2012), *depressive disorders* are characterised by lowered mood, lack of energy, decreased activity and reduced capacity for enjoyment and interest. Other symptoms include fatigue, difficulty concentrating, loss of appetite, sleep disturbances, low self-esteem and confidence, feelings of worthlessness or guilt and suicidal thoughts or actions. Depressive disorders can be classified according to severity (mild, moderate, severe), and severe depressive episodes can be further classified according to the presence or absence of psychotic symptoms. To be diagnosed, symptoms of depression must usually have been present almost every day for at least 2 weeks, and the mood must be unaffected by circumstances. A depressive disorder can be a single episode or be recurrent (Depression: Current Care Guidelines 2025; Komulainen *et al.* 2012).

2.1.1 Assessment of depressive symptoms

Several rating scales are used to assess *depressive symptoms* and their severity. Clinician-rated scales include the Hamilton Depression Rating Scale (HDRS) (Hamilton 1960), originally developed for adult hospital inpatients, and the Montgomery-Åsberg Depression Rating Scale (MADRS) (Montgomery & Asberg 1979), an adaptation of the HDRS that has been validated in the adult population and specifically designed to be sensitive to changes in symptoms over time. Self-rating scales include the Beck Depression Inventories (BDI, BDI-1A, BDI-II) (Beck *et al.* 1961, 1996; Beck & Steer 1993) for adults and adolescents over 12 years of age, the Center for Epidemiologic Studies Depression Scale (CES-D) (Radloff 1977) for the general population, the Hospital Anxiety and Depression Scale (HADS) (Zigmond & Snaith 1983) for general medical populations aged 16–65 years and the Patient Health Questionnaire (PHQ-9) (Kroenke *et al.* 2009) for medical populations in clinical settings. There are also assessment tools designed specifically for older adults, such as the Geriatric Depression Scale (GDS) (Yesavage *et al.* 1982), and for children and adolescents, such as the Children's Depression Rating Scale (CDRS) (Poznanski *et al.* 1979). The number of items in each questionnaire varies from 9 (in the PHQ-9) to 30 (in the long form of the GDS), and most often symptoms are instructed to be assessed within the past week or two (e.g. in CES-D, HADS and PHQ-9) (Kroenke *et al.* 2009; Radloff 1977; Yesavage *et al.* 1982; Zigmond & Snaith 1983).

In this study, the assessment of depressive symptoms is based on the BDI-II, the latest version of the BDI questionnaire (Beck *et al.* 1996). The BDI-II consists of 21 statement groups, and the respondent is guided to pick the statement that describes the past two weeks. The BDI-II has been modified to better detect severe depression possibly demanding hospital care, as well as symptoms that meet the DSM-IV diagnostic criteria. The BDI-II was originally validated in college students, adult psychiatric outpatients and adolescent psychiatric outpatients (Beck *et al.* 1996) and has since been validated in the Finnish adult population (Beck *et al.* 2005) as well as in many other countries. Several language versions have been published (García-Batista *et al.* 2018; Ghassemzadeh *et al.* 2005; Gomes-Oliveira *et al.* 2012; González *et al.* 2015; Kojima *et al.* 2002). A previous review (Wang & Gorenstein 2013) found the BDI-II to be globally applicable for measuring the severity of depression in both research and clinical practice. BDI-II was shown to have high reliability (Cronbach's alpha around 0.9); high sensitivity ($\geq$ 0.70) to discriminate between depressed and non-depressed individuals; and high concurrent, content and structural validity. For example, convergent validity between the BDI-II and other assessment scales for depressive symptoms ranged from 0.66 to 0.86 when measured by Pearson's product-moment correlation coefficient.

2.1.2 Prevalence of depression

The World Health Organization (WHO) has identified depression as the single largest contributor to global disability (as measured by years lived with disability, YLD), with over 300 million people (4.4%) estimated to suffer from depression worldwide. In the most severe cases, depression can lead to suicide, by which more than 700,000 people die each year (WHO 2017). Depression is globally more common in women than in men (Ferrari *et al.* 2013), while the prevalence of suicide is higher among men (WHO 2017). The prevalence of depression in the WHO regions varies from 2.6% among men in the Western Pacific Region to 5.9% among women in the African Region. More than 80% of the disability caused by depression occurs in low- and middle-income countries (WHO 2017), yet less than 25% of people in low- and middle-income countries receive treatment for mental disorders (Evans-Lacko *et al.* 2018). Figure 1 shows a prevalence map of depression based on the 2021 Global Burden of Disease data. In Finland, the prevalence of depressive disorders is estimated to be between 5 and 7% (Dattani *et al.* 2023, Depression: Current Care Guidelines 2025).

A systematic review showed that the COVID-19 pandemic was associated with significant levels of psychological distress (Xiong *et al.* 2020). Although another meta-analysis of longitudinal cohort studies found that the increase in mental health symptoms by mid-2020 was mostly comparable to pre-pandemic levels, symptoms of depression showed the largest and most persistent increase (Robinson *et al.* 2022). Based on a comparison between the two Northern Finland birth cohorts, depressive symptoms have increased in the younger generation (born in 1986) compared to the older generation (born in 1966) at ages 31–34, especially among women (Miettunen *et al.* 2024).

Globally, the prevalence of depression has been found to be highest between the ages of 20 and 64 years, with the lowest prevalence in early childhood and an increase from the age of 75 (Ferrari *et al.* 2013). Similar age-dependent prevalences were found also in Finland, where the highest prevalence of depression (9.6%) was found among 30- to 44-year-olds, the lowest prevalence (4.5%) in the 65–74 age group, and an increased prevalence of 6.7% among those aged 75 and over (Markkula *et al.* 2015).

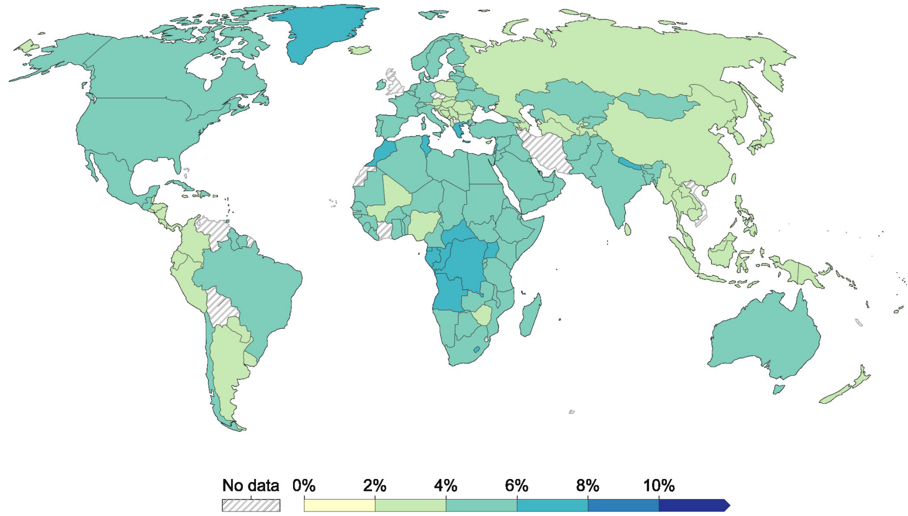

Figure 1. Age-standardised estimated prevalence of depressive disorders (based on representative surveys, medical data and statistical modelling) in 2021. Reprinted and modified from Our World in Data (2024) (Dattani *et al.* 2023) based on CC-BY 4.0 licence. Data source: IHME, Global Burden of Disease (2024) – with major processing by Our World in Data.

2.1.3 Aetiology and risk factors of depression

The aetiology of depression is complex, with the risk factors including genetic, psychological and social factors (Kessler & Bromet 2013; Klein *et al.* 2011; Wray *et al.* 2018). In addition, behavioural and environmental factors have received increasing attention in recent years (Pearce *et al.* 2022; Rautio *et al.* 2018). The heritability of depression is highest in childhood (50%–70%) and decreases in adulthood (35%–50%) due to the increase in environmental variance, which leads to a lower influence of genetic factors (Nivard *et al.* 2015). Possible factors influencing the higher prevalence of depression in women have been suggested to include several biological (such as genetics, gene–environment interactions and hormonal factors), psychological (such as neuroticism, absence of positive affect and body shame) and environmental factors (such as childhood sexual abuse, life events and structural gender inequalities in society) (Kuehner 2017).

Depression has also been associated with three general personality traits from the Five-Factor Model (also known as the Big Five) (Costa & McCrae 1992), namely high neuroticism, low extraversion and low conscientiousness, and with related temperament traits described in Cloninger's model (Cloninger *et al.* 1993), such as harm avoidance, rumination and self-criticism (Klein *et al.* 2011). Other types of mental health problems, particularly anxiety disorders, are also often associated with the same personality traits as depression (Klein *et al.* 2011).

A previous meta-analysis showed that low SES was associated with higher odds of being depressed, and the risk of depression was higher if individuals had lower education or income. The results depended on how the studies defined or measured depression and SES (Lorant *et al.* 2003). A review of cross-national data found that many similar sociodemographic factors were associated with depression internationally, such as low education, unstable employment, high teenage childbearing and marital problems (Kessler & Bromet 2013). In Finland, depression has been also associated with being widowed, separated or unmarried (Markkula *et al.* 2015). Based on a systematic review and meta-analysis, childhood adversities, such as physical abuse, emotional abuse and neglect, significantly increased the risk of depression (Norman *et al.* 2012).

Behavioural factors, such as insufficient or excessive sleep (Zhai *et al.* 2015) and alcohol use disorders (Li *et al.* 2020), have been found to be associated with an increased risk of depression. Although depression often co-occurs with substance use, the evidence on the causal connection between substance use (alcohol, tobacco and cannabis) and depression is unclear. Some studies support the self-medication hypothesis, while others suggest that substances induce or increase vulnerability to anxiety and depressive disorders (Garey *et al.* 2020). A recent review of meta-analyses suggested that maintaining a healthy diet, consuming fish, drinking coffee and using alcohol in light to moderate amounts are associated with a lower risk of depression (Xu *et al.* 2021). Physical activity can also help prevent depression (Schuch *et al.* 2018). Environmental factors, such as characteristics typical of urban areas (Generaal *et al.* 2019) and lack of exposure to green spaces (Liu *et al.* 2023), also contribute to the risk of depression.

Depression's associations with physical activity and environmental factors are discussed in more detail in separate chapters: 2.2 'Physical activity and depression' and 2.3 'Residential environment and depression'.

2.2 Physical activity

Physical activity (PA) can be defined as all bodily movements produced by skeletal muscles that require energy expenditure (EE) (Caspersen *et al.* 1985). PA is distinct from *exercise*, which is defined as planned, structured PA aimed at improving or maintaining physical fitness (Caspersen *et al.* 1985). EE is often measured in metabolic equivalents (METs), and MET values can be used to categorise PA based on purpose, type and intensity (Ainsworth *et al.* 1993). Definitions and examples of light-intensity PA (LPA; 1.5–2.9 METs), moderate-intensity PA (MPA; 3.0–5.9 METs) and vigorous-intensity PA (VPA; ≥6.0 METs), are shown in Table 1. Standing (defined as a *"position in which one has or is maintaining an upright position while supported by one's feet"*) is classified as LPA, as well as any waking activity in sitting posture with an EE over 1.5 METs (Rosenberger *et al.* 2019).

In this thesis, *movement behaviours* also include *sedentary behaviour* (defined as any waking behaviour of ≤1.5 METs) and sleep (defined as a state of reduced or absent consciousness, around 0.9 METs), which are described in more detail in Table 1. Together the movement behaviours (PA, sedentary behaviour and sleep) form the *24-hour activity cycle* (Rosenberger *et al.* 2019). This holistic approach recognises that all these behaviours are interrelated and collectively influence health outcomes. The 24-hour perspective is based on the activity balance model introduced by Pedišić (2014), which emphasises the importance of balancing different types of activity to promote overall health and well-being. This model has provided new insights into the relative importance of different activities and their health outcomes, highlighting the need to consider the full range of daily behaviours rather than focusing on PA in isolation (Chastin *et al.* 2015; Pedišić 2014).

Table 1. Definitions, MET values and examples of sleep, sedentary behaviour and physical activity of different intensities based on definitions by Rosenberger *et al.* (2019) and the Physical Activity Guidelines for Americans 2nd edition (US Department of Health and Human Services 2018).

Behaviour	Definition	METs	Examples
Sleep	A naturally recurring and easily reversible state, characterised by reduced or absent consciousness, perceptual disengagement, immobility and the adoption of a characteristic sleeping posture.	~0.9	
Sedentary behaviour	Waking behaviour with an EE ≤1.5.	≤1.5	Sitting and reading, lying.
Light-intensity PA (LPA)	Voluntary movement produced by skeletal muscles with an EE between 1.5 and 2.9.	1.5–2.9	Slow walking, cooking, light household chores, including standing and active sitting. *During LPA, most people are able to sing.*
Moderate-intensity PA (MPA)	Voluntary movement produced by skeletal muscles with an EE between 3.0 and 5.9.	3.0–5.9	Brisk walking, cycling, active forms of yoga, dancing, yard or home repair work. *During MPA, talking is possible, singing is not.*
Vigorous-intensity PA (VPA)	Voluntary movement produced by skeletal muscles with an EE over 6.0.	≥6.0	Jogging or running, swimming, shovelling snow, hiking uphill or carrying loads upstairs. *During VPA, even talking is difficult.*

MET: metabolic equivalent; EE: energy expenditure; PA: physical activity, LPA: light-intensity physical activity; MPA: moderate-intensity physical activity; VPA: vigorous-intensity physical activity.

2.2.1 Physical activity and health

The health benefits of PA include, but are not limited to, a reduced risk of mortality and cardiovascular diseases (CVD) (Lear *et al.* 2017), depression (Schuch *et al.* 2018), type 2 diabetes, multiple cancers and dementia (Piercy *et al.* 2018). Additionally, PA improves cognition, sleep and quality of life and can help with weight loss and maintenance after weight loss (Piercy *et al.* 2018). PA among middle-aged and older adults is associated with healthier ageing (Lafortune *et al.* 2016; Paterson & Warburton 2010) through positive associations with mental health, cognitive and physical functioning, and mobility. Especially, moderate- to vigorous-intensity PA (MVPA) has been found to be associated with health outcomes (Bull *et al.* 2020; Lear *et al.* 2017; Singh *et al.* 2023), and even though research on LPA is more scarce, it seems that LPA also has beneficial effects on cardiometabolic health and mortality risk (Amagasa *et al.* 2018; Chastin *et al.* 2019), but there might be no association with mental health (Felez-Nobrega *et al.* 2021). Health outcomes of PA have been found to differ between leisure-time PA and occupational PA, with occupational PA increasing the risk of long-term sickness absence, while leisure-time PA has the opposite effect (Holtermann *et al.* 2012) In addition, PA also has potential negative mental health outcomes. Exercising over 6 hours per week was associated with worse mental health (Chekroud *et al.* 2018), and among patients with anorexia nervosa, PA was correlated with body image distortion (Di Lodovico *et al.* 2022).

Physical inactivity, defined as *"an insufficient PA level to meet present PA recommendations"* (Bull *et al.* 2020), increases the risk of developing coronary heart disease, type 2 diabetes, breast cancer, and colon cancer (Lee *et al.* 2012). It is estimated that physical inactivity accounts for 9% of premature deaths worldwide. By eliminating inactivity, global life expectancy could rise by 0.68 years (Lee *et al.* 2012). Sedentary behaviour (SB) is associated with higher risk of mortality from all causes, CVDs, cancer incidence and type 2 diabetes regardless of the PA level (Biswas *et al.* 2015; Katzmarzyk *et al.* 2009). Similar risk factors are associated with insufficient or excessive sleep, except for cancer incidence (Alvarez & Ayas 2004). In adults, the composition of 24-hour movement behaviours has been found to be associated with mortality (McGregor *et al.* 2021), adiposity (Chastin *et al.* 2015) and cardiometabolic health markers (Blodgett *et al.* 2025; Chastin *et al.* 2015; Farrahi *et al.* 2021; Gupta *et al.* 2019). Especially, a higher proportion of daily time spent in MVPA and a smaller proportion spent in SB were associated with favourable outcomes, with some beneficial associations also found when more time was spent in LPA (Chastin *et al.* 2015; Farrahi *et al.* 2021; McGregor *et al.* 2021).

2.2.2 Physical activity recommendations

According to the WHO's latest PA recommendations (Bull *et al.* 2020), to achieve the health benefits of PA, adults should include at least 150 minutes of moderate-intensity aerobic or at least 75 minutes of vigorous-intensity aerobic PA per week, or an equivalent combination of both. In addition, adults should perform muscle-strengthening activities at least twice a week. On the other hand, the recommendation highlights the importance of all PA for health, decreasing and breaking up long sedentary time bouts with activities of any intensity, and the benefits of PA for sleep and mental and cognitive health. Similar updates have been made to the PA recommendations in Finland (UKK Institute 2019), which are based on the latest US guidelines (US Department of Health and Human Services 2018). In contrast to the recommendations of both the WHO and the US Department of Health and Human Services, the Finnish recommendations also mention a sufficient amount of sleep, even though the amount is not specified (UKK Institute 2019). In the US, the National Sleep Foundation has, however, suggested that for health, most adults require 7–9 hours of sleep every day (Hirshkowitz *et al.* 2015). The Canadian 24-hour movement guidelines for adults also include 7–9 hours of sleep per day as well as a recommendation of 8 or fewer hours of sedentary behaviour per day, of which 3 hours or less should be recreational screen time (Ross *et al.* 2020).

Globally, it has been estimated that 69% of the adult population reaches the amount of PA recommended by the WHO, with a higher prevalence of inactivity among women and adults over the age of 60 (Bull *et al.* 2024). However, only 9.1% of Canadians met the combined 24-hour guidelines (Rollo *et al.* 2023). In Finland, the estimated number of adults achieving both aerobic and muscle-strengthening PA recommendations was 40%, but only 20%–26% for older adults aged 65+ years (Wennman & Borodulin 2021). The most popular PA types were walking, cleaning, maintenance work and stair climbing, and different PA types were reported during summer and winter. In particular, workouts and muscle-strengthening exercises were associated with higher odds of meeting the PA guidelines (Wennman & Borodulin 2021). The majority of adults' leisure-time PA in Finland takes place on cycle/pedestrian paths or in natural environments (Husu *et al.* 2022).

2.2.3 Assessment of physical activity

Assessment of PA aims to quantify its various dimensions, including its frequency, intensity, duration and type, to better understand their impact on health outcomes (Bauman *et al.* 2006). PA is important for preventing and treating adverse health outcomes, and accurate measurement of PA is crucial for research and effective public health initiatives. Misunderstanding the multidimensionality of PA behaviour or using inappropriate measures can lead to misleading results and underestimating PA's effect size (Celis-Morales *et al.* 2012; Warren *et al.* 2010). The choice of method for assessing PA depends on the specific research objectives, the population being studied and the resources available (Warren *et al.* 2010).

In general, PA can be assessed using *subjective* or *objective* methods. Subjective methods refer to indirect methods, usually based on individuals recording their own activities (Ridgers & Fairclough 2011). These methods include, for example, questionnaires, diaries and interviews, and are widely used due to their cost-effectiveness and ease of administration (Hills *et al.* 2014; Warren *et al.* 2010). Objective approaches are based on the numerical assessment of physiological parameters, without the need for the individual to record or interpret the information (Ridgers & Fairclough 2011). Objective methods include measures of EE (including indirect calorimetry, the doubly labelled water method or direct observation), physiological measures (heart rate monitoring) and motion sensors (e.g., pedometers and accelerometers) (Hills *et al.* 2014; Strath *et al.* 2013). Doubly labelled water and indirect calorimetry are considered the gold standards for measuring EE. Doubly labelled water involves tracking the elimination rates of isotopes in body water, while indirect calorimetry measures oxygen consumption and carbon dioxide production (da Rocha *et al.* 2006). However, in population-based studies, subjective methods, heart rate monitoring and *device-based* methods utilising motion sensors are the most applicable (Warren *et al.* 2010). In this thesis, PA has been measured using a questionnaire and accelerometers, and the following chapters will especially focus on those methods.

Questionnaires

Questionnaires can vary in the number of questions they include, with some designed to capture global trends in PA (Godin & Shephard 1985; Guthold *et al.* 2008; Warren *et al.* 2010). Examples of validated and widely internationally used questionnaires include the International Physical Activity Questionnaire (IPAQ) and the Global Physical Activity Questionnaire (GPAQ) (Helmerhorst *et al.* 2012; Lee *et al.* 2011). Questionnaires have several strengths, including the possibility to collect data from a large number of individuals and to assess structured PA as well as different dimensions and domains (occupational, domestic, transportation or leisure time) of PA (Strath *et al.* 2013). Questionnaires are also valid for ranking less or more physically active individuals within a sample (Strath *et al.* 2013).

Subjective methods can, however, generally be prone to recall bias, as they strongly depend on the individual's recollection of the past events, which can lead to both under- and over-reporting of PA (Hills *et al.* 2014; Prince *et al.* 2008). They are also subject to social desirability bias, which can affect the accuracy of the data collected (Prince *et al.* 2008). Use of self-report measures of PA, particularly in children or older people, can be unreliable because of cognitive immaturity or degeneration of the respondent. In addition, as opposed to objective measures, questionnaires can be highly culturally dependent (Warren *et al.* 2010). Questionnaires have been found to be most accurate when measuring VPA, but less so for MPA and LPA. They also have low validity for assessing incidental or lifestyle PA (Strath *et al.* 2013).

Accelerometers

Accelerometers measure accelerations during movement in order to estimate PA levels and provide detailed information on PA's intensity, frequency and duration (Strath *et al.* 2013). Other advantages of accelerometers include the ability to record high-resolution data and store it for several weeks, as well as their relatively low cost and ease of use (Strath *et al.* 2013). Accelerometers can be uniaxial, biaxial or triaxial, depending on the number of directions they record. Triaxial accelerometers record vertical, medio-lateral and anterior-posterior movements, while uniaxial ones typically record vertical and biaxial ones record vertical and medio-lateral movements (Mathie *et al.* 2004).

Accelerometer-based wearable sensors can be placed on different parts of the human body, including the sternum, lower back, waist, wrists, thighs or ankles. The device's placement can influence the accuracy of the measurements, with waist-measurement suggested to present the major motions better, as it is close to the human body's centre of mass. Waist-worn accelerometers are able to capture wide variety of basic daily activities, such as walking, postures and activity transitions. Wrist-worn accelerometers can measure sleep time duration and activity levels during sleep, while ankle-attached accelerometers capture gait-related features, making it possible to estimate steps, distance, speed and EE (Yang & Hsu 2010).

Accelerometers also have their limitations. Activities such as cycling, stair use or any activity involving lifting can be especially difficult to capture with accelerometers (Strath *et al.* 2013). Another possible source of bias is that wearing an accelerometer can itself promote PA (Skender *et al.* 2015). Accelerometers are also unable to capture the domains of PA. Due to the differences in PA information gained by subjective and device-based methods, combining these methods in research has been suggested for a more accurate understanding of PA and health outcomes (DiPietro *et al.* 2020).

2.2.4 Factors associated with physical activity

In the context of public health, ecological models have been developed to provide a comprehensive understanding of people's interactions with their socio-cultural and physical environments (Stokols 1992). They respond to the need for a framework for promoting physical activity at the population level, where interventions typically involve a small number of individuals and the effects are moderate and temporary (Sallis *et al.* 2006). Physical inactivity is a global public health problem, and to support increased population PA, a systems approach and multilevel interventions addressing both individuals and the social environment, as well as the physical environment and policies, are necessary (Kohl *et al.* 2012; Sallis *et al.* 2006).

Based on the ecological model of the determinants of PA by Bauman *et al.* (2012) (Figure 2), the factors influencing PA behaviour can be categorised into individual, interpersonal, environmental, regional or national policy and global levels. Similarly, determinants of SB can be divided into different levels, including intrapersonal, interpersonal, environmental or policy-related, based on the ecological model by Owen *et al.* (2011). Genetic factors also influence PA, and its heritability has been estimated to be 51%–56% based on studies using accelerometer-measured PA (Zhang & Speakman 2019). Looking at the demographic, psychosocial, behavioural and social factors that determine PA in adults, Bauman *et al.* (2012) found that health status and self-efficacy were the strongest determinants, followed by personal history of PA in adulthood and intention to exercise. In addition, male gender, higher education level, white ethnicity and higher social support were correlated with higher levels of PA, while older age, being overweight, having more stress and less perceived effort were correlated with lower levels of PA (Bauman *et al.* 2012). For women, having young children at home was associated with lower amounts of MVPA (Prince *et al.* 2016). In general, life events have been found to influence PA behaviour in adulthood, with negative associations found between overall PA and the transition to university and pregnancy or having a child (Condello *et al.* 2017). Higher SES has been associated with higher leisure-time PA and lower occupational PA (O'Donoghue *et al.* 2018). Important factors in maintaining PA in adults appear to be motivation, goals and beliefs about ability, and perceived health status (Amireault *et al.* 2013).

A systematic review of the correlates of SB in adults found that older age, lower PA levels and higher body mass index were associated with more SB. The study identified five domains of self-reported sedentary time (ST): total screen time, television and screen entertainment, transport sitting time, total sitting time and leisure sitting time. Higher total screen time was associated with symptoms of depression, anxiety or tension, perceived stress and fatigue. Associations of SES with SB varied according to the domain of SB, with higher levels of education being associated with higher total ST but lower levels of television or screen entertainment. Among interpersonal factors,

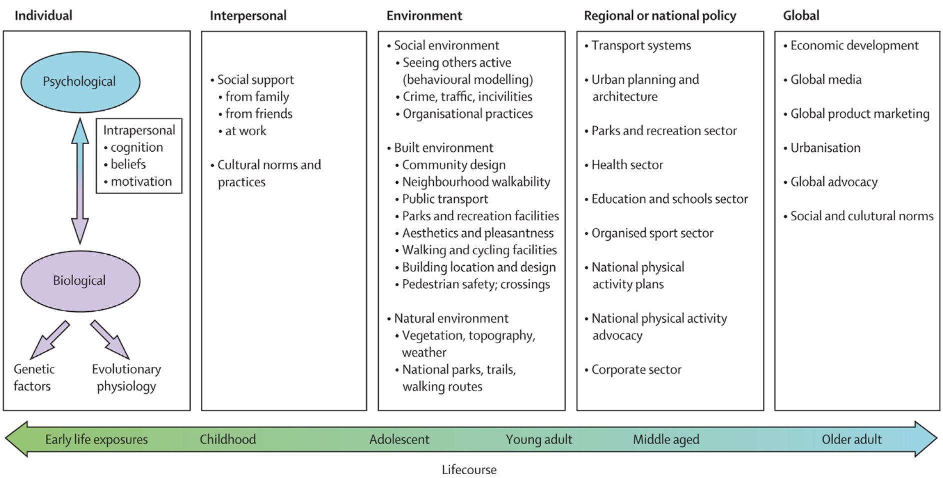

Figure 2. Adapted ecological model of the determinants of physical activity. Reprinted from *The Lancet*, 380, Bauman *et al.* Correlates of physical activity: why are some people physically active and others not?, p. 259, Copyright (2012), with permission from Elsevier. Reuse without permission is prohibited.

being married or cohabiting was associated with more leisure screen time, while having children was associated with less total sitting time (O'Donoghue *et al.* 2016).

Environmental factors that determine PA can be divided into factors related to the social environment (such as traffic, crime and seeing other people being active), the built environment (such as walkability, recreational facilities and aesthetics) and the natural environment (such as vegetation, topography and weather) (Bauman *et al.* 2012). Environmental factors are also associated with SB and can be viewed from the perspective of the natural environment, social-cultural environment and information environment (such as health care counselling, news and sports spectatorship), as well as factors of the perceived environment (factors related to safety, comfort or attractiveness) and policy environment (e.g., sidewalk requirements, parking regulations or park design policies) (Owen *et al.* 2011). More detailed associations between these environmental factors and PA are discussed in Chapter 2.3.2 'Residential environment and physical activity'.

In addition to environmental factors, policies at the local, regional or national level, as well as global factors, influence PA, particularly in middle-aged and older adults (Bauman *et al.* 2012). Policies can affect large populations over extended periods, for example through urban planning, health care or education. Global factors, such as economic development, urbanisation and social and cultural norms, can also influence PA (Bauman *et al.* 2012). Possible ways to increase PA and reduce SB equally, while addressing broader socio-economic, political and cultural contexts, have been suggested. These include supporting local and state governments to develop policies and practices, community-wide campaigns to promote PA, and transport policies and practices. Daily conditions for PA should be taken into account, for example, in neighbourhood designs, settings of early childhood, schools, workplaces and health care facilities (Ball *et al.* 2015).

2.2.5 Physical activity and depression

A systematic review based on longitudinal designs showed that PA is associated with lower risk of future depression (Schuch *et al.* 2018). In addition, recent reviews based on randomised controlled trials and intervention studies highlighted the importance of including PA in the treatment of depression (Noetel *et al.* 2024; Singh *et al.* 2023). In fact, PA's effect size has been found to be similar to that of cognitive behavioural therapy, with some types of exercise (walking or jogging, yoga and strength training) showing larger effect sizes than medication (Noetel *et al.* 2024). At the same time, MVPA appears to be the most important for improving depression (Singh *et al.* 2023). While it must also be acknowledged that people diagnosed with depression engage in lower amounts of PA and higher amounts of SB (Schuch *et al.* 2017), there is evidence that exercise-based interventions can reduce depressive symptoms even in individuals without clinical depression (Bellón *et al.* 2021). Findings on the context of PA have been so far mixed, with some findings suggesting that any domain of PA (leisure-time, transport or work-related) is beneficial for depressive symptoms (De Cocker *et al.* 2021), while others show an unfavourable association between work-related PA and mental health in general and no association between household PA and mental health (White *et al.* 2017).

A meta-analysis suggested that a particularly high amount of mentally passive SB may increase the risk of depression. In that study, mentally passive behaviours included watching television, chatting while sitting and sitting around, while mentally active behaviours included using a computer, reading and driving a car (Huang *et al.* 2020). In addition, both short and long sleep duration were shown to be associated with the risk of depression in a meta-analysis based on longitudinal studies (Zhai *et al.* 2015). Similar findings regarding movement behaviours and depressive symptoms have been reported in recent studies based on a compositional approach to 24-hour movement behaviours. Reallocating more time to MVPA at the expense of LPA, SB or sleep has been associated with a lower risk of depression (Blodgett *et al.* 2023), with other studies suggesting that reallocating time from SB to sleep (del Pozo Cruz *et al.* 2020; Kandola *et al.* 2021) or LPA (Kandola *et al.* 2021) may also be beneficial, in addition to increased MVPA.

Proposed mechanisms behind PA's beneficial effects on depressive symptoms include both biological and psychosocial mechanisms (Kandola *et al.* 2019). Biological mechanisms include stimulation of several neuroplastic processes associated with depression, such as neurotrophin release at the molecular level, beneficial changes at the cellular and structural levels associated with neuroplasticity, improved regulation of the hypothalamic-pituitary-adrenal axis and changes in cortisol activity. In addition, PA reduces inflammation and increases resistance to oxidative and physiological stress. Psychosocial mechanisms include improved self-esteem, increased social interaction and support, as well as improved self-efficacy (Kandola *et al.* 2019). The mechanisms between sleep disturbances and depression are not fully understood, with possible explanations including increased levels of inflammation, biochemical pathways, genetic factors and the disruption of circadian rhythms (Fang *et al.* 2019).

Table 2 provides a summary of the studies concerning the association between PA and depression, with focus on recent systematic reviews and population-based studies conducted on adult population.

2.3 Residential environment

The space in which individuals live and engage in daily activities is often referred to as a *neighbourhood* (e.g., Moudon *et al.* 2006), *residential area* (e.g., Groenewegen *et al.* 2012) or *activity space* (e.g., Perchoux *et al.* 2013). In this thesis, the concept of the *residential environment* is used to describe the broader context of living environments, including aspects such as environmental characteristics (e.g., amount of green space, services or cycle paths), the level of urbanicity and the country where the individual lives.

2.3.1 Assessment of residential environment

Exposure to environmental characteristics can be measured using various spatial units and approaches, including administrative areas (e.g. postal code areas or census tracts), buffers (polygons created around an individual's residence), or more individualised home range models (Figure 3) (Laatikainen *et al.* 2018). Administrative boundaries have been used mostly for their availability, while they have been highly criticised for their lack of capability to capture true exposure to the environment, as the administrative areas might not match with the individual's experienced neighbourhood, and the perceptions of neighbourhood probably also vary between individuals living in the same administrative area (Perchoux *et al.* 2013). Buffers offer a more representative,

Table 2. Previous studies on the associations between physical activity, sedentary behaviour, sleep and depression, with emphasis on recent systematic reviews and population-based studies focusing on adults.

Study	Study design	Study population	Exposure	Outcome	Main findings
Bellón *et al.* 2021	Systematic review and meta-analysis (14 randomised control trials)	Adults without depression, *n*=1,737	Exercise interventions	Depressive symptoms and/or incidence of new cases of depression	In people without clinical depression, exercise-based interventions have a small effect on reducing depressive symptoms.
Blodgett *et al.* 2023	Cross-sectional (compositional approach)	Adults (UK), *n*=4,738	MVPA, LPA, SB and sleep (accelerometer-measured)	Use of anti-depressants or reported visit to doctor or specialist due to low, depressed or sad mood	Replacing time spent in LPA, SB or sleep with MVPA was associated with a lower risk of depression.
De Cocker *et al.* 2021	Cross-sectional	Adults (EU), *n*=261,121	PA (self-reported)	Depressive symptoms	Each domain of PA (leisure, transport and work) was associated with depressive symptoms. The association was strongest when the symptoms were more severe.
Del Pozo Cruz *et al.* 2020	Cross-sectional (compositional approach)	Adults and older adults (US), *n*=3,233	PA, SB (accelerometer-measured) and sleep (self-reported)	Depressive symptoms	Replacing time spent in SB with MVPA or sleep was associated with lower depressive symptoms.
Fang *et al.* 2019	Review	-	Sleep disturbance	Depression	Sleep disturbance is not just a comorbidity of depression, but also a predictor of onset and outcome. Sleep disorders should be treated before and during depression.
Huang *et al.* 2020	Systematic review and meta-analysis (12 prospective cohort studies)	Adults, *n*=128,553	SB	Depression or depressive symptoms	Mentally passive SB was associated with the risk of depression.
Kandola *et al.* 2019	Review	-	PA	Depression	Conceptual framework of the mechanisms underlying the relationship between physical activity and depressive symptoms, and the factors influencing it.

Kandola *et al.* 2021	Cross-sectional (compositional approach)	Adults (UK), *n*=60,235	MVPA, LPA, SB (accelerometer-measured) and sleep (self-reported)	Depressive symptoms	Replacing time spent in SB with MVPA, LPA or sleep was associated with lower depressive symptoms.
Noetel *et al.* 2024	Systematic review and network meta-analysis (218 randomised trials)	All ages, depressed, *n*=14,170	Exercise interventions	Depression or depressive symptoms	Exercise effectively treats depression, with comparable effect sizes to other forms of therapy and medication. Walking or jogging, yoga and strength training are more effective than other exercises, especially if they are intense.
Schuch *et al.* 2017	Systematic review and meta-analysis (24 interventional or observational studies)	Adults, depressed, *n*=10–840	Depression	PA and SB (self-reported or objectively measured)	People with depression engage in less PA and higher levels of SB compared to controls.
Schuch *et al.* 2018	Systematic review and meta-analysis (49 prospective cohort studies)	All ages, *n*=266,939	PA (self-reported or objectively measured)	Depression or depressive symptoms	People with high levels of PA are less likely to develop depression. PA protects against depression in all age groups and geographical regions.
Singh *et al.* 2023	Umbrella review (97 systematic reviews with meta-analyses, comprising 1,039 randomised control trials)	Adults, healthy participants, participants with mental health disorders and various chronic diseases, *n*=128,119	PA interventions	Depression, anxiety or depressive, anxiety or psychological distress symptoms	PA is highly beneficial for improving depression, anxiety and distress in adults, whether or not they have a diagnosed mental disorder or chronic condition.
White *et al.* 2017	Systematic review and meta-analysis (98 studies)	All ages, *n*=648,726	PA (quantitative assessment including at least one specified domain)	A quantitative assessment of at least one mental health outcome variable	Leisure-time and transport PA had a positive association with mental health. Work-related PA was associated with mental ill-health. Household exercise and physical education were not associated with mental health.
Zhai *et al.* 2015	Systematic review and meta-analysis (7 prospective studies)	Adults, *n*=48,934	Sleep duration (self-reported or objectively measured)	Depression or depressive symptoms	Both short and long sleep duration was associated with increased risk of depression.

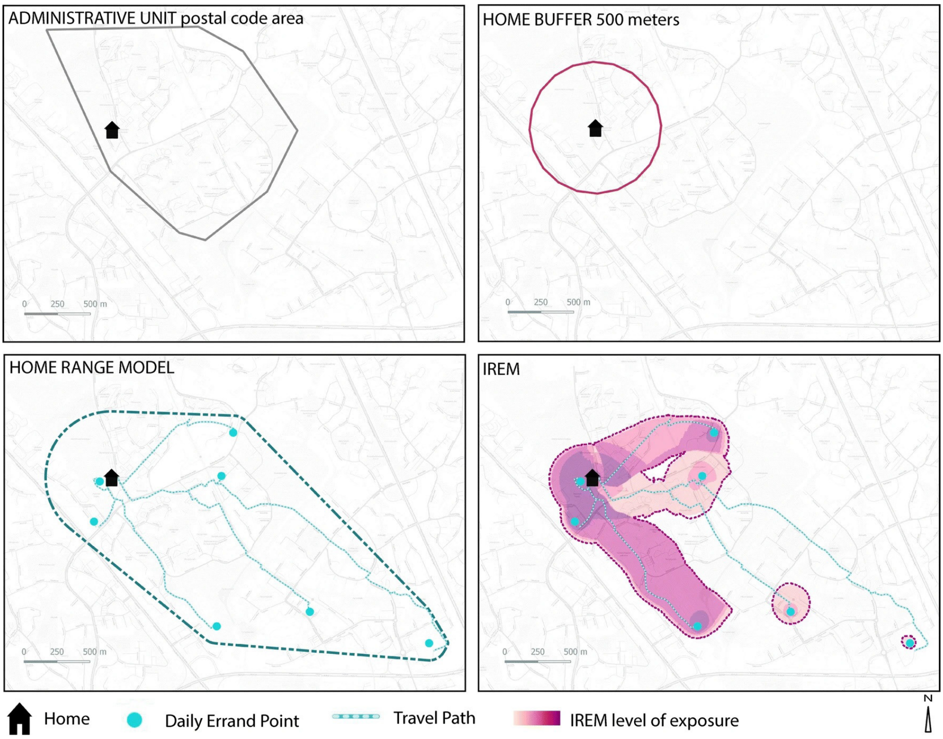

Figure 3. Different ways to model the residential area or activity space. Reprinted from Laatikainen *et al.* (2018) based on CC-BY 4.0 licence. IREM: individualised residential exposure model.

still easy-to-use alternative. Buffers with varying sizes and shapes (such as circular or network-based buffers) have been popular in health research (see e.g., Feng *et al.* 2010). However, there is evidence that the use of buffers can be problematic for PA behaviour modelling, as buffers have poor spatial overlap with adult physical activity spaces (Holliday *et al.* 2017), and international comparisons of observation-specific spatial buffers have shown that larger buffer sizes are generally associated with greater health outcomes, as indicated by Su *et al.* (2019). In general, different spatial units can lead to differing results regarding environmental characteristics and health outcomes (Laatikainen *et al.* 2018).

Problems in using buffers when modelling PA behaviour arise because buffers are a simplification of the actual area in which individuals move within their residential environment. This is one of the most significant challenges in assessing residential environments, called the uncertain geographic context problem, highlighting the complexity of accurately assessing the true geographic context that influences individuals (Kwan 2012). Closely related, the modifiable areal unit problem describes how the results of spatial analysis change based on how we divide the land into units of choice (Flowerdew *et al.* 2008). To better address this issue, Hasanzadeh *et al.* (2018) introduced an individualised residential exposure model (IREM, Figure 3), which takes into account place exposure to create a spatially sensitive model of individual activity spaces. IREM provides a more personalised assessment of residential environments but requires individualised data collected through a public participation geographic information system (PPGIS) survey, as well as more advanced technical skills to model.

The differences between urban and rural areas in relation to health outcomes have been one point of interest during recent decades (Verheij 1996). Urbanisation refers to the *"change in size, density, and heterogeneity of cities"*, while urbanicity refers to *"the impact of living in urban areas at a given time"* (Vlahov & Galea 2002). There are several ways of defining urban and rural areas. In the context of US epidemiologic studies, for example, population density and different national classifications of urban and rural areas have been suggested (Hall *et al.* 2006). In Finland, cities are defined as having more than 15,000 residents, as a part of a detailed national classification of urban and rural areas, based on multiple datasets including information on, for example, population and land use (Finnish Environment Institute 2010; Helminen *et al.* 2014).

Different residential environment characteristics are often assessed using, for example, surveys, administrative data or geospatial analysis, involving the use of geographic information systems (GIS) (Leal & Chaix 2011). Surveys, such as PPGIS, can offer qualitative and detailed data on the experiences and values related to surrounding environments (e.g., Brown & Raymond 2007; Kyttä *et al.* 2013). Quantitative, objective environmental variables based on GIS have also been widely used, for example, in the context of the built environment and physical activity. Commonly measured factors include land use, access to recreation facilities or street patterns (Brownson *et al.* 2009).

2.3.2 Residential environment and depression

The role of the residential environment and neighbourhood characteristics in the development of depression have been researched more during the 21st century (Kim 2008; Rautio *et al.* 2018), and the association between urbanicity and depression has been one of the areas of interest. A systematic literature review found that globally, living in urban areas was associated with a higher risk or level of depressive symptoms in several studies, but the results from China were the opposite, and some studies found no association (Sampson *et al.* 2020). In another systematic review, seven studies out of 17 found that living in an urban residential area or a more urbanised residential area was associated with the presence of depressive mood, while nine studies found no association between the level of urbanisation or the degree of remoteness and depressive mood, and one study found that residents in micropolitan or rural areas had a higher risk of depressive mood (Rautio *et al.* 2018).

It has also been suggested that the presence and severity of depressive disorders are linked not to a neighbourhood's population density, but instead to neighbourhoods with low SES, more social security beneficiaries and immigrants, higher levels of traffic noise, lower social cohesion and less safety (Generaal *et al.* 2019). Based on a systematic review, the evidence for the association between neighbourhood socio-economic conditions and depression is inconsistent (Richardson *et al.* 2015). For example in China, living in neighbourhoods with lower SES was associated with more social interaction, resulting in higher social cohesion and lower depression in older adults (Miao *et al.* 2019). A recent study conducted in the US, however, suggested that individual-level SES might be more important for depressive symptoms than the neighbourhood's deprivation level (Neally *et al.* 2022).

Other factors that have been associated with a lower risk of depression include the presence of neighbourhood services such as health services, fast-food restaurants and healthy food stores (Gariepy *et al.* 2015). Physical environment factors often associated with a higher risk of depression include residing in unsafe communities, neighbourhoods with more car traffic nuisance and more railway noise (Putrik *et al.* 2015). For European adults, depressive symptoms have also been associated with neighbourhood perceived crime (Baranyi *et al.* 2022).

Based on a meta-analysis, a 10% increase in the proportion of green space exposure or a 0.1-unit increase in the Normalised Difference Vegetation Index (NDVI) is associated with a lower risk of depression (Liu *et al.* 2023). One of the longitudinal studies included in the meta-analysis was conducted in Finland and found that NDVI-based residential greenness was associated with a lower risk of depression. However, the association depended on the depression assessment, the quality of greenness indicators and the buffer scale of the analysis. The strongest associations were found when greenness was measured with NDVI from a 100-m buffer and depression was based on diagnosis (Gonzales-Inca *et al.* 2022). Another study included in the review by Liu *et al.* (2023) was based on UK Biobank data and found a consistent protective effect of NDVI-measured greenness on depression, with the most beneficial effects observed among women, participants younger than 60 years, and those residing in areas with low SES or high urbanicity (Sarkar *et al.* 2018). Based on another systematic review, air quality, perceived stress and physical activity might mediate the association between green spaces and mental health, but more longitudinal studies are still required to confirm a causal relationship between green space exposure and mental health (Zhang *et al.* 2021).

Finally, the wider context of the residential environment, such as the country-level environmental conditions and the individual cultural context, can also be associated with depressive symptoms. In Finland, there is a high peak in depressive disorders during October–November, the months with the lowest amount of daylight (Virtanen *et al.* 2023). In a study conducted in the US, the associations between depressive symptoms, anhedonia and momentary emotions depended on the cultural context (Chentsova-Dutton *et al.* 2015). Stigma (defined as *"the negative attitude (based on prejudice and misinformation) that is triggered by a marker of illness"*, such as behaviour or receipt of psychiatric treatment; Sartorius 2007) and moral attributions to depression have been found to be higher in Eastern countries compared to Western countries (Krendl & Pescosolido 2020). In Asian cultures, somatisation of psychiatric disorders is common because of the stigma on psychological symptoms (Lauber & Rössler 2007). In Asian societies, mental health issues can often be seen as signs of personal weakness or failure of self-control, bringing shame to the family (Chen & Mak 2008). In Latin American cultures, mental illness is also associated with personal weakness or lack of willpower (Ahad *et al.* 2023). Cultural beliefs also impact stigma, with South Asians attributing greater supernatural and moral causes to depression, compared to the biological beliefs of white British individuals (Birtel & Mitchell 2023). Spiritual or supernatural causes are often associated with mental illness also in African cultures, while in Arab societies, they can be seen as a divine punishment (Ahad *et al.* 2023).

Table 3 summarises referenced studies conducted on the association between residential environment and depression.

2.3.3 Residential environment and physical activity

In the UK, it has been estimated that 40% of outdoor LPA or MVPA occurs within 800 metres of the home location, with the distance varying depending on several factors, such as the urbanicity of the location (Hillsdon *et al.* 2015). There are several recognised built and natural characteristics of urban residential areas that are associated with PA (Prince *et al.* 2022), while rural areas have been less studied (Müller *et al.* 2024). However, some research has explored the differences between urban and rural areas. A recent global study including 22 countries and 138,206 adults (Boakye *et al.* 2023) found that urbanisation was overall associated with lower total PA. The association between urbanisation and different domains of PA differed according to countries' income levels. Especially in low- and middle-income countries, urbanisation was associated with lower household and occupational PA, while in high-income countries, urbanisation was associated with higher recreational PA (Boakye *et al.* 2023). In a study conducted in the US, rural residents reported more total PA than urban residents, while urban residents had more high-intensity accelerometer-measured PA. The authors suggested that these differences might be related to rural residents engaging in more low-intensity household PA (Fan *et al.* 2014).

A systematic review of the longitudinal studies on the built-environment determinants of PA found that improved accessibility and new infrastructure for walking, cycling and public transport were associated with higher levels of PA, both overall and transport-related (Kärmeniemi *et al.* 2018). Another systematic review also found that improving walkability components, active transport infrastructure, playgrounds and parks can have a positive impact on PA, although some of the findings suggested that higher SES groups benefited most from infrastructure improvements (Smith *et al.* 2017). A study conducted in Finland also showed that participants who moved to areas with increased neighbourhood density, mixed land use and access networks were more likely to increase their walking and cycling (Kärmeniemi *et al.* 2019).

In rural areas, the most important residential environmental features to support leisure-time PA have been shown to be the availability and accessibility of places for exercise and recreation. Weaker associations have been found between green spaces and total PA, cycling infrastructure, aesthetics and MVPA, and pedestrian infrastructure and walking. Additionally, a lack of safety and security may act as a barrier to walking in rural areas (Müller *et al.* 2024).

An umbrella review of green spaces and health concluded that green spaces were beneficially associated with physical activity, among several other health outcomes. The authors concluded that green spaces may encourage people to be more physically active, as well as mediate the association between green spaces and other health outcomes. However, as most of the studies analysed were cross-sectional, the level of evidence remained low, and causality could not be established (Yang *et al.* 2021). Associations of green space and PA might also differ by the intensity of PA, as another systematic review found strong evidence for the beneficial association of green space and MVPA, while the association with green space and walking trips was negative (Pontin *et al.* 2022). On the other hand, a recent study found that green spaces were associated with higher PA during active travel on days off from work or on retirement days, but not on working days (Pasanen *et al.* 2024). In addition to green spaces, living closer to blue space or having a higher amount of blue space within a certain geographical area has also been associated with higher PA levels based on a systematic review and meta-analysis, but the effect sizes were low, although the studies' quality was evaluated to be

Table 3. Previous studies on the associations between residential environment and depression, with emphasis on recent systematic reviews and population-based studies focusing on adults.

Study	Study design	Study population	Exposure	Outcome	Main findings
Ahad *et al.* 2023	Review	-	-	Similarities and differences of stigma in different cultures	The stigma of mental illness is influenced by cultural beliefs, attitudes and values. It can manifest itself in different ways in different cultures.
Baranyi *et al.* 2022	Longitudinal	Adults (Europe), *n*=15,624	Perceived neighbourhood crime (mediators: health behaviours and social participation)	Depressive symptoms	Perceived crime was associated with a higher risk of depressive symptoms and was mediated by lower engagement in social activities, particularly among participants with low household wealth.
Birtel & Mitchell 2023	Cross-sectional	Adults (UK, different ethnicities), *n*=137	Vignette describing individual with symptoms of depression	Causal explanations for depression, stigma towards people with depression and stigma by association.	South Asians were more likely to attribute supernatural, moral and psychological causes to depression as well as report greater stigma associated with it, while white Britons were more likely to believe in biological causes.
Chen & Mak, 2008	Cross-sectional	Students (US, Hong Kong, China), *n*=747	Cultural beliefs about the causes of mental illness	Help-seeking history and help-seeking likelihood	Beliefs about the causes of mental illness and a history of help-seeking significantly predicted the likelihood of help-seeking and were positively related to environmental/hereditary causes but negatively related to social/personal causes.
Chentsova-Dutton *et al.* 2015	Cross-sectional	All ages (US, different ethnicities), *n*=111	Depressive and anhedonia symptoms, life satisfaction	Momentary reports of emotions and pleasure	Reports of anhedonia and depressed mood appear to indicate changes in the balance between positive and negative emotions, with cultural context playing a role.
Gariepy *et al.* 2015	Longitudinal	Adults (Canada), *n*=7,114	Neighbourhood built environment characteristics	Depressive symptoms	Neighbourhood services and parks were associated with a lower likelihood of depressive symptoms.
Generaal *et al.* 2019	Cross-sectional	Adult cohort participants (Netherlands), (*n*=2,980)	Socio-economic, physical and social neighbourhood factors	Depression, anxiety and severity of their symptoms	Socio-economic and physical factors, as well as social factors, were associated with depressive and anxiety disorders, rather than urbanisation levels. These neighbourhood characteristics were also linked to more severe symptoms.
Gonzales-Inca *et al.* 2022	Longitudinal	Adults (Finland), *n*=24,057	Residential greenness (NDVI)	Depression diagnosis and depressive symptoms	Higher residential greenness was associated with a lower risk of depression.
Kim 2008	Systematic review (28 studies)	Adults, *n*=103–4,516,787	Neighbourhood characteristics	Depression or depressive symptoms	Neighbourhood social disorder has a harmful effect on depression, while neighbourhood SES might have a protective effect.
Krend & Pescosolido 2020	Cross-sectional	Adults (four Eastern, seven Western countries), *n*=11,004	Vignettes describing individuals with symptoms of depression or schizophrenia	Components of stigma (prejudice and discriminatory potential)	There were higher levels of stigma and more moral attributions in Eastern countries, particularly for depression.

Lauber & Rössler 2007	Review	Populations from developing Asian countries	-	Stigmatisation of people with mental illness in Asia	Stigmatising and discriminating against people with mental illness is common in Asia, resulting also in somatisation of symptoms.
Liu *et al.* 2023	Systematic review and meta-analysis (18 studies)	All ages, *n*=2,734,693 (depression studies)	Green space	Depression diagnosis or depressive symptoms Anxiety diagnosis or anxiety symptoms	Higher green space exposure was associated with a lower risk of depression.
Miao *et al.* 2019	Cross-sectional	Older adults (China), *n*=2,715	Neighbourhood characteristics, social cohesion and social engagement	Depressive symptoms	Social cohesion affects older people's well-being. Chinese older adults in deprived neighbourhoods socialise more with neighbours, which is linked to lower rates of depressive symptoms.
Neally *et al.* 2022	Cross-sectional	Adults (US), *n*=6,308	Neighbourhood deprivation	Depressive symptoms	High-deprivation neighbourhoods were associated with depressive symptoms. Individual-level SES weakened the association between neighbourhood deprivation and depressive symptoms.
Putrik *et al.* 2015	Cross-sectional	Adults (Netherlands), *n*=9,879	Neighbourhood characteristics	Depressive and anxiety symptoms, self-rated health	Feeling less safe was associated with poor health and depressive symptoms, and a less cohesive environment was associated with worse self-rated health. Car traffic nuisance and more disturbance from railway noise were associated with worse mental health.
Rautio *et al.* 2018	Systematic review (44 studies)	All ages, *n*=2784.4 million	Measures of urbanisation, population density, aesthetics of living environment, house/built environment, green areas, walkability, noise, air pollution or services	Depression or depressive symptoms	Poor-quality house and built environment, lack of green space, noise and air pollution were associated with depressed mood. Results for population density, neighbourhood aesthetics and walkability, and service availability were more mixed.
Richardson *et al.* 2015	Systematic review and meta-analysis (14 longitudinal studies)	Adolescents and adults (high-income countries), *n*=172–4.5 million	Neighbourhood socio-economic conditions	Depression or depressive symptoms	About half of the studies found an association between neighbourhood socio-economic conditions and depression.
Sampson *et al.* 2020	Systematic review (11 studies)	All ages (India, US, Vietnam, Netherlands, China, United Kingdom, Ghana and South Africa), *n*=4,118–122,993	Urbanicity or urbanisation	Depression or depressive symptoms	Overall, depressive symptoms are more prevalent in urban areas, but the results were mediated by various factors and modified by country.
Sarkar *et al.* 2018	Cross-sectional	Adults (UK), *n*=122,993	Residential greenness (NDVI)	Questionnaire-based probable depressive disorder	Higher residential greenness was associated with lower risk of probable depressive disorder.
Virtanen *et al.* 2023	Longitudinal	Adults (Finland), *n*=413,435	Photoperiods	Psychiatric sickness absence episodes with the most common diagnoses in working-age populations	There is seasonal variation in sickness absence due to mental health disorders, with peaks in depressive, anxiety and sleep disorders towards the end of the year and a spring peak in manic episodes.
Zhang *et al.* 2021	Systematic review (26 studies)	All ages, *n*=2,153,198	Green space exposure (objectively measured) (including mediation analysis)	Mental health	Air quality, perceived stress and physical activity mediated the effect of green space exposure on mental well-being.

very high (Georgiou *et al.* 2021). One of the studies revealed, for example, that living less than 5 km from the coast was associated with specific domains of PA, such as self-reported walking and total and non-recreational PA, but not with sports or exercise (Garrett *et al.* 2020). Another recent study found that closeness to the sea was associated with MVPA, but only among those with high levels of total PA (Kangas *et al.* 2024).

A previous review (O'Donoghue *et al.* 2016) showed that there are fewer studies on the environmental factors associated with SB, resulting in a lack of evidence for several factors, such as the presence of parking or public transport infrastructure or air/noise pollution. In addition, inconsistent evidence was found for walkability, safety and aesthetic features. The most consistent evidence was found for the associations between bad weather and more ST, higher neighbourhood deprivation and increased leisure screen time, and the higher presence of or proximity to green space and lower SB. Results regarding urban–rural differences in SB were shown to vary based on what type of SB is considered and the nationality and gender of the studied individuals. Residing in rural areas was associated with transport-related SB. (O'Donoghue *et al.* 2016) Previous studies on the association between residential environment, PA and SB are summarised in Table 4.

2.4 Summary of the literature review

The positive effects of PA on depression are well established in recent literature (e.g., Noetel *et al.* 2024; Schuch *et al.* 2018; Singh *et al.* 2023). However, the associations appear to vary according to the type, context and intensity of PA (De Cocker *et al.* 2021; Noetel *et al.* 2024; Singh *et al.* 2023; White *et al.* 2017), and these differences are not yet fully understood. According to recent systematic reviews, globally, living in urban areas is generally associated with a higher risk of depressive symptoms. However, there are still studies that contradict this trend, suggesting a need for further investigation (Rautio *et al.* 2018; Sampson *et al.* 2020). In addition, although cultural stigma and societal attitudes towards depression vary significantly accross countries (e.g., Krendl & Pescosolido 2020; Lauber & Rössler 2007) the association of the broader context of culture and country with depressive symptoms is less studied.

Evidence suggests that several characteristics of urban residential environments may promote PA (e.g. Kärmeniemi *et al.* 2018; Smith *et al.* 2017). However, rural environments and rural-urban comparisons have been less explored. Urbanisation is generally associated with lower total PA, especially in low- and middle-income countries, while urbanisation is associated with recreational PA in high-income countries (Boakye *et al.* 2023). More research is still needed on PA and SB in rural areas, and the role of residential environment for different types of PA.

In particular, studies are needed that comprehensively examine the interactions of residential environment, PA and depression. Especially studies using a compositional data analysis approach to examine the association between all 24-h movement behaviours (PA, SB and sleep) and depression, let alone including an environmental perspective, are scarce or absent.

Table 4. Previous studies on the associations between residential environment, physical activity and sedentary behaviour, with emphasis on recent systematic reviews and population-based studies focusing on adults.

Study	Study design	Study population	Exposure	Outcome	Main findings
Boakye *et al.* 2023	Cross-sectional	Adults (22 countries), *n*=138,206	Urbanisation	PA (self-reported)	Urbanisation was associated with lower total PA. In low- and middle-income countries, urbanisation was associated with lower household and occupational PA, while in high-income countries, urbanisation was associated with higher recreational PA.
Fan *et al.* 2014	Cross-sectional	Adults (US), *n*=5,056	Rural/urban residence	PA (self-reported and accelerometer-measured)	Rural residents had less high-intensity accelerometer-measured PA but more self-reported total PA due to higher amount of household PA.
Garrett *et al.* 2020	Cross-sectional	Adults (UK), *n*=23,388	Green space and blue space	PA (self-reported and accelerometer-measured)	Living close to the coast was associated with meeting UK PA guidelines through self-reported total, walking and non-recreational PA. Green space was associated with meeting the guidelines through non-recreational PA.
Georgiou *et al.* 2021	Systematic review and meta-analysis (50 studies)	All ages, *n*=22–1,930,048	Blue space	PA (self-reported or objectively measured), restoration and social interaction	Living closer to blue space and higher amounts of blue space within a geographical area were both associated with higher physical activity levels.
Hillsdon *et al.* 2015	Cross-sectional	Adults (UK), n=195		Location and intensity of PA (GPS and accelerometer-measured)	60% of outdoor LPA and MVPA occurred outside the 800 m home buffer, while distances varied by gender, home location, area deprivation and car ownership.
Kangas *et al.* 2024	Cross-sectional	Adults (Finland), *n*=5,470	Biodiversity, forest characteristics and blue space	PA (accelerometer-measured)	Higher residential forest area was associated with more LPA among those with high total PA, and with less MVPA among those with low total PA. Environments with diverse tree structure or near the sea were associated with more MVPA in high total PA group.
Kärmeniemi *et al.* 2018	Systematic review (21 prospective cohort studies and 30 natural experiments)	All ages, *n*=32–1,300,000	Change in the built environment	Change in PA (self-reported or objectively measured)	Higher levels of objective accessibility and new infrastructure for walking, cycling and public transport were associated with increases in total and transport-related PA.
Kärmeniemi *et al.* 2019	Longitudinal	Adults (Finland), *n*=5,947	Neighbourhood density, mixed land use and access networks	PA (self-reported and objectively measured)	Increased neighbourhood density, mixed land use and access networks were associated with increased regular walking and cycling.

Müller *et al.* 2024	Systematic review (70 studies)	Adults living in rural areas, *n*=143–473,296 (for quantitative studies), *n*=11–118 (for qualitative studies)	Any self-reported or objectively measured characteristic of the built or natural environment in rural areas	PA (self-reported or objectively measured)	Strongest positive relationships were found between the availability and accessibility of places for exercise and recreation and leisure-time PA and between the overall environment and leisure-time PA. Several facilitators and barriers for PA were found based on qualitative studies.
O'Donoghue *et al.* 2016	Systematic review (74 studies)	Adults, *n*=10–246,920	Any determinants or correlates of SB	SB (self-reported or objectively measured)	Several environmental correlates of SB were found, including proximity of green space, neighbourhood walkability and safety, and weather.
Pasanen *et al.* 2024	Longitudinal	Adults (Finland) working in public sector, *n*=102	Green space	PA (during active travel, GPS and accelerometer-measured)	A higher proportion of usable green space was associated with more PA during active travel on days off and on retirement days, but not on workdays.
Pontin *et al.* 2022	Systematic review (94 studies)	Adults, *n*=10–65,967	Objective measure of the built environment	PA (objectively measured)	Participants' ethnicity and SES were often not reported. MVPA was the most common measure of physical activity, followed by walking. Commonly assessed elements of the built environment included walkability and access to parks and green spaces.
Prince *et al.* 2022	Overview of systematic reviews (116 systematic reviews)	All ages (high-income countries), *n*=5–16,787,934	Objectively measured or self-reported built environment characteristics	PA (self-reported, objectively measured or direct observation)	Environments promoting active travel were positively linked to transportation and total PA among adults. There was also some evidence that green spaces are linked to increased transportation, leisure and total PA.
Smith *et al.* 2017	Systematic review (28 studies)	All ages, *n*=102–7,105	Objectively measured built environment features	PA (self-reported or objectively measured)	Walkability components, provision of quality parks and playgrounds, and installation of or improvements in active transport infrastructure positively affected active transport, physical activity, and visits to or use of settings.
Yang *et al.* 2021	Umbrella review (40 systematic reviews)	All ages, *n*=7–201 (primary studies)	Green space	Over 100 health outcomes	Green space was beneficially associated with all-cause and stroke-specific mortality, cardiovascular disease morbidity, cardiometabolic factors, mental health, low birth weight, physical activity, sleep quality and urban crime.

3 Aims of the study

The main objective was to examine the associations between the residential environment, physical activity and depressive symptoms among adults. The specific aims were:

1. To assess the overall prevalence and severity of depressive symptoms (measured with BDI-II) within the Finnish population and to compare symptom scores with those from population-based samples from other countries.
2. To explore the relationship between residential environment characteristics and the presence of depressive symptoms, and to determine if this association is modified by physical activity.
3. To investigate associations between 24-hour movement behaviours (physical activity of different intensities, sedentary time and sleep) with depressive symptoms in urban and rural residents.

4 Materials and methods

The study consists of three publications (I–III), which are mainly based on data from the Northern Finland Birth Cohort 1966. Table 5 summarises the aims, statistical methods, data, study designs, geographical scales and sample sizes of the three studies.

4.1 Northern Finland Birth Cohort 1966 (Studies I–III)

The Northern Finland Birth Cohort (NFBC1966) (https://www.oulu.fi/nfbc/) is a longitudinal epidemiological research programme (University of Oulu 2024) that comprises all people born in 1966 in Finland's two northernmost provinces, Oulu and Lapland (n=12,058 live-born individuals) (Rantakallio 1988). The cohort members underwent monitoring through interviews, postal questionnaires, and clinical measurements starting from the prenatal period, including follow-ups at the ages of 1, 14, 31 and 46 years. Ethical approval for NFBC1966 was granted by the Ethical Committee of the Northern Ostrobothnia Hospital District (94/2011), and explicit written consent was obtained from all participants to use their information in a pseudonymised format for scientific research purposes. Participants had the right to refuse to participate and withdraw their consent later. Those who did not give permission to use their data were excluded from the study. The participants' current or future treatment was not in any way affected by their refusal to take part or decision to withdraw.

The present study focuses on analysing data from the most recent assessment in 2012, conducted when the individuals were 46 years old, involving 10,331 cohort members who were alive and whose address was known (Figure 4). Of all those invited, 7,146 cohort members (69.2%) answered at least one of the four postal questionnaires, and 5,832 participants attended the clinical examinations. Most of those who attended the clinical examinations also answered at least one of the questionnaires (Nordström *et al.* 2022). Results of the previously published attrition analysis of the 46-year follow-up showed that women were more likely than men to participate in the questionnaires and clinical examinations. In addition, questionnaire and clinical examination participants were more likely to have a higher level of education, to be employed, to be married and to have children than cohort members who did not participate (Nordström *et al.* 2022).

To be eligible for this study, the participants had to complete the BDI-II questionnaire (n=5,489). For Study II, they also needed to have valid self-reported (n=4,936) or wrist-worn accelerometer data (n=5,193), and for Study III, valid hip-worn accelerometer data (n=4,305). In addition, for studies II and III, valid address information to define the relevant residential environment variables was required. The regional distribution of the participants of the 46-year follow-up study is presented in Figure 5.

Table 5. Summary of the aims, methods and study sizes of studies.

Study	Aim	Statistical methods	Data	Study design	Geographical scale	N
I	To compare the distribution of BDI-II items between population-based samples from six different countries (including NFBC1966).	Random-effects meta-analysis and meta-regression	NFBC1966, 46-year follow-up Five peer-reviewed research articles with population-based samples from Norway, Dominican Republic, Brazil, Mexico and Japan	Cross-sectional	Global; comparison between countries	5,860 (Finland); 875 (Norway); 954 (Dominican Republic); 182 (Brazil); 205 (Mexico); 766 (Japan)
II	To investigate whether residential environment variables are associated with depressive symptoms and whether the possible associations are modified by self-reported or wrist-worn accelerometer-measured PA.	Ordinal logistic regression	NFBC1966, 46-year follow-up	Cross-sectional	Local; 1-km buffers or closest distances from home coordinates	5,489
III	To examine how compositions of 24-hour time-use are associated with depressive symptoms in urban and rural environments.	Compositional data analysis, isotemporal substitution	NFBC1966, 46-year follow-up	Cross-sectional	Regional: Comparison between urban and rural	4,295

BDI-II: Beck Depression Inventory-II; NFBC1966: Northern Finland Birth Cohort 1966.

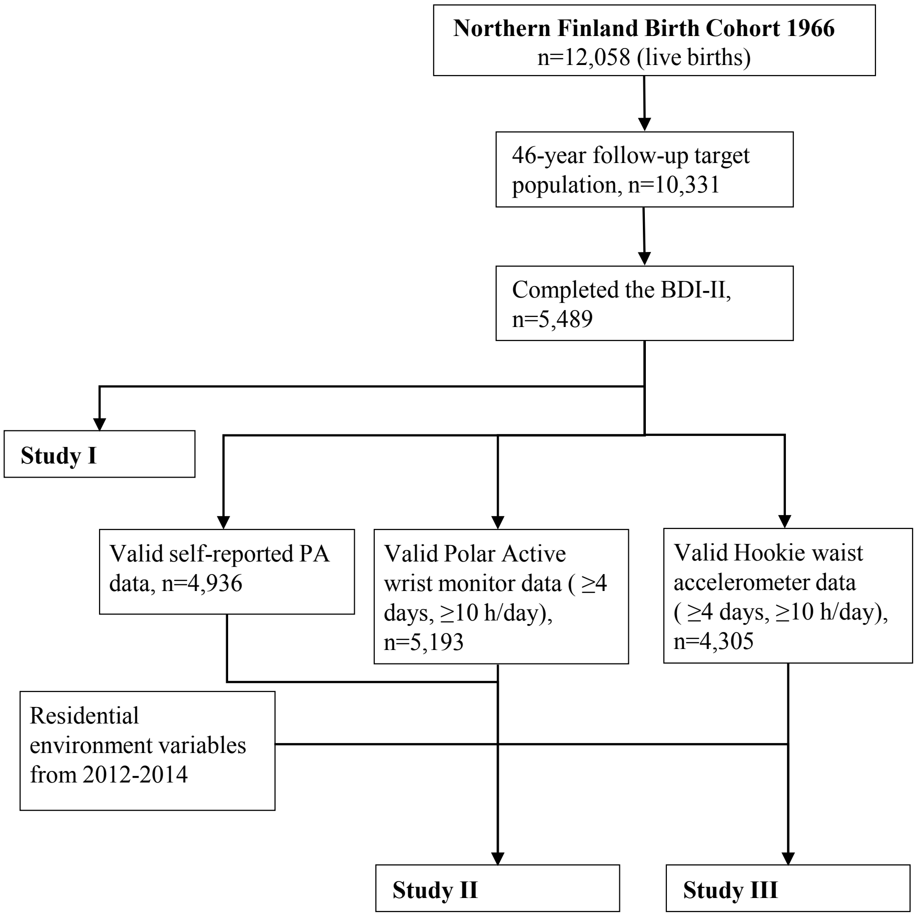

Figure 4. Flow chart of the study populations of Studies I–III.

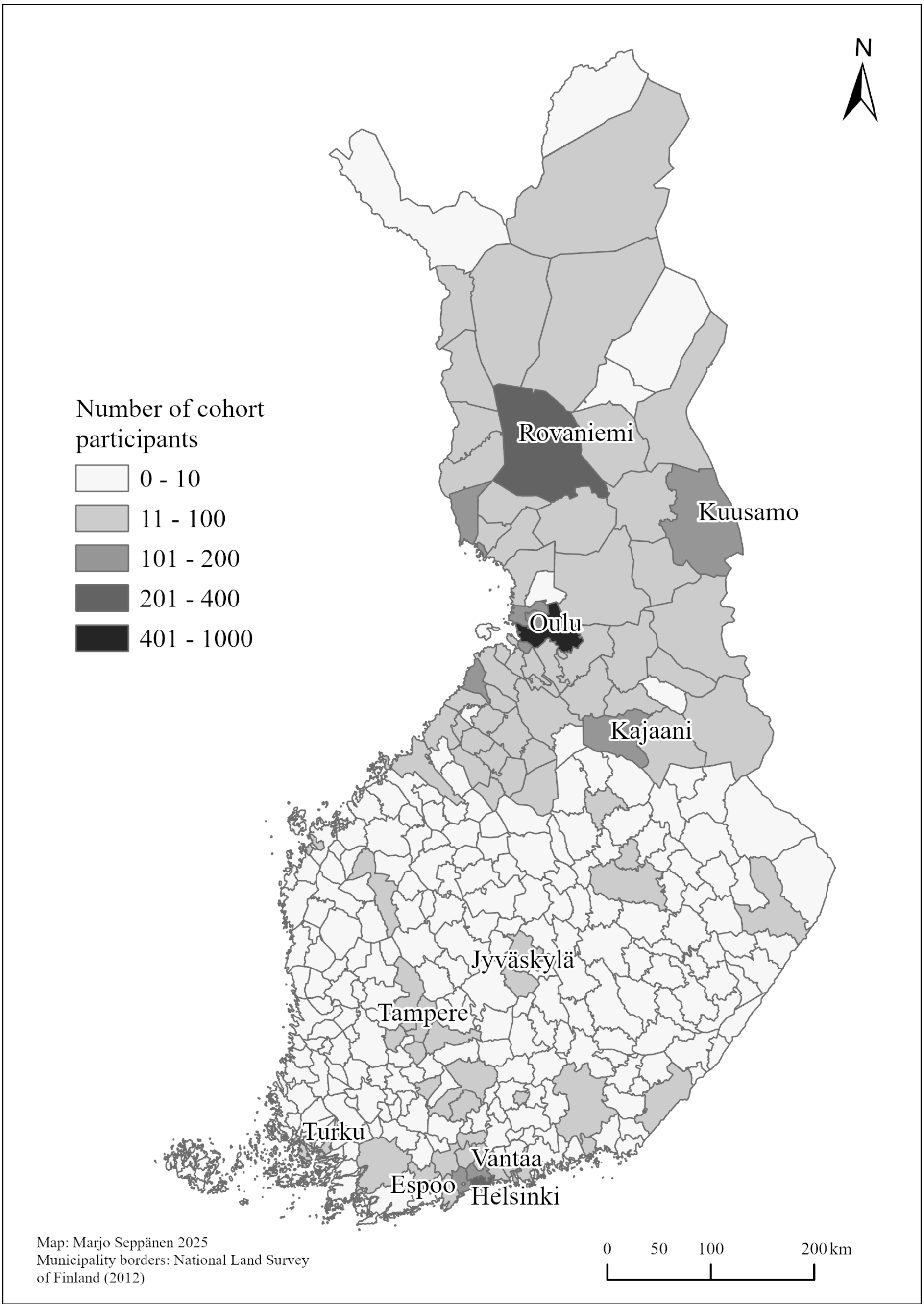

Figure 5. Geographical distribution of the participants from Northern Finland Birth Cohort 1966 in 2012. Participants of the 46-year clinical examinations with valid home coordinates included (n=5,787).

4.1.1 Questionnaires (Studies I–III)

Beck Depression Inventory-II

The BDI-II was used in all studies (Studies I–III) to measure depressive symptoms. The participants filled in the BDI-II questionnaire on the day of their clinical examination. The BDI-II consists of 21 items recognised as indicative of depressive symptoms, including sadness, pessimism, past failure, loss of pleasure, guilty feelings, feelings of punishment, self-dislike, self-criticalness, suicidal thoughts, crying, agitation, loss of interest, indecisiveness, worthlessness, loss of energy, changes in sleeping, irritability, changes in appetite, difficulty concentrating, tiredness or fatigue and loss of interest in sex. Participants responded to each item on a 0–3 scale based on their feelings over the past two weeks, with higher cumulative scores indicating greater depressive symptom severity. The total score of the BDI-II can be divided into the following categories: no depressive symptoms (scores of 0–13), mild depressive symptoms (14–19), moderate depressive symptoms (20–28) and severe depressive symptoms (29–63) (Beck *et al.* 1996). For the study populations in Studies I–III, the BDI-II items' internal consistency was excellent, with Cronbach's alpha coefficient values of 0.91–0.92.

Leisure-time physical activity

Self-reported leisure-time PA was used in Study II. It was assessed separately for LPA and MVPA based on questions about frequency and duration during leisure time. Exact questions and response options were: 'How often do you exercise during your leisure-time' ('daily', 'four to six times a week', 'two to three times a week', 'once a week', 'two to three times a month' and 'once a month or less') and 'How long do you exercise for at a time' ('more than 90 minutes', '60–90 minutes', '40–59 minutes', '20–39 minutes', 'less than 20 minutes', and 'not at all') (Suija *et al.* 2013). LPA was defined as causing no sweating or breathlessness, whereas MVPA was described as causing some sweating or breathlessness. To calculate the amount of LPA and MVPA, the frequency was multiplied by duration.

Lifestyle, personality and sociodemographic factors

Variables related to lifestyle, personality and sociodemographic factors were chosen as potential confounders based on earlier literature and preliminary univariate analyses. These variables included marital status, education, present smoking, alcohol intake and a harm avoidance temperament item (Studies II & III).

Marital status was assessed with the question, 'What is your marital status at the moment?''. In Study II, responses were classified into 'married/cohabiting/registered partnership' and 'unmarried/divorced/widow'. In Study III, unmarried was separated as a third class.

Education was determined based on two questions: 'What is your basic education?' and 'What is your vocational education?'. Responses were classified into three categories: basic (≤ 9 years of school and no vocational education or only short course), secondary (vocational school or college degree and/or matriculation examination) and tertiary (polytechnic or university degree).

Current smoking was assessed with the question, 'Do you smoke at the moment?" and classified as either 'no' or 'yes'.

Current alcohol intake was evaluated based on questions regarding the frequency of use and typical quantity per occasion for mild drinks, wines and spirits. Frequency of use was measured using a 10-point scale (1=never, 10=daily), while the quantity was measured on a 9-point scale (e.g. for mild drinks, 1=none, 9=15 bottles or more). The daily consumption of alcohol in grams for each beverage was calculated by multiplying frequency with quantity. More details on the classification of alcohol intake have been described by Vladimirov *et al.* (2018).

The harm avoidance temperament score was derived from questions in Cloninger's Temperament and Character Inventory (Cloninger *et al.* 1994). The questionnaire consists of 107 items related to temperament, out of which 35 items specifically focused on harm avoidance (Cloninger *et al.* 1994). These 35 items were used in this study to calculate a summary score for harm avoidance temperament trait.

For Study III, we also included employment and the physical strenuousness of work. Employment status was assessed with a question about the current employment situation, which included several options such as different types of employment, unemployment of different lengths, parental leave, etc. Responses were classified into 'employed', 'unemployed' and 'other', with the last category including for example students and homemakers.

The physical strenuousness of work was evaluated based on multiple questions concerning the physical tasks and body postures of the participants' work. The responses were scored and summed up together. More details on the exact questions and scoring of the responses have been described elsewhere (Punakallio *et al.* 2019).

4.1.2 Clinical examination (Study III)

The participants took part in a clinical examination where trained nurses carried out a comprehensive medical examination. In Study III, information on the participants' waist circumference was used as a covariate. Waist circumference was measured midway between the lowest rib margin and the iliac crest.

4.1.3 Accelerometer-measured physical activity (Studies II & III)

Wrist-worn accelerometer (Polar Active)

A waterproof Polar Active wrist-worn monitor (Polar Electro Oy, Kempele, Finland) was worn on the non-dominant hand for at least 2 weeks (including during sleep) by all study participants who attended the clinical examination. The Polar Active monitor incorporates a uniaxial capacitive accelerometer (Kinnunen *et al.* 2019) and has been shown to correlate with the doubly labelled water technique for the assessment of EE during exercise and in daily life (Kinnunen *et al.* 2012, 2019). Participants were instructed to go about their daily lives as usual during data collection, and the accelerometer provided no feedback to the participants.

Participants with ≥4 valid days (wear time of at least 10 h/day during waking hours) (Niemelä *et al.* 2019) were included in the analyses (Study II). Four valid days was chosen as a criterion, as it has been shown to reliably estimate the amount of PA (Trost *et al.*

2005) and ST (Donaldson *et al.* 2016) and has been widely used in previous research (Skender *et al.* 2016). Polar Active uses the user's height, weight, gender and age as predefined inputs and provides MET value estimates every 30 seconds based on daily PA (Hautala *et al.* 2012). These data were categorised into five intensity levels based on the cut points provided by the device manufacturer (very light: 1–2 METs; light: 2–3.5 METs; moderate: 3.5–5 METs; vigorous: 5–8 METs; and very vigorous: ≥8 METs) (Jauho *et al.* 2015). In addition, daily and weekly averages of duration spent in different PA intensity levels (min/day) were calculated. LPA (min/week) was defined as any activity at an intensity of 2–3.5 METs and MVPA (min/week) as any activity at an intensity of at least 3.5 METs. These cut points for the Polar Active have been shown to provide results comparable to those obtained using the commonly accepted cut points (LPA: 1.5–3 METs, MPA: 3–6 METs) for the Actigraph GT3X hip-worn accelerometer (Leinonen *et al.* 2017).

Hip-worn accelerometer (Hookie AM20)

Participants in the clinical examination were also asked to wear a hip-worn accelerometer (Hookie AM20; Traxmeet Ltd., Espoo, Finland) for 2 weeks during all waking hours, except for water-based activities. The Hookie accelerometer measures and stores raw acceleration signals at 100 Hz, and it was shown to have excellent agreement with the commonly used Actigraph GTX3 accelerometer when the mean amplitude deviation (MAD) values were compared (Vähä-Ypyä *et al.* 2015a).

Data from the participants with ≥4 valid days (wear time of at least 10 h/day during waking hours) of Hookie accelerometery were used in Study III to acquire 24-hour time use composition. Data collected from the accelerometer were calculated into wear-time intervals, which were cross-referenced with self-reported sleep times (based on two questions: 'At what time do you normally go to bed?' and 'At what time do you normally get out of bed?'), and overlapping data were discarded (Farrahi *et al.* 2021). After this, the data were classified as sedentary time (sitting or lying), standing still, LPA, MPA or VPA based on the MAD values, which were computed for 6-s epochs (Farrahi *et al.* 2021; Vähä-Ypyä *et al.* 2015b, 2018). The time spent in each activity was divided by the number of valid days to obtain mean minutes per day in each activity. Light physical activity included minutes per day spent standing still and in LPA, whereas MVPA included minutes per day spent in MPA or VPA. To acquire the 24-hour composition, we included the duration of sleep, which was self-reported in response to the question, 'How many hours do you sleep on average per day?' Answers were converted to minutes per day. The season of the year (divided in summer and winter season) in which the accelerometer data was collected was also included in the analyses to adjust for seasonal variation in PA (Study III). Seasons were defined based on the equinoxes: summer from the March equinox to the September equinox, and winter for the remaining period.

4.1.4 Residential environment measures (Studies II & III)

Coordinates of the NFBC1966 participants' home addresses were acquired from the Digital and Population Data Services Agency of Finland for all the cohort members whose addresses were known at the time of the 46-year follow-up data collection (2012–2014). Based on these coordinates, residential environment variables were calculated using ArcMap 10.2 (Environmental Systems Research Institute 2013). These variables included population density; distance to the closest grocery store, park and forest; number of bus stops; length of cycle/pedestrian paths; residential greenness; level of urbanicity (Study II); and urban/rural classification of the residential environment (Figure 6, based on the classification by Helminen *et al.* 2014) (Study III).

A circular buffer with a 1-km radius was fixed around each participant's residence, which was used to calculate the residential environment variables. The 1-km radius was chosen as it was estimated to represent the participants' everyday living environment, and this choice is supported by a systematic review, which suggested that buffer sizes between 500 and 1,999 m were best to predict the association of greenness with physical health (Browning & Lee 2017). Distances were calculated either via the road network or linearly depending on the destination (e.g. grocery stores are more likely to be accessed via the road network, while there might be no road network leading to forests). More detailed information about the measurement and data sources of the residential environment variables are listed in Table 6. The residential environment variables were linked to the cohort questionnaire and clinical data based on the date of the participants' clinical examination and the information on the beginning and ending dates of residence included in the residential coordinate data. If the exact start date of residence was not available, the last day of the previous month was used as the start date of residence.

Table 6. Residential environment variables, measurement description, units, data sources and data year.

Variable	Measurement	Unit	Data source	Data year
Population density	Population density within a 1-km buffer around cohort participants' homes	Inhabitants/km^2	Finnish Monitoring System of Spatial Structure and Urban Form (Finnish Environment Institute; Statistics Finland 2024)	2012
Urban/rural classification	Figure 6 shows a map of the urban/rural classification in Finland. Categories 'sparsely populated rural area', 'rural area close to urban area', 'local centres in rural areas' and 'rural heartland' were classified as rural areas, and 'outer urban area', 'inner urban area' and 'peri-urban area' were classified as urban areas. Rural heartland is defined as relatively densely populated rural area with either a strong primary production or a wide range of functions.	Categorised variable	Finnish Urban-Rural Classification (Finnish Environment Institute 2010; Helminen *et al.* 2014)	2010
Level of urbanicity	An index combining standardised z-scores of densities of residents, services and intersections within a 1-km buffer (Kärmeniemi *et al.* 2019)	Index value	Finnish Monitoring System of Spatial Structure and Urban Form (Finnish Environment Institute; Statistics Finland 2024) Finnish Transport Infrastructure Agency: Digiroad (Finnish Transport Infrastructure Agency 2024)	2012
Residential greenness	NDVI within a 1-km buffer	Index value (range -1.0 to +1.0)	United States Geological Survey (2024)	June to July 2013–2016 (mean value)
Distance to closest grocery store	The distance (via road network) from the participant's residence to the focal point (250 m × 250 m), where the closest grocery store (supermarket or store) existed	Metres	Finnish Monitoring System of Spatial Structure and Urban Form (Finnish Environment Institute; Statistics Finland 2024) Finnish Transport Infrastructure Agency: Digiroad (Finnish Transport Infrastructure Agency 2024)	2012
Distance to closest park	Distance (linearly) from the participant's residence to the closest park	Metres	CORINE land cover vector dataset (Finnish Environment Institute) (partly LUKE, MAVI, LIVI, DVV, EU, MML Maastotietokanta 01/2017, 2024)	2012
Distance to closest forest	Distance (linearly) from the participant's residence to the closest forest	Metres	CORINE land cover vector dataset (Finnish Environment Institute) (partly LUKE, MAVI, LIVI, DVV, EU, MML Maastotietokanta 01/2017, 2024)	2012
Number of bus stops	Number of bus stops within a 1-km buffer	Total value	Finnish Transport Infrastructure Agency: Digiroad (Finnish Transport Infrastructure Agency 2024)	2014
Length of cycle/pedestrian paths	Length of cycle/pedestrian paths within a 1-km buffer	Metres	Finnish Transport Infrastructure Agency: Digiroad (Finnish Transport Infrastructure Agency 2024)	2014

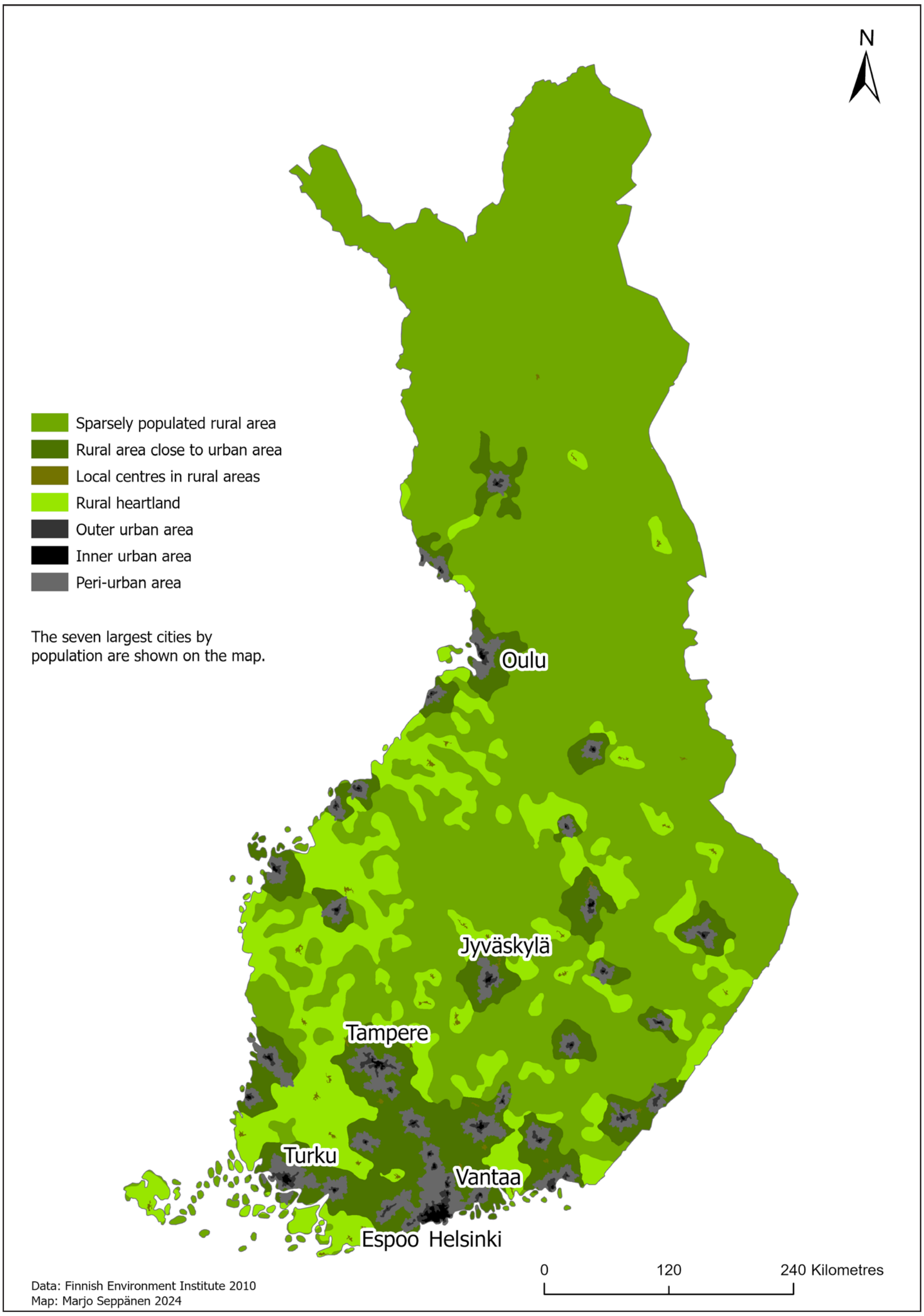

Figure 6. Rural and urban areas in Finland, 2010. For Study III's analysis, the categories 'sparsely populated rural area', 'rural area close to urban area', 'local centres in rural areas' and 'rural heartland' were combined to form rural areas, and 'outer urban area', 'inner urban area' and 'peri-urban area' were combined to form urban areas.

4.2 Literature review (Study I)

Three electronic databases (SCOPUS, PsycInfo and PubMed) were searched for original peer-reviewed journal articles using the BDI-II. The search strategy was developed in cooperation with a librarian using medical subject headings and adapted for other databases by using free-word searches. The search was conducted manually on 22 June 2020 using the following keywords: *BDI-II, Beck Depression Inventory-II, validation, population, psychometr*, adaptation* and *dimension*. The initial literature search produced 522 articles. In addition, suitable articles were also identified by searching the references of papers retrieved by the search strategy. After removing duplicate articles, screening the titles and abstracts, and reading full-text articles, five articles were finally deemed eligible. The studies were considered eligible if they met the following criteria: used the BDI-II, reported both the mean values and standard deviations (SD) of all BDI-II items, and used population-based sampling. In addition, we limited the search to articles written in English and published in open-access journals or otherwise accessible within the University of Oulu. The author (MS) conducted the search and selection of all articles.

4.3 Statistical analyses

The descriptive data is presented in counts and percentages or means and standard deviations. A chi-square test of independence is used for categorical variables, and a t-test for continuous variables for comparing study characteristics. All the results of the statistical analyses are expressed as p-values and 95% confidence intervals (95% CI).

Study I compared BDI-II items between different populations using random-effects meta-analysis and meta-regression. First, relative mean scores for each BDI-II item were calculated by dividing the mean value of each symptom by the total mean and then dividing the resulting value by the number of BDI-II items (item mean/(total mean/21)). This made it possible to compare the relative mean scores of different populations, as a relative mean <1 on any item indicates that the symptom scores below the average item score for the sample, while a score >1 indicates that the symptom scores higher than the average item score. Using random-effects meta-analysis, we pooled the six different populations based on the relative mean score and then conducted a meta-regression to statistically compare these populations' scores by comparing each sample to the average of the other samples. In addition, spider graphs were used to visually examine the relative mean scores and meta-regression results.

The associations between residential environment variables, self-reported and wrist-worn accelerometer-measured PA, and depressive symptoms were analysed using ordinal logistic regression models (Study II). BDI-II scores were categorised into four categories based on severity of depressive symptoms ('no depressive symptoms', 'mild', 'moderate' and 'severe') and used as an outcome of the models, with 'no depressive symptoms' as the reference category. All the residential environment variables were modelled separately due to collinearity, and we also had separate models including self-reported LPA or MVPA and wrist-worn accelerometer-measured LPA or MVPA. The final models were adjusted for sex, marital status, harm avoidance, education, present smoking and alcohol intake based on earlier literature and preliminary analyses. The odds ratios (ORs) were estimated per 60-min increase in LPA and MVPA, per 1-inhabitant/0.1 ha increase for population density, and per 1-km increase for distance to the nearest grocery store, park or forest as well as for the length of cycle/pedestrian paths. In addition, we used inverse probability weighting to account for attrition (Study II). This was done by calculating weights based on sex, register-based marital status and register-based education.

For Study III, the compositional associations between 24-hour movement behaviours and depressive symptoms were studied in urban and rural residents using the PA data obtained from the hip-worn accelerometer. Compositional means were calculated for 24-hour movement behaviours (MVPA, LPA, ST and sleep) by scaling the geometric mean of each behaviour to sum 24 hours. Following an earlier-described method for compositional data (Gupta *et al.* 2018), the differences in 24-hour movement behaviours between urban and rural residents were compared by computing the log ratio of the geometric mean values of 24-hour movement behaviours in urban and rural residents. Confidence intervals were calculated using bootstrapping with 1,000 replicates and replacements. To test for a possible U-shaped association of sleep duration and depressive symptoms (Wang *et al.* 2023), we used a two-lines test, which has been shown to be a robust method for assessing U-shapedness (Simonsohn 2018). Based on the test, no U-shaped association was found between sleep duration and BDI-II score.

For the main analyses, we used multivariable adjusted regression analysis, specifically the compositional data analysis approach based on isometric log-ratio transformation (Chastin *et al.* 2015; Dumuid *et al.* 2018). Analyses were stratified by the residential environment (urban, n=2,868 and rural, n=1,172). To further analyse the associations, we estimated how the pairwise theoretical time reallocations from one movement behaviour to another were associated with the estimated percentage change in the participants' BDI-II scores (Dumuid *et al.* 2018). Due to the lower mean amount of MVPA, the change in outcome was assessed for reallocations between 10 and 30 minutes to/from MVPA and for reallocations between 10 and 60 minutes to/from the remaining behaviours. Time reallocations were done using 10-minute increments. Forest plots showing the percentage change in mean BDI-II scores were used to visually present the results of pairwise time reallocation analyses. In addition, sensitivity analyses were conducted for participants with the recommended (Hirshkowitz *et al.* 2015) 7–9 hours of sleep per day.

All statistical analyses were performed on participants with no missing values for relevant covariates, exposures or outcome variable. Analyses were conducted using IBM SPSS Statistics versions 25 (Study I) and 26 (Study II) (IBM Corp. 2011), R (R Core Team 2022), R-Studio (Posit Team 2023) (Study III) and Stata version 16 (StataCorp. 2019) (Study I). Specifically, the R packages *robCompositions* (Templ *et al.* 2011) and *compositions* (van den Boogaart *et al.* 2023) were used to perform compositional data analysis in Study III. For figures and tables, ArcGIS Pro 3.0.3 (Environmental Systems Research Institute 2022) (Study II) and the R packages *tidyverse* (Wickham *et al.* 2019) (Studies II and III), *gridExtra* (Baptiste 2017) (Study III) and *table 1* (Rich 2023) (Study III) were used.

5 Results

5.1 Prevalence and comparison of depressive symptoms between Finland, Norway, the Dominican Republic, Mexico, Brazil and Japan (Study I)

The literature review resulted in five population-based articles conducted in Norway (*n*=875) (Aasen 2001), the Dominican Republic (*n*=954) (García-Batista *et al.* 2018), Brazil (*n*=182) (Gomes-Oliveira *et al.* 2012), Mexico (*n*=205) (González *et al.* 2015) and Japan (*n*=766) (Kojima *et al.* 2002). Table 7 summarises the key features of the studies included. The average number of participants across the studies was 603 (SD=378), with sample sizes ranging from 182 to 954. Recruitment methods varied among the studies. All participants were adults or adolescents, with an average age of 40.6 years (ranging from 29.9 to 50.0 years). The studies were conducted between 2001 and 2018.

In the NFBC1966 study's 46-year data collection, 6,074 participants filled in the BDI-II questionnaire, either during the health examination or at home after receiving it by mail. Participants who failed to answer at least one question were excluded (*n*=214). The most frequently unanswered questions were 'loss of energy' (*n*=140, 65.4% missing values), 'tiredness or fatigue' (*n*=139, 65.0%), and 'loss of interest in sex' (*n*=139, 65.0%). Women were more likely to skip the question about loss of energy, while men were more likely to skip the question about loss of interest in sex. Among those who did not complete the BDI-II questionnaire, 92 (43.0%) were men and 122 (57.0%) were women. The final study sample consisted of 5,860 participants, with 2,576 (46.2%) men and 3,284 (53.8%) women. Most participants rated their health as good or excellent (*n*=3,755, 64.1%), and 1,577 (26.9%) had higher education.

The mean BDI-II score among NFBC1966 participants was 5.55 (SD=0.08, range 0–55). Ten per cent (*n*=594) of the final study population had mild depressive symptoms (BDI-II: 14–19 points), 4.1% (*n*=401) had moderate depressive symptoms (BDI-II: 20–28 points) and 1.2% (*n*=71) reported severe depressive symptoms (BDI-II: 29–63 points). Most (66.2%) of the individuals with depressive symptoms were women. The mean BDI-II scores for those without depressive symptoms and those with depressive symptoms were 3.89 (SD=3.55) and 20.28 (SD=6.68), respectively.

The results of the meta-analysis, including the relative mean score for each BDI-II item in the Finnish sample, are shown in Table 8. The symptom items with the highest relative mean scores in the Finnish sample were 'changes in sleep pattern' (M: 2.57, 95% CI: 2.50–2.64), 'loss of energy' (M: 1.89, 95% CI: 1.84–1.95) and 'tiredness or fatigue' (M: 1.63, 95% CI: 1.57–1.68). The items with the lowest relative mean scores were 'suicidal thoughts' (M: 0.30, 95% CI: 0.28–0.33), 'punishment feelings' (M: 0.42, 95% CI: 0.38–0.45), 'sadness' (M: 0.45, 95% CI: 0.42–0.49) and 'crying' (M: 0.45, 95% CI: 0.41–0.50).

Table 7. Summary of the population-based studies included in the comparison of Study I. Reprinted from Table 1 in Study I (Seppänen *et al.* 2022) with the permission from Cambridge University Press.

Reference	Location	Sample selection	Sample size (women/men)	Mean age (SD/ range)	BDI-II translation	Cronbach's alpha	BDI-II total scores			
							0–13	14–19	20–28	29–63
NFBC1966	Finland	Cohort study	5,860 (3,284/2,576)	46.6 (0.6)	Finnish	0.92	4794 (82.0%)	594 (10.0%)	401 (4.1%)	71 (1.2%)
Aasen 2001	Norway	Randomly recruited using telephone register	875 (512/363)	44.5 (18.0–86.0)	Norwegian	0.91	711 (81.0%)	93 (10.6%)	52 (6.0%)	21 (2.4%)
García-Batista *et al.* 2018	Dominican Republic	Convenience sample from the general public	954 (438/516)	31.6 (16.0)	Spanish	0.89	726 (76.1%)	102 (10.7%)	90 (9.4%)	36 (3.8%)
Gomes-Oliveira *et al.* 2012	Brazil	Community-dwelling adults, population-based household survey	182 (102/80)	41.0 (10.8)	Brazilian Portuguese	0.93	NA	NA	NA	NA
Gonzalez *et al.* 2015	Mexico	Community sample	205 (117/88)	29.9 (16.0–70.0)	Spanish	0.87	160 (78%)	27 (13%)	10 (5%)	8 (4%)
Kojima *et al.* 2002	Japan	General population recruited from annual communal health check-up visit	766 (303/463)	50.0 (8.6)	Japanese	0.87	618 (80.7%)	99 (12.9%)	37 (4.8%)	12 (1.6%)

Table 8. Relative mean score and 95% CI for each BDI-II symptom item in Finnish sample. A relative mean score <1 on any item indicates that the symptom scored below the average item score for the Finnish sample, while a score >1 indicates that the symptom scored higher than the average item score. *BDI-II: Beck Depression Inventory-II; CI: confidence interval.*

BDI-II item	Relative mean scores	
	Mean	95% CI
Sadness	0.45	0.42–0.49
Pessimism	0.72	0.67–0.76
Past failure	0.61	0.56–0.65
Loss of pleasure	0.95	0.90–0.99
Guilty feelings	1.32	1.27–1.38
Punishment feelings	0.42	0.38–0.45
Self-dislike	0.64	0.60–0.68
Self-criticalness	0.80	0.75–0.84
Suicidal thoughts	0.30	0.28–0.33
Crying	0.45	0.41–0.50
Agitation	0.87	0.83–0.91
Loss of interest	0.87	0.83–0.92
Indecisiveness	0.49	0.45–0.53
Worthlessness	0.57	0.53–0.61
Loss of energy	1.89	1.84–1.95
Changes in sleep pattern	2.57	2.50–2.64
Irritability	1.21	1.16–1.26
Change in appetite	1.55	1.50–1.61
Concentration difficulty	1.06	1.01–1.11
Tiredness or fatigue	1.63	1.57–1.68
Loss of interest in sex	1.59	1.52–1.65

Figure 7 shows the mean score of each BDI-II symptom item across the six cultural populations, with asterisks indicating statistically significant results based on meta-regression. The item ‘changes in sleep pattern’ (range 0.68–0.95) had the highest scores in Finland, the Dominican Republic, Brazil and Mexico. In Norway, ‘loss of energy’ (0.74) was the highest-scoring item, while in Japan, it was ‘loss of interest in sex’ (0.91). ‘Suicidal thoughts’ (range 0.08–0.17) was consistently the lowest-scoring item in all populations. The next-lowest-scoring items were ‘feelings of punishment’ in Finland (0.11) and Norway (0.18), ‘worthlessness’ in Brazil (0.27) and Mexico (0.16), ‘pessimism’ in the Dominican Republic (0.25), and ‘self-dislike’ in Japan (0.19).

The meta-regression results (Table 9) showed that the Finnish population scored significantly lower on ‘indecisiveness’ (p=0.034) and significantly higher on ‘changes in sleep pattern’ (p=0.039) and ‘irritability’ (p=0.019) than other populations. Norway had significantly higher scores than other populations for ‘loss of pleasure’ (p=0.033), the Dominican Republic for ‘loss of interest’ (p=0.009), Mexico for ‘self-criticalness’ (p=0.049) and ‘feelings of punishment’ (p=0.048), and Japan for ‘sadness’ (p=0.013).

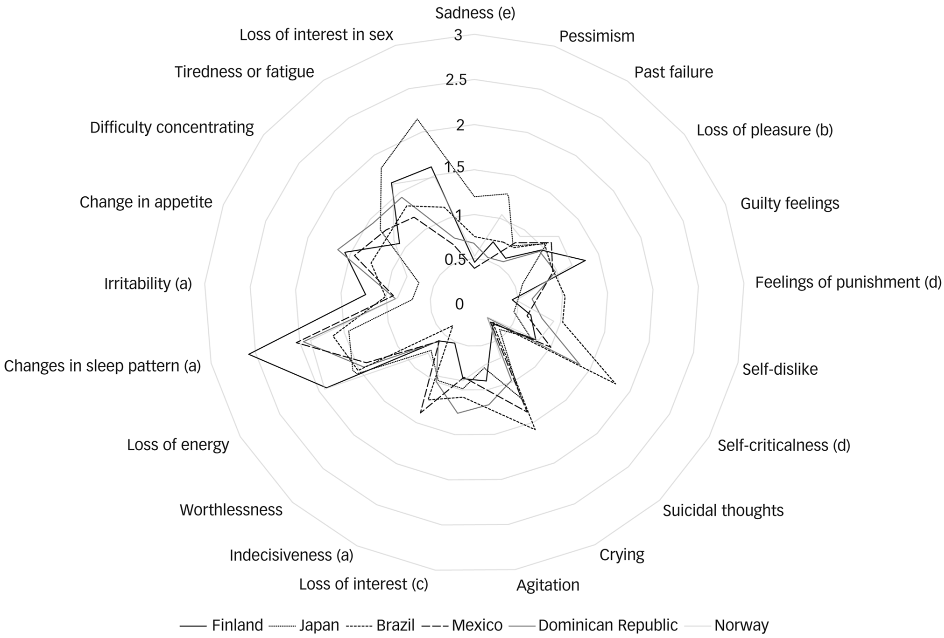

Figure 7. Spider chart showing relative means of BDI-II items in population-based samples from Finland, Japan, Brazil, Mexico, Dominican Republic and Norway. Significant difference ($p<0.05$) between all other countries and Finland (a), Norway (b), Dominican Republic (c), Mexico (d) and Japan (e). Reprinted from Figure 2 in Study I (Seppänen *et al.* 2022) with the permission from Cambridge University Press.

Table 9. Relative mean scores and meta-regression coefficients together with corresponding 95% CIs for BDI-II symptom items that differed statistically significantly in the mentioned country, when compared to all other countries.

	Relative mean scores		Meta-regression	
	Mean	**95% CI**	**Coef.**	**95% CI**
Sadness				
Japan	1.18	1.10–1.28	0.64	0.22–1.06
Loss of pleasure				
Norway	1.20	1.09–1.30	0.22	0.03–0.41
Punishment feelings				
Mexico	1.01	0.73–1.28	0.49	0.01–0.97
Self-criticalness				
Mexico	1.82	1.56–2.07	0.88	0.01–1.76
Loss of interest				
Dominican Republic	1.24	1.13–1.35	0.34	0.14–0.54
Indecisiveness				
Finland	0.49	0.45–0.53	-0.54	-1.01– -0.07
Changes in sleep pattern				
Finland	2.57	2.50–2.64	0.80	0.06–1.52
Irritability				
Finland	1.21	1.16–1.26	0.38	0.10–0.66

5.2 The associations of residential environment characteristics, self-reported and accelerometer-measured physical activity, and depressive symptoms (Study II)

Table 10 shows the characteristics of the NFBC1966 study population (Study II) based on the severity of depressive symptoms. The majority of participants were women (56.0%), were married or cohabiting (78.8%) and had secondary education (68.5%). Participants without depressive symptoms (*n*=4,964) had higher levels of both self-reported and accelerometer-measured LPA and MVPA compared to those with mild (*n*=321), moderate (*n*=146) or severe (*n*=58) depressive symptoms. Those with severe depressive symptoms lived in the residential environment with the highest urbanicity (Mean=1.7, SD=4.3), shortest distance to the nearest park (Mean=11, SD=20.3) and longest distance to the nearest forest (Mean=0.7, SD=0.7). Residential greenness was 0.4 in all groups.

Figure 8 presents the associations between various residential environment characteristics, self-reported or accelerometer-measured physical activity (both LPA and MVPA), and depressive symptoms, with the odds ratio indicating the odds of experiencing more severe depressive symptoms compared to the reference category ('no depressive symptoms'). The results from the final models, including self-reported LPA or MVPA as well as adjustment for all individual factors, indicated that higher population density (LPA model: OR = 1.13, 95% CI: 1.06, 1.21; MVPA model: OR = 1.13, 95% CI: 1.06, 1.20) and higher urbanicity (LPA model: OR = 1.07, 95% CI: 1.03, 1.11; MVPA model: OR = 1.08, 95% CI: 1.03, 1.12) were associated with a higher odds of experiencing more severe depressive symptoms. In addition, higher residential greenness (LPA model: OR = 0.39, 95% CI: 0.18, 0.83; MVPA model: OR = 0.40, 95% CI: 0.18, 0.84) was associated with a lower odds of experiencing more severe depressive symptoms.

Fully adjusted models including accelerometer-measured LPA or MVPA resulted in similar findings. Higher population density (LPA model: OR = 1.10, 95% CI: 1.02, 1.17; MVPA model: OR = 1.12, 95% CI: 1.05, 1.20) and higher urbanicity (LPA model: OR = 1.05; 95% CI: 1.01, 1.10; MVPA model: OR = 1.07, 95% CI: 1.02, 1.11) were associated with a higher odds of experiencing more severe depressive symptoms. Higher residential greenness was associated with a lower odds of experiencing more severe depressive symptoms in the MVPA model (OR = 0.43, 95% CI: 0.20, 0.94).

The results showed that the residential environment's characteristics were similarly associated with depressive symptoms when PA was included in the models, regardless of how PA was measured or its intensity (LPA or MVPA), except for the association between higher residential greenness and accelerometer-measured LPA, which was not statistically significant. In addition, higher self-reported MVPA and higher accelerometer-measured LPA were associated with a lower odds of experiencing more severe depressive symptoms in all models.

Table 10. Characteristics of the study population (n = 5,489) according to the severity of depressive symptoms based on BDI-II. Reprinted and modified from Table 1 in Study II (Rautio *et al.* 2024) based on CC BY 4.0 licence.

		Depressive symptoms				
Characteristics	**Total (n=5,489)**	**No depressive symptoms (BDI-II<14) (n=4,964)**	**Mild (BDI-II: 14-19) (n=321)**	**Moderate (BDI-II: 20–28) (n=146)**	**Severe (BDI-II: 29–63) (n=58)**	**p-value***
Demographics						
Sex						
Men	2,416 (44.0)	2,234 (45.0)	124 (38.6)	41 (28.1)	17 (29.3)	<0.001
Women	3,073 (56.0)	2,730 (55.0)	197 (61.4)	105 (71.9)	41 (70.7)	
Marital status						
Married or cohabiting	4,112 (78.8)	3,773 (79.8)	216 (72.0)	93 (66.9)	30 (55.6)	<0.001
Unmarried/ divorced/ widowed	1,109 (21.2)	953 (20.2)	84 (28.0)	46 (33.1)	24 (44.4)	
Education						
Basic	125 (2.5)	104 (2.3)	8 (2.8)	8 (5.9)	5 (9.6)	0.001
Secondary	3,475 (68.5)	3,129 (68.1)	215 (74.1)	92 (67.6)	39 (75.0)	
Tertiary	1,474 (29.1)	1,363 (29.7)	67 (23.1)	36 (26.5)	8 (15.4)	
Lifestyle factors and personality traits						
Present smoking						
No	3,698 (75.5)	3,399 (76.7)	182 (64.1)	89 (67.4)	28 (52.8)	<0.001
Yes	1,202 (24.5)	1,032 (23.3)	102 (35.9)	43 (32.6)	25 (47.2)	
Alcohol intake (g/day)	11.4 (19.2)	10.8 (17.5)	15.8 (27.3)	18.4 (36.3)	17.3 (32.8)	<0.001
Harm avoidance	13.2 (6.3)	12.5 (5.7)	19.1 (6.5)	21.8 (6.8)	24.4 (6.1)	<0.001
PA						
Self-reported LPA (h/week)	2.7 (2.7)	2.7 (2.7)	2.3 (2.5)	2.4 (2.5)	2.1 (2.8)	0.001
Self-reported MVPA (h/week)	1.9 (2.0)	1.9 (2.0)	1.3 (1.8)	1.4 (1.8)	0.9 (1.1)	<0.001
Accelerometer-measured LPA (h/week)	32.4 (8.4)	32.6 (8.4)	31.3 (8.5)	30.5 (10.1)	27.8 (7.5)	<0.001
Accelerometer-measured MVPA (h/week)	8.0 (4.0)	8.1 (3.9)	7.5 (5.0)	7.2 (4.8)	6.5 (3.7)	0.001
Wear time (h/day)	16.3 (1.0)	16.3 (1.0)	16.3 (1.2)	16.0 (1.4)	16.0 (1.2)	0.037

Characteristics	Total (n=5,489)	Depressive symptoms				p-value*
		No depressive symptoms (BDI-II<14) (n=4,964)	Mild (BDI-II: 14-19) (n=321)	Moderate (BDI-II: 20–28) (n=146)	Severe (BDI-II: 29–63) (n=58)	
Neighbourhood characteristics						
Population density (inhabitants/0.1 ha)	1.1 (1.5)	1.0 (1.4)	1.1 (1.6)	1.3 (1.8)	2.0 (3.0)	0.002
Distance to the closest grocery store (km)	3.1 (5.4)	3.1 (5.5)	2.9 (4.7)	3.5 (6.4)	1.6 (3.1)	0.509
Number of bus stops	4.3 (8.0)	4.2 (7.8)	4.1 (7.8)	6.1 (10.5)	7.6 (12.0)	0.036
Cycle/pedestrian paths (km)	11.4 (9.3)	11.3 (10.3)	11.6 (10.7)	13.7 (12.5)	15.6 (11.0)	0.009
Distance to the closest park (km)	19.4 (28.2)	19.6 (28.4)	18.5 (25.6)	18.4 (27.0)	11.0 (20.3)	0.100
Distance to the closest forest (km)	0.5 (0.6)	0.5 (0.6)	0.5 (0.6)	0.5 (0.6)	0.7 (0.7)	0.028
Level of urbanicity	-0.1 (2.5)	-0.2 (2.5)	0.01 (2.7)	0.6 (3.2)	1.7 (4.3)	<0.001
Residential greenness	0.4 (0.1)	0.4 (0.1)	0.4 (0.2)	0.4 (0.2)	0.4 (0.2)	0.021

Values are mean (SD) or count (%). Values were calculated for the number of participants having data on the variable in question. *P-values indicate the difference between participants with no depressive symptoms (BDI-II<14) and participants with any level of depressive symptoms (BDI-II ≥14). A chi-square test of independence is used for categorical variables, and a t-test for continuous variables. *BDI-II: Beck Depression Inventory-II; SD: standard deviation; PA: physical activity; LPA: light physical activity; MVPA: moderate- to vigorous-intensity physical activity.*

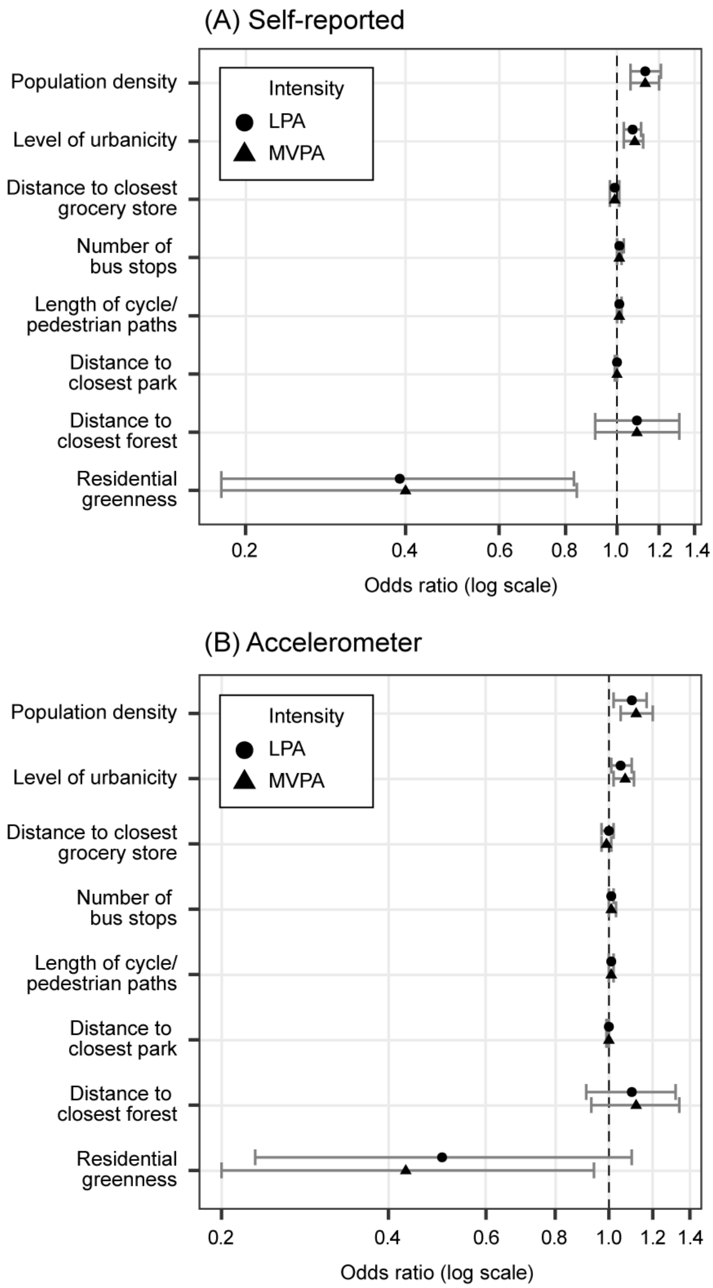

Figure 8. The associations between separate residential environment characteristics, (A) self-reported and (B) accelerometer-measured PA and depressive symptoms according to ordinal logistic regression analyses. LPA: light physical activity; MVPA: moderate-to-vigorous physical activity. Reprinted from Figure 2 in Study II (Rautio *et al.* 2024) based on CC BY 4.0 licence.

5.3 The associations of 24-hour movement behaviours and depressive symptoms in urban and rural residents (Study III)

Table 11 shows descriptive statistics for eligible NFBC1966 participants in Study III. Of the 4,295 participants, 57.3% were female. The mean BDI-II score was 5.3 (SD=6.1) for the whole study sample, as well as for urban (SD=6.2) and rural (SD=5.8) residents. Urban residents were more educated ($p<0.001$), were more likely to be employed ($p=0.021$), and had smaller waist circumferences ($p<0.001$) than rural residents. Conversely, rural residents had higher strenuousness of work ($p<0.001$) and were more likely to be married ($p<0.001$), to have a higher score in the harm-avoidance personality trait ($p<0.001$) and to consume less alcohol ($p<0.001$). Data on PA were more frequently collected from rural residents during the summer ($p<0.001$).

Figure 9 shows the differences in each component of 24-hour movement behaviours between urban and rural residents. Participants living in urban areas had higher levels of MVPA (0.06, 95% CI: 0.02, 0.09) and ST (0.08, 95% CI: 0.07, 0.10) but lower levels of LPA (-0.10, 95% CI: -0.12, -0.09) compared to those living in rural areas. No statistically significant differences were found for sleep.

We found that the 24-hour movement behaviour composition was significantly associated with BDI-II scores, regardless of whether the participant was living in an urban or rural area (model p-value<0.05 for all) (Table 12). For the whole sample, more daily ST relative to other behaviours was associated with higher depressive symptoms, whereas more sleep was associated with lower depressive symptoms after adjustment for confounders. Among urban residents, more ST relative to other behaviours was associated with higher depressive symptoms. For rural residents, more LPA was associated with higher depressive symptoms, and more sleep was associated with lower depressive symptoms.

The results of reallocating time between different movement behaviours for urban and rural residents, as well as for the entire population, are shown in Figure 10. Statistically significant associations were observed for urban and rural residents and the overall population. Among urban residents, reallocating time from ST to any other behaviour was associated with lower BDI-II score. For example, reallocating 30 min from ST to MVPA or sleep was associated with a -4.6% (95% CI: -8.7, -0.4) and a -2.5% (95% CI: -5.1, -0.002) lower BDI-II score, respectively. Reallocating time from LPA to ST was associated with a higher BDI-II score.

Among rural residents, reallocating 30 min from LPA or ST to MVPA was associated with a -8.4% (95% CI: -14.8, -2.0) and -6.8% (95% CI: -12.6, -0.9) lower BDI-II score, respectively. Furthermore, reallocating 60 min from LPA or ST to sleep was associated with a -13.2% (95% CI: -20.2, -6.2) and -9.8% (95% CI: -16.9, -2.8) lower BDI-II score in rural residents, respectively. Conversely, reallocating time from MVPA to LPA or ST, or from sleep to LPA or ST, was associated with a higher BDI-II score.

In the total population, reallocating 60 min from LPA or ST to sleep was associated with a -5.1% (95% CI: -9.0, -1.1) and -5.9% (95% CI: -9.6, -2.2) lower BDI-II score, respectively. Conversely, reallocating 60 min from sleep to LPA or ST was associated with a 5.2% (95% CI: 1.3, 9.1) and a 6.0% (95% CI: 2.2, 9.8) higher BDI-II score.

Table 11. Characteristics of the whole sample and urban (n=2,868) and rural (n=1,427) residents by depressive symptoms. Reprinted and modified from Table 1 in Study III (Seppänen *et al.* 2025) based on CC BY 4.0 licence.

	All (n=4,295)	**Urban residents (n=2,868)**	**Rural residents (n=1,427)**	**p-value***
Sex				
Male	1,833 (42.7%)	1,204 (42.0%)	629 (44.1%)	0.202
Female	2,462 (57.3%)	1,664 (58.0%)	798 (55.9%)	
Highest education				
Basic	147 (3.4%)	71 (2.5%)	76 (5.3%)	<0.001
Secondary	3,121 (72.7%)	1,966 (68.5%)	1,155 (80.9%)	
Tertiary	1,025 (23.9%)	830 (28.9%)	195 (13.7%)	
Employment				
Employed	3,521 (82.0%)	2,383 (83.1%)	1,138 (79.7%)	0.021
Unemployed	187 (4.4%)	114 (4.0%)	73 (5.1%)	
Other (e.g., student or homemaker)	514 (12.0%)	323 (11.3%)	191 (13.4%)	
Strenuousness of work	4.0 (3.0)	3.6 (2.9)	4.8 (2.9)	<0.001
Marital status				
Married or cohabiting	3,403 (79.2%)	2,207 (77.0%)	1,196 (83.8%)	<0.001
Divorced or widowed	426 (9.9%)	323 (11.3%)	103 (7.2%)	
Unmarried	451 (10.5%)	332 (11.6%)	119 (8.3%)	
Harm-avoidance personality trait	13.1 (6.3)	12.9 (6.3)	13.6 (6.3)	<0.001
Alcohol consumption (g/day)	10.5 (17.0)	11.3 (17.4)	8.87 (16.0)	<0.001
Smoking status				0.663
Non-smoker	2,317 (53.9%)	1,535 (53.5%)	782 (54.8%)	
Former smoker	1,167 (27.2%)	791 (27.6%)	376 (26.3%)	
Current smoker	772 (18.0%)	516 (18.0%)	256 (17.9%)	
Waist circumference (cm)	91.3 (13.5)	90.8 (13.2)	92.3 (14.0)	<0.001
Season of the PA data collection				<0.001
Summer	2,324 (54.1%)	1,462 (51.0%)	862 (60.4%)	
Winter	1,971 (45.9%)	1,406 (49.0%)	565 (39.6%)	
Mean accelerometery wear time (min/day)	854 (59.0)	854 (58.6)	855 (59.8)	0.554
BDI-II score	5.3 (6.1)	5.3 (6.2)	5.3 (5.8)	0.791

Continuous variables are presented as means (SD), and categorical variables as counts (%). * P-values indicate the difference between urban and rural residents. A chi-square test of independence is used for categorical variables, and a t-test for continuous variables. *BDI-II: Beck Depression Inventory-II; SD: standard deviation; PA: physical activity.*

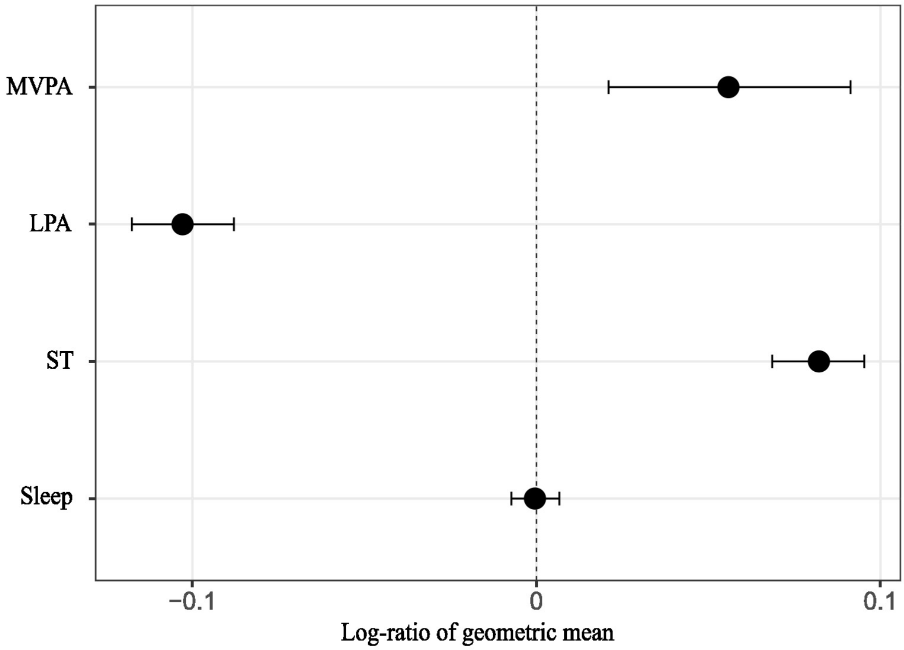

Figure 9. Differences with 95% bootstrap percentile CIs between urban and rural residents in the log-ratio of geometric mean values for MVPA, LPA, ST and sleep. Urban was used as the numerator and rural as the denominator in the calculation of the log ratios. A positive value of the log ratio indicates that urban residents spent more time in that behaviour compared to rural residents, whereas a negative value indicates that urban residents spent less time in that behaviour compared to rural residents. A particular behaviour is considered to be significantly different between groups if its CI does not include zero. Reprinted from Figure 1 in Study III (Seppänen *et al.* 2025) based on CC BY 4.0 licence.

Table 12. Compositional multiple linear regression estimates for BDI-II score by depressive symptom status and urban/rural residence. Reprinted from Table 2 in Study III (Seppänen *et al.* 2025) based on CC BY 4.0 licence.

	Model R^2	**Model *p***	**MVPA β (95% CI)**	***p***	**LPA β (95% CI)**	***p***	**ST β (95% CI)**	***p***	**Sleep β (95% CI)**	***p***
All (*n*=3,498)	0.23	**<0.001**	-0.20 (-0.56–0.16)	0.284	0.68 (-0.09–1.46)	0.083	**1.29 (0.46–2.11)**	0.002	-1.77 (-2.98– -0.56)	0.004
Urban residents (*n*=2,364)	0.24	**<0.001**	-0.12 (-0.57–0.33)	0.596	-0.11 (-1.07–0.85)	0.824	**1.29 (0.25–2.33)**	**0.015**	-1.06 (-2.57–0.46)	0.171
Rural residents (*n*=1,134)	0.23	**<0.001**	-0.47 (-1.09–0.14)	0.131	**2.42 (1.11–3.72)**	**<0.001**	1.25 (-0.13–2.63)	0.076	**-3.19 (-5.21– -1.17)**	**0.002**

Significant associations at $p<0.05$ are shown in bold. All the models were adjusted for sex, education, employment status, strenuousness of work, marital status, harm-avoidance personality trait score, alcohol consumption, smoking status, waist circumference and the season of the PA data collection. *MVPA: moderate-to-vigorous-intensity physical activity; LPA: light-intensity physical activity; ST: sedentary time.*

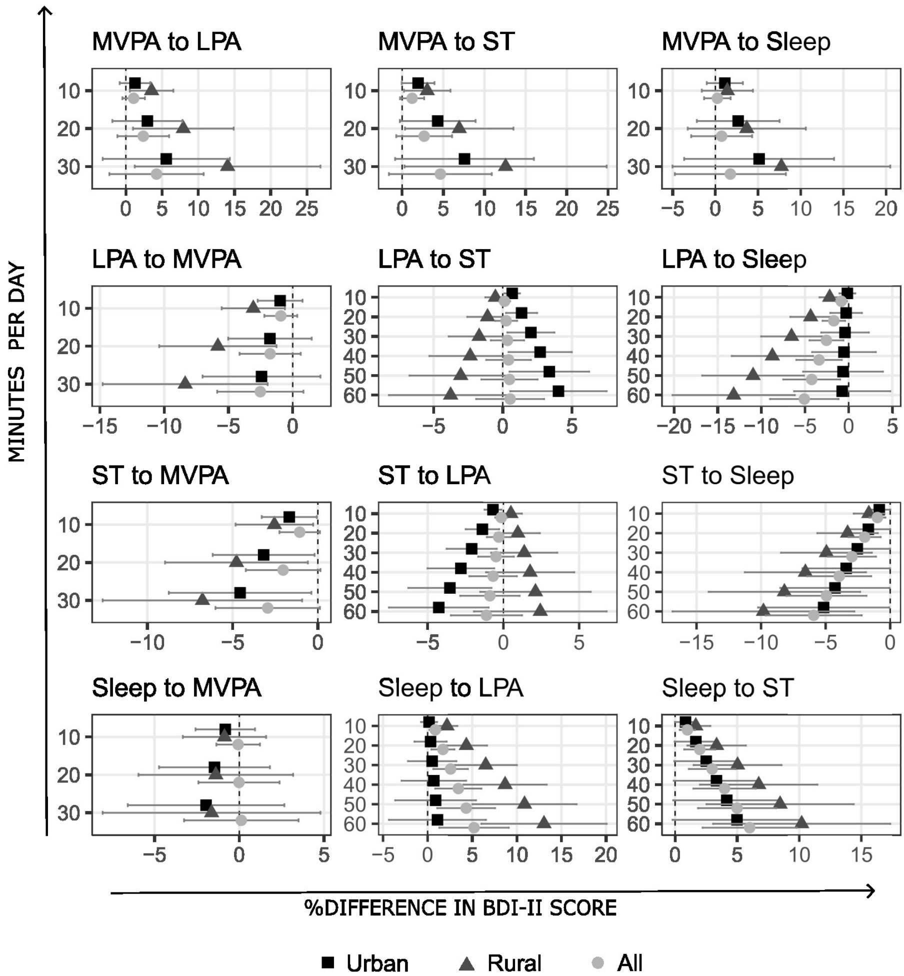

Figure 10. Estimated % differences (95% CI) in BDI-II scores from pairwise time reallocations between movement behaviours among the urban (*n=2,364*), rural (*n=1,134*) and total population (n=3,498). Note that the scale of the x-axis varies. *BDI-II, Beck Depression Inventory-II.* Reprinted and modified from Figure 2 in Study III (Seppänen *et al.* 2025) based on CC BY 4.0 licence.

6 Discussion

The main objective of this thesis was to examine the associations between residential environment, PA and depressive symptoms. The association of depressive symptoms with the residential environment was assessed at three geographical scales: globally, by comparing population-based studies from different countries (Study I); at the regional level, by examining urban-rural differences (Study III); and locally, by focusing on the residential environment characteristics of the participants' home locations (Study II). Depressive symptoms were also examined in association with self-reported and accelerometer-measured PA (Study II) at different intensities (Studies II and III), with accelerometer-measured ST and with self-reported sleep (Study III).

The main finding of Study I was that the scores of several BDI-II items differed from one country to another. In Finland, there were lower indecisiveness, higher changes in sleep pattern and higher irritability; in Norway, higher loss of pleasure; in the Dominican Republic, higher loss of interest; in Mexico, higher self-criticalness and feelings of punishment; in Japan, higher sadness. In Study II, in the Finnish population, residing in areas with higher population density and urbanisation was associated with increased odds of experiencing more severe depressive symptoms. Greater residential greenery was independently associated with a reduced odds of severe depressive symptoms. Higher levels of self-reported MVPA and accelerometer-measured LPA were independently associated with lower odds of severe depressive symptoms. In Study III, 24-hour movement behaviour composition, including MVPA, LPA, ST, and sleep, was associated with depressive symptoms among both urban and rural residents in Finland. Reallocating time from ST to any other behaviour was associated with lower depressive symptoms among urban residents, while among rural residents, reallocating more time to MVPA or sleep at the expense of LPA or ST were associated with lower depressive symptoms.

6.1 Prevalence and comparison of depressive symptoms between Finland and five other countries (Study I)

The highest-scoring symptoms in the NFBC1966 sample were 'changes in sleep pattern', 'loss of energy', and 'tiredness or fatigue'. These items also scored highest in the Finnish validation study for the BDI-II (Beck *et al.* 2005). Conversely, the symptoms with the lowest relative mean scores in our sample were 'suicidal thoughts', 'punishment feelings', 'sadness', and 'crying'. While 'suicidal thoughts' and 'punishment feelings' were also the lowest-scoring items in the validation study, the results differed in that 'self-dislike' and 'worthlessness' were the next-lowest-scoring items in the validation study, followed by 'sadness' and 'indecisiveness' with the same mean scores. 'Crying' was only the 11th-lowest-scoring item (Beck *et al.* 2005).

These results suggest that the way individuals experience or report their symptoms might vary over time within the same country and culture. For example, the scoring of the item 'crying' differed drastically between our sample and the Finnish validation study conducted in 2005. In Western cultures, public crying is often viewed as inappropriate, and reactions to crying can vary. At worst, it may be perceived as a sign of emotional instability or weakness (Vingerhoets 2013). One explanation for our results could be that Finnish attitudes toward crying have become more positive over time.

When comparing the relative item scores of BDI-II between countries, statistically significant differences were found in all countries, except for Brazil, where none of the item scores differed compared to all the other countries. Our results suggest that depressive symptoms may be experienced differently across cultures, which is consistent with previous research on depressive symptoms using the original version of the BDI (Nuevo *et al.* 2008) and a study observing cultural variations in experiencing emotions (Chentsova-Dutton *et al.* 2015).

Environmental factors could contribute to the variation in depressive symptoms between countries. In Finland, 'indecisiveness' scored lower, while 'changes in sleep pattern' and 'irritability' scored higher compared to samples from other countries. The peak in depressive, anxiety and sleep disorders in Finland during October–November (Virtanen *et al.* 2023), when daylight decreases rapidly, might partly explain especially the result concerning the item 'changes in sleep pattern'. However, despite the prevalence of self-reported seasonal variations in mood and behaviour being around 21% among Norwegians (Bjorvatn *et al.* 2021), our study's results differed between Finland and Norway, with only the item 'loss of pleasure' scoring higher in Norway compared to all other countries.

The level of stigma associated with depression varies between countries, with higher stigma more common in Eastern countries (Krendl & Pescosolido 2020). In particular, Asian societies often perceive mental health issues as bringing shame to the family and view them as signs of personal weakness or failure of self-control (Chen & Mak 2008). The only Asian country in our study was Japan, which scored higher in 'sadness' compared to all other countries in our study.

Language differences might also influence how participants respond to BDI-II questions. Both the Mexican and Dominican Republic samples used the Spanish-language version of the BDI-II. A study comparing it to the original version of the BDI found that the Spanish sample scored higher on the items 'sadness', 'discouraged of the future' and 'self-criticalness' (Nuevo *et al.* 2008), with the latter item being similar to one that scored higher in the Mexican sample in our study.

6.2 Associations of residential greenness, population density, urbanicity and PA with depressive symptoms (Study II)

In Study II, we found that in Finland, residential greenness was associated with a lower odds of experiencing more severe depressive symptoms. This is consistent with the results of a Finnish longitudinal study which also showed that NDVI-based residential greenness was associated with a lower odds of depression, with the strongest associations observed when greenness was measured using NDVI from a 100-m buffer and depression was diagnosed (Gonzales-Inca *et al.* 2022). We also used NDVI in our study, but our study did not compare different buffer sizes and used only the BDI-II as an indicator of depressive symptoms, without diagnostic information.

No statistically significant associations were found between the distance to the nearest park or forest and depressive symptoms. This lack of association might be due to the fact that most urban residents live within 300 m of green spaces and there is small variation in distances to green areas in Finland (Viinikka *et al.* 2023). Therefore, it has been suggested that the quality of green spaces should be considered alongside distance when assessing accessibility in Finland (Viinikka *et al.* 2023). Unfortunately, we had no measure of quality available in our study.

While previous research has shown mixed results regarding the association between urbanicity and depression (Rautio *et al.* 2018; Sampson *et al.* 2020), our study found that higher population density and higher levels of urbanicity were associated with a higher odds of experiencing more severe depressive symptoms. Earlier research has suggested that rather than urbanicity, other factors related to urban areas, such as low SES, traffic noise or unsafety, could explain the association between urban areas and depression (Generaal *et al.* 2019). In our study, we were able to adjust the statistical models for the level of education but could not address traffic noise or unsafety.

The associations of greenness, urbanicity and population density with depressive symptoms remained similar when PA measures were included in the ordinal logistic regression models, except for the model including greenness and accelerometer-measured LPA. A recent meta-analysis found that while there is strong evidence that PA mediates the association between green space and mental well-being, the evidence on PA's mediating role between green space and mental illness is still mixed (Zhang *et al.* 2021). Although we did not evaluate PA's mediating effect, our results support the idea that a lack of green space could be independently associated with higher levels of depressive symptoms.

Furthermore, higher levels of self-reported MVPA and accelerometer-measured LPA were independently associated with a lower odds of depressive symptoms. This finding is consistent with previous studies showing a clear association between PA and depressive symptoms (Bellón *et al.* 2021; Noetel *et al.* 2024; Singh *et al.* 2023). The association between higher self-reported MVPA and a lower odds of depressive symptoms is supported by studies emphasising the importance of MVPA for lower levels of depression (Blodgett *et al.* 2023; Singh *et al.* 2023) and leisure-time PA for better mental health (White *et al.* 2017). However, the association between higher accelerometer-measured LPA and a lower odds of depressive symptoms contrasts with those earlier findings. While we could not look further into the context of the PA, the domain and type of PA might explain our results, as, for example, work-related PA has been found to be unfavourably associated with mental health (White *et al.* 2017), and different types of exercise have also been found to have different effect sizes on depression (Noetel *et al.* 2024).

6.3 Comparing the associations of 24-hour movement behaviours with depressive symptoms between urban and rural residents (Study III)

In Study III, we found that the composition of 24-hour movement behaviours (including MVPA, LPA, ST and sleep) was associated with depressive symptoms among both urban and rural residents in Finland. Yet, when looking at the individual behaviours, there were differences between urban and rural residents. More relative time spent in SB was associated with higher depressive symptoms among urban residents, while more relative time spent in LPA was associated with higher depressive symptoms and more sleep was associated with lower depressive symptoms among rural residents.

The theoretical time reallocations showed that among urban residents, reallocating time from ST to MVPA or LPA was associated with lower depressive symptoms, while among rural residents, reallocating time from LPA or ST to MVPA was associated with lower depressive symptoms. In our study, urban residents had lower amount of LPA compared to rural residents, which might partly explain our results. Previous umbrella review has also shown that while MVPA seems to have a beneficial effect on depression, LPA seems not to have a similarly strong effect (Singh *et al.* 2023). There could be several explanations for this. First, it could be that LPA is insufficient to trigger the hormonal and neurological changes associated with depressive symptoms (Arent *et al.* 2020). Secondly, PA affects depressive symptoms also through psychosocial factors (Kandola *et al.* 2019). It could be that MVPA is more often voluntary and more enjoyable leisure-time PA compared to LPA, which could be related to work or household PA, for example. Although we could not differentiate the context of PA in this study, previous research suggests that mental health benefits may differ between different domains of PA (White *et al.* 2017), and some types of exercise (such as walking, jogging, yoga and strength training) have also been found to be particularly beneficial for depression (Noetel *et al.* 2024).

More time spent in sleep at the expense of ST was associated with lower depressive symptoms both among urban and rural residents, and among rural residents, more time spent in sleep at the expense of LPA was also associated with lower BDI score. Poor sleep has previously been found to predict the onset of depression and even disability retirement due to depression in Finland (Paunio *et al.* 2015). In Study I, we also found that sleep disturbances were more common in the NFBC1966 sample compared to population-based samples from other countries (Seppänen *et al.* 2022). As sleep disturbances are prominent symptoms of depression, treating them is especially important for improving outcomes and preventing depression from recurring (Fang *et al.* 2019).

Reallocating time from ST to any other behaviour was associated with lower depressive symptoms among urban residents, and reallocating time from ST to MVPA or sleep among rural residents. A harmful association of more time spent in SB with depressive symptoms and a benefit from substituting SB with other behaviours are consistent with previous research suggesting that more time spent in SB is associated with a higher risk of depressive symptoms (del Pozo Cruz *et al.* 2020; Huang *et al.* 2020; Kandola *et al.* 2021).

Overall, Study III's results are in line with the ecological model of PA determinants (Bauman *et al.* 2012), which suggests that in later adulthood, environmental factors play a more important role in movement behaviours. The results also highlight the need to consider all movement behaviours together, as they are highly interrelated. We found that less time spent in SB was associated with lower depressive symptoms among urban residents, and spending more time in MVPA and sleep was associated with lower depressive symptoms among rural residents. It is important to note that these behaviours are also mutually supportive: PA can improve sleep quality (Kredlow *et al.* 2015), especially MPA (Wang & Boros 2021), also in individuals with depression or depressive symptoms (Brupbacher *et al.* 2021), while sufficient sleep has been associated with higher leisure-time PA (Wennman *et al.* 2014).

6.4 Strengths of the study

This study has several strengths. The NFCB1966 birth cohort, used in all three studies, is a unique, large, systematically collected, population-based dataset. The cohort includes the entire age group born in 1966 in Northern Finland, from whom extensive background information has been collected. This design minimises sample bias, and the data are representative of similar age groups of the same ethnicity, including both sexes and participants from different educational and occupational backgrounds. As all participants lived in Finland, the risk of bias due to cultural, climatic or other geographical factors is low. The participation rate was relatively high, with 7,146 (69.2%) participants responding to the postal questionnaires and 5,832 (56.5%) attending the clinical examinations (Nordström *et al.* 2022).

This study also provided a unique geographical perspective on PA behaviour and depressive symptoms, as the different scales provide a comprehensive understanding of how geographical context influences PA behaviour and depressive symptoms. In addition, Study II examined several objectively measured residential environment characteristics, including the presence, distance and volume of different built and natural environment features, based on several high-quality datasets.

Studies II and III used several different methods for measuring PA. Study II used a wrist-worn accelerometer and self-report questionnaires, while Study III used a hip-worn accelerometer. In Study II, the different measurement types complemented each other and provided valuable information on the frequency, volume and context of PA when examined together in association with environmental characteristics and depressive symptoms. The accelerometers were also worn for an exceptionally long period. In Study III, the accelerometer-measured ST and self-reported sleep data were combined with the PA data, allowing all of the 24-hour movement behaviours to be examined using a compositional data analysis approach. This was the first time that this approach was used when studying the associations between urban/rural environments, movement behaviours and depressive symptoms, providing a more comprehensive understanding of how these factors interact.

Depressive symptoms were assessed in all studies using the same BDI-II questionnaire, which improves the comparability of the studies.

6.5 Limitations of the study

The major limitation of this study is its cross-sectional design, which restricts the ability to draw causal interpretations. Reverse causality is a significant concern when studying the association between PA and depressive symptoms, as individuals with depression tend to be less active (Schuch *et al.* 2017). It is also known that the association between sleep disturbance and depression is bidirectional (Fang *et al.* 2019). The association between urbanicity and depression, for example, can also be very complex. According to Sampson *et al.* (2020), 'the healthy migrant effect' suggests that those with more resources are more likely to move to urban areas. On the other hand, the opposite may also be true if, for example, those suffering from mental illness move to urban areas where health care facilities are closer (Lankila *et al.* 2013). Separating the effects of living in a certain area from the underlying reasons of migration is especially difficult in cross-sectional studies.

Despite the high participation rate of the NFBC1966, it is important to note that participants were more often women, employed and from higher social classes. They were also more likely to be married, have children and have higher education (Nordström *et al.* 2022). While the representativeness is good for populations with similar backgrounds, generalizability to other age groups, ethnicities or cultures may be limited. On the other hand, Study I compared the NFBC1966 with populations of different ages from other countries, selected using varying sampling methods, which may have influenced the results.

In this study, depression was measured using a self-assessment tool, which only allowed for the evaluation of depressive symptoms rather than diagnoses. Clinical evaluation is always necessary in addition to a questionnaire when diagnosing depression. Using a survey makes it possible to examine symptoms' prevalence and determinants at the population level, including all participants instead of only those with a diagnosis. However, all questionnaires are also limited by potential response bias, which in the case of the BDI-II can include issues such as exaggeration or denial of symptoms (Beck *et al.* 2005). Furthermore, in Study II, the cut points for the BDI-II were used to assess the level of depressive symptoms (no symptoms, mild, moderate and severe), which might introduce bias because different cut points are recommended for healthy populations, primary care and psychiatric settings (von Glischinski *et al.* 2019).

We used various methods for measuring PA, but we could not differentiate between different domains of PA; however, there is evidence suggesting that, for example, leisure-time PA and occupational PA have different associations with mental health (White *et al.* 2017). With self-reports of PA, there is always the risk of bias through recall or social desirability (Prince *et al.* 2008). Although participants wearing accelerometers were advised not to change their daily behaviour, it is possible that they became more active during the measurement period. This potential change in behaviour, known as the 'Hawthorne effect', occurs when individuals alter their behaviour because they are aware of being observed. However, this effect's underlying mechanisms and magnitude are not well understood (McCambridge *et al.* 2014). From the accelerometer data, we combined moderate- and vigorous-intensity physical activities together as MVPA in Studies II–III, and in Study III, standing still was classified as LPA. These decisions could have led to a potential bias in our results, as higher-intensity PA might have a stronger effect on depression (Singh *et al.* 2023). The eligibility criterion of at least 4 valid days with 10 hours of accelerometer wear time during each day may have also influenced our results. It is possible, that requiring at least 7 valid days could more effectively minimise the variation in ST and PA patterns and levels that has been found (Ekblom-Bak *et al.* 2015) between weekdays and weekends.

In Study III, we used compositional data analysis, which is a novel technique for studying the movement behaviour of the 24-hour day. However, there are some limitations when using the compositional data analysis approach. Since the analysis uses log-transformation, zero values (i.e., no time spent on a certain behaviour in a day) can be problematic (Gupta *et al.* 2018). In addition, studies using compositional data analysis and those using more 'traditional' approaches may not be directly comparable. It should also be noted that in our analyses, sleep was self-reported and based on an single estimated value, which might be less accurate than accelerometer-measured PA and ST, even though an earlier study found that the differences between self-reported and accelerometer-measured sleep duration were most likely small (Lauderdale *et al.* 2006).

The measurements of residential environment characteristics were based on quantitative data, the quality of the residential environment was not assessed, and no data was available on perspectives, opinions, motivators, etc., related to the residential environment. For example, the quality of green areas was not considered. We also had no data on factors such as traffic noise, safety or neighbourhood SES, which could be associated with depression (Generaal *et al.* 2019). Individuals with higher SES have been found to reside in areas with more greenness (Liu *et al.* 2021; Sharifi *et al.* 2021). On the other hand, in Finland, green areas are very common, which might result in bias and false conclusions when comparing this study's findings to those from different countries. Another major limitation is the way the residential environment was defined in Study II. Buffers are artificial estimates of the residential environment, and no data on where people actually spend their time was available in this study. Different units of the residential environment have been shown to result in different health outcomes, making it difficult to compare studies using different units (Laatikainen *et al.* 2018).

6.6 Ethical considerations

NFBC1966 and this study were carried out following the guidelines of the Finnish Advisory Board on Research Integrity and the Declaration of Helsinki. They followed the legislation, decrees and ethical principles concerning medical research on humans in Finland and EU and national laws and recommendations. All data collection, storage and publication in NFBC1966 respect the participants' privacy, and the subjects' personal data are protected using code numbers. National and international (General Data Protection Regulation) standards and recommendations concerning data transfer and protection were followed. By using the data in multiple studies, the need for new data collection was reduced, and the environmental impact associated with large-scale data collection was minimised. This conserved resources and honoured the participants' contributions by extracting maximum value from the data they provided.

6.7 Future research prospects

Longitudinal studies are needed to confirm this study's findings. Although PA's benefits on depression are well established based on prospective studies (Pearce *et al.* 2022), evidence on, for example, greenness and urbanicity on depression or PA is mixed or mostly based on cross-sectional studies (Rautio *et al.* 2018; Sampson *et al.* 2020; Yang *et al.* 2021). Without longitudinal evidence, it is difficult to establish causality or understand these factors' long-term effects on depressive symptoms. As evidence is also lacking for the mediators of green space exposure and mental illness, further research is needed on the role of these factors, namely PA, air quality, perceived stress, perceived restorativeness, residential noise, social cohesion, and social support (Zhang *et al.* 2021). In addition, it should be noted that several systematic reviews and meta-analyses have combined diagnosis-based depression and depressive symptoms as the outcome of interest, which may affect the results obtained. In future reviews, it may be useful to specify whether the outcome of interest is diagnosed depression or depressive symptoms, as the associations with, for example, PA may be different.

This study examined depressive symptoms and their association with PA across different geographical scales, with varying findings in each setting. These findings highlight the importance of considering the environment in which we live and where our experiences take place. In Study I, we found that depressive symptoms vary between countries, and further research is needed to understand the underlying reasons for these differences, which may include varying norms and values influencing how people perceive and express their emotions. All of our behaviour occurs in a spatial context, and future studies should also explore these interactions further, using more detailed information about the spaces where people actually spend their time and how this affects their health. Combining objective measures of the residential environment, such as satellite imagery or data on road networks and services, with subjective data, such as where and why individuals engage in PA, could be one recommended approach for future research. Furthermore, combining different methods to assess PA, for example accelerometers, GPS-tracking and PPGIS-surveys, could help better understand the environmental factors that promote or limit PA.

The 24-hour perspective on movement behaviours offers a comprehensive approach that should be further developed to gain more detailed information on the health impacts of movement behaviours. Prospective study designs are needed in future when studying 24-hour movement behaviours. One possibility offered by the 24-hour approach is to determine the optimal composition of movement behaviours for different health outcomes, sometimes referred to as the 'Goldilocks day' (Dumuid *et al.* 2020). Another interesting future research topic could be to examine in more detail how the periods, breaks and rhythms of movement behaviours are associated with health. For example, sleep should be studied further together with PA and SB, while examining sleep rhythm and its association with depressive symptoms and PA. Additionally, with more detailed information on the context of PA, future research should clarify how the domain, intensity and type of PA are associated with mental health when considering the behaviours of the entire 24-hour day.

6.8 Practical implications

This study's results should be taken into account in urban planning solutions to create healthier living environments. It has been suggested that green areas might be more beneficial to those with lower SES, thus offering an opportunity to increase health equity (Rigolon *et al.* 2021). The results from Study II imply, that green spaces should be increased and reserved, especially in densely populated urban areas where the risk of depression may be higher. The 3-30-300 rule introduced by Konijnendijk (2023) provides a practical guideline for urban forestry: every home, school or workplace should have a view of at least three mature trees, the tree canopy in every neighbourhood should be at least 30%, and the distance to the nearest public green space from every residence should be 300 m or less.

In addition, this study provides valuable information for health professionals on the relationship between the residential environment, PA and depressive symptoms. This study's results support the use of nature prescriptions (Stanhope & Weinstein 2023) and the promotion of PA as a way to support mental health. In particular, the results of Study III highlight the important beneficial effects of MVPA and sufficient sleep on depressive symptoms, which also emphasises the 24-hour perspective of our movement behaviours. This knowledge should be taken into account in PA counselling and when updating PA guidelines, including more detailed recommendations for SB and sleep, following the Canadian recommendations (Ross *et al.* 2020). The amount of MVPA seems to be particularly low in rural areas, so the promotion of meaningful, motivating opportunities to engage in MVPA is especially important for rural residents.

7 Conclusions

Based on the aims of this study, it can be concluded that:

1. There were significant differences in several BDI-II item scores between countries, possibly due to cultural differences.
2. Higher population density and urbanicity level were associated with higher odds of experiencing more severe depressive symptoms, and higher residential greenness with lower odds of having more severe symptoms, irrespective of self-reported and accelerometer-measured light physical activity and moderate to vigorous physical activity.
3. The composition of 24-hour movement behaviours was associated with depressive symptoms in both urban and rural residents. For urban residents, lower relative time spent in sedentary behaviour was associated with lower depressive symptoms. For rural residents, higher relative time spent in moderate to vigorous physical activity or sleep at the expense of light physical activity or sedentary time was associated with lower depressive symptoms.

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