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Greenery exposure and suicide mortality later in life: A longitudinal register-based case-control study

Marco Helbich[a,*], Rory C. O'Connor[b], Marc Nieuwenhuijsen[c], Paulien Hagedoorn[a]

[a] Department of Human Geography and Spatial Planning, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands
[b] Suicidal Behaviour Research Laboratory, Institute of Health and Wellbeing, University of Glasgow, Glasgow, Scotland, United Kingdom
[c] ISGlobal, Barcelona, Catalonia, Spain

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ABSTRACT

Background: Exposure to residential greenery accumulates over people's lifetimes, and possibly has a protective association with suicide later in life.
Objectives: To examine the associations between suicide mortality and long-term residential greenery exposure in male and female adults.
Methods: Our population-based nested case-control study used longitudinally georeferenced Dutch register data. Suicide cases aged 18–64 years between 2007 and 2016 were matched by gender, age, and date of suicide to 10 random controls. We measured long-term greenery exposure along people's 10-year residential address histories through longitudinal normalized difference vegetation indices (NDVI) from Landsat satellite imagery between 1997 and 2016. We assigned accumulated greenery exposures, weighted by people's exposure duration, within 300, 600, and 1,000 m concentric buffers around home addresses. To assess associations between suicide and greenery, we estimated gender-specific conditional logistic regressions without and with adjustment for individual-level and area-level confounders. Stratified models were fitted for areas with a high/low level of urbanicity and movers/non-movers.
Results: Our study population consisted of 9,757 suicide cases and 95,641 controls. In our models adjusted for age, gender, and date of suicide, the odds ratios decreased significantly with higher quartiles of accumulated NDVI scores. NDVI associations were attenuated and did not remain significant after adjustment for socio-economics, urbanicity, air pollution, social fragmentation, etc. for either males or females. For females, but not males, our model with 300 m buffers for areas with a low level of urbanicity showed a significant suicide risk reduction with increasing levels of NDVI. Individual risk factors (e.g., lack of labor market participation) outweighed the contribution of greenery.
Conclusion: We found limited evidence that long-term greenery exposure over people's lifetimes contributes to resilience against suicide mortality. Ensuring exposure to greenery may contribute to suicide prevention for specific population groups, but the effectiveness of such exposure should not be overstated.

1. Introduction

Suicide accounts for 800,000 premature deaths worldwide each year and poses a persistent global health challenge (World Health Organization, 2014). The pathways to suicide are complex (O'Connor and Nock, 2014; Franklin et al., 2017; Turecki et al., 2019), with evidence mounting that environmental conditions within a person's living environment have neurobiological effects that might play a role in suicide mortality (Lambert et al., 2015; Tost et al., 2015; Rehkopf and Buka, 2006).

Empirical investigations into the extent to which environmental exposures are associated with suicide are evolving only slowly (Helbich, 2018). There is tentative evidence for air pollution being associated with suicide mortality (Gu et al., 2019), but other environmental exposures such as greenery (e.g., parks, forests) have received little attention (Helbich et al., 2018). Although there is no consensus about the mechanisms underlying the mental health benefits of greenery (Nieuwenhuijsen et al., 2017; Bratman et al., 2019), a number of

* Corresponding author at: Department of Human Geography and Spatial Planning, Faculty of Geosciences, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, the Netherlands.
E-mail addresses: m.helbich@uu.nl (M. Helbich), Rory.OConnor@glasgow.ac.uk (R.C. O'Connor), mark.nieuwenhuijsen@isglobal.org (M. Nieuwenhuijsen), p.hagedoorn@uu.nl (P. Hagedoorn).

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psychophysiological pathways have been suggested, for example, that greenery reduces negative emotions (Kaplan, 1995) and supports stress recovery (Ulrich et al., 1991).

Experimental studies using neurobiological imaging have shown that short-term exposure to greenery reduces neural activities in those areas of the brain thought to be associated with mental illness (Bratman et al., 2015). Similarly, observational research—mainly cross-sectional and rarely longitudinal in nature—suggests a dose–response relationship between long-term exposure to greenery in the residential environment and resilience against psychiatric disorders (van den Bosch and Meyer-Lindenberg, 2019; Engemann et al., 2019; Klompmaker et al., 2019), which is likely to be independent of people's demographic, psychological, behavioral, socioeconomic, and genetic predispositions. However, whether analogous mechanisms translate into a reduction in suicide mortality is unknown. Since suicide is a leading cause of death (Naghavi, 2019), greenery as a modifiable environmental factor warrants attention in our attempts to mitigate suicide mortality.

Only a few studies have examined the relationship between greenery exposure and suicide, and they yielded contradictory findings (Helbich et al., 2018; Bixby et al., 2015; Shen and Lung, 2018; Min et al., 2017; Mitchell and Popham, 2008). We contend that these discrepancies may be due to differences in methodology and conceptualization. First, previous studies relied on ecological research designs; such studies are therefore substantially confounded due to a lack of adjustment for individual-level factors (Chang and Gunnell, 2018). Second, the predominant practice was to measure greenery cross-sectionally where people lived at the time of death (Helbich, 2018).

However, as outlined in the integrated motivational–volitional model of suicidal behavior (O'Connor and Kirtley, 2018), the factors leading to suicide can be distal—for example, environmental influences across the lifespan—as well as proximal, for instance, entrapment. To assess whether long-term greenery has long-lasting effects on suicide mortality later in life, it is thus necessary to consider accumulated within-person variation in greenery exposure longitudinally over people's lifetimes (Helbich, 2018). Such a life course-oriented perspective (Kuh et al., 2003) is particularly important because the levels of greenery people are exposed to may change due to moving to another residential place (Alcock et al., 2014) and/or due to changes in the residential environment itself (Pearce et al., 2018), which may be particularly marked due to ongoing urbanization (Bratman et al., 2019).

To address this knowledge gap, we examined associations between suicide mortality and long-term greenery exposure separately for males and females. Based on longitudinal and georeferenced Dutch register data between 2007 and 2016, we hypothesized that males and females who are exposed to more residential greenery over time have an attenuated suicide risk later in life. Unlike previous studies, we considered people's individual trajectories of long-term exposure to greenery over their 10-year residential address histories.

2. Methods

2.1. Study design and population

This nested case-control study for the Netherlands had nationwide coverage based on longitudinal register data. Dutch national registers covering the whole population were linked on a person-by-person basis and georeferenced at an address level. Data linkage relied on anonymized unique personal identification codes assigned to each resident. Our initial study population (Fig. 1) included all officially registered people aged 18–64 years legally residing in the Netherlands between January 1, 2007 and December 31, 2016 (N = 14,171,753).

2.1.1. Suicide cases

We considered all officially recorded suicide cases aged 18–64 years between January 1, 2007 and December 31, 2016 as outcome variable.

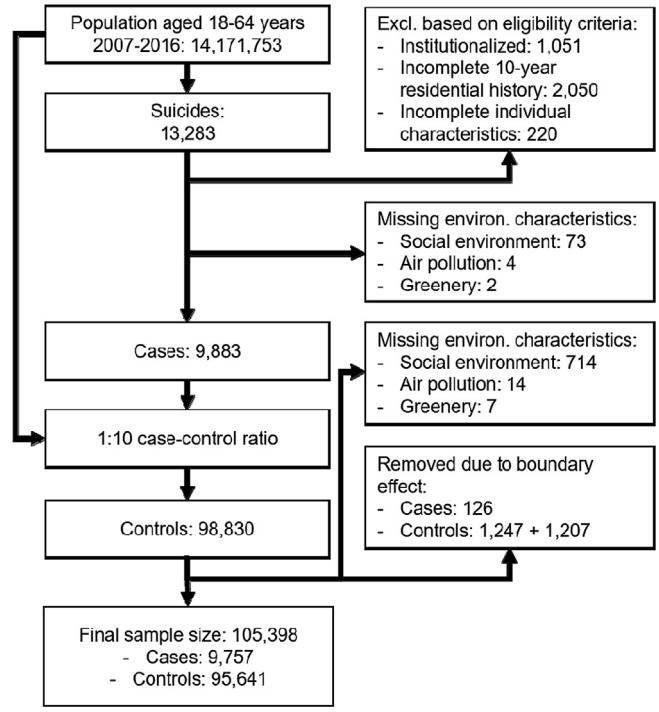

Fig. 1. Study population selection from registers.

Suicides coded as X60.0–X84.9 according to the 10th edition of the International Statistical Classification of Diseases and Related Health Problems were extracted from the cause of death register. The following eligibility criteria applied to each case (Fig. 1): (a) not institutionalized (N = 1,051 excluded), (b) complete 10-year Dutch residential history (N = 2,050 excluded), and (c) non-missing individual characteristics (N = 220 excluded). Cases with missing area-level characteristics (i.e., social environment (N = 73), air pollution (N = 4), and greenery (N = 2)) were also excluded. We removed cases (N = 126) who had ever lived within 1,000 m of the German or Belgian border in order to avoid boundary effects due to data being unavailable in those countries. In total, our study population included 9,757 suicide cases.

2.1.2. Controls

To minimize selection bias, controls were drawn randomly from the entire source population aged 18–64 years applying similar eligibility criteria (Kass and Gold, 2005). For each case, we randomly sampled 10 controls with the same age and sex who were alive at the date of suicide, by means of incidence-density sampling and matching (N = 98,830) (Keogh and Cox, 2014). Controls with a missing value for area-level social characteristics (N = 714), air pollution (N = 14), or greenery (N = 7), or where the matched case was removed (N = 1,247), or had ever lived within 1,000 m of the German or Belgian border (N = 1,207), were excluded (Fig. 1). This resulted in 95,641 valid controls.

2.1.3. Residential history

Data on residential moves were obtained for each case/control from the population register. Each time a change of place of residence occurs in the Netherlands, a record of the date of the move is generated and records of historical moves are retained. The overall period for which data on residential moving were available was January 1, 1997 to December 31, 2016. For each case/control, we included all residential addresses retrospectively over the previous 10 years before the day of suicide or a control's matching date. All locations where cases/controls had ever lived were georeferenced through the cadaster at an address level.

2.1.4. Ethics and data privacy

In line with Dutch privacy legislation, microdata are non-publicly accessible for scientific research in the secure environment of Statistics Netherlands (Reitsma et al., 2003). Data records were fully anonymized. As there was no interaction with subjects, the need for informed consent was waived. The study protocol (Helbich, 2019) was approved by the Ethics Review Board of Utrecht University (FETC17–060).

2.2. Long-term greenery exposure assessment

Exposure to long-term greenery was measured longitudinally for a 20-year period of residential moves. We used satellite-derived normalized difference vegetation indices (NDVI) as exposure metric (Tucker, 1979). The NDVI describes the level of green biomass based on land surface reflectance of visible and near-infrared radiation. The index ranges from +1 to −1. Positive values are indicative of larger amounts of greenery, negative ones of non-biomass (e.g., water).

We obtained all Landsat scenes covering the Netherlands for the period 1997–2016 via the Google Earth Engine cloud computing platform (Gorelick et al., 2017). We considered all Tier 1 satellite imagery scenes (N = 1,651) available from Landsat 5 Multispectral Scanner System (MSS), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) to derive annual NDVI maps at a 30 × 30 m resolution, as detailed in the Supplementary Materials (Table S1) (Chander et al., 2009). Due to seasonal vegetation cycles, we only considered atmospherically corrected scenes collected during the growing season, namely May to September. Scenes with > 40% cloud cover and pixels with a cloudiness score of > 25 were removed. Pixels with non-positive NDVI values (i.e., water bodies) were masked before computing pixel-wise median NDVI composites per year (Ekkel and de Vries, 2017; Helbich, 2019).

Annual mean NDVI scores for concentric exposure areas (buffers) with radii of 300, 600, and 1,000 m centered on actual and past home addresses were computed. We used a 300 m buffer to capture the immediate surroundings, and the larger buffers to capture the greenery within walking distance. Representative Dutch travel data pooled for 2010–14 (N = 92,298, Statistics Netherlands) indicated an average daily walking trip duration of 11.7 min per person, corresponding to a trip distance of 983 m, assuming a walking speed of 1.4 m/s. Up to three missing NDVI scores per address-based time series were imputed by a Kalman filter (Moritz and Bartz-Beielstein, 2017); otherwise the case/control was removed. In total, we imputed 0.071% of the NDVI time series for the 300 m buffer, 0.010% for the 600 m buffer, and none for the 1,000 m buffer.

To establish accumulated greenery exposure, we split each residential history into annual spells and determined the number days of residence at each location during each year. Annual mean NDVI scores were then matched with residential spells based on the corresponding year. Residential duration served as weighting factor for the number of days a case/control lived at an address. We calculated the relative exposure per spell by dividing the number of days a case/control lived at a residential location per spell by the total number of days in the 10-year residential history. We obtained our final accumulated greenery metric by summing the weighted NDVI scores over a person's 10-year residential history.

2.3. Confounders

2.3.1. Individual-level confounders

We adjusted for a comprehensive set of confounders throughout the lifespan (Franklin et al., 2017; Turecki et al., 2019). Register-based confounders were derived at matching date, because adverse life events are suggested to increase suicide risk instantaneously (Hagedoorn et al., 2020). Given our matched design, analyses were implicitly adjusted for age and gender. We considered nationality dichotomized into Dutch and non-Dutch to capture ethnic differences in suicide risk (Termorshuizen et al., 2014). As proxy for socioeconomic status, we collected annual data on standardized household income (in euros) classified into quartiles. Because a lack of labor market participation results in material losses and declining self-esteem, we adjusted for employment status divided into employed, unemployed, or non-working (Nordt et al., 2015). Dysfunctional family background is another risk factor (Agerbo et al., 2002). We included marital status grouped into married, never married, or not currently married, as well as household type coded as couple with children, couple without children, single parent with children, or other.

2.3.2. Area-level confounders

Three area-level confounders were included. Social fragmentation reflects poor community integration (Hagedoorn et al., 2020; Congdon, 2012). It was measured through z-scoring and summing the percentage of adult residents (> 18 years) who were unmarried, lived in a single-person household, and had moved to the address within the previous 12 months. We adjusted for urbanicity (i.e., population density) to model urban–rural differences in suicide mortality (Hirsch and Cukrowicz, 2014). For both confounders, we aggregated the individual characteristics of all residents in the Netherlands on January 1st of each year in the period 1997–2016 within a 300, 600, and 1,000 m buffer centered on a case/control's home address. We incorporated annual average concentrations of particulate matter (PM) with an aerodynamic diameter of < 2.5 μm (Gu et al., 2019). We estimated the $PM_{2.5}$ concentrations (μm/m^3) per address through a land-use regression calibrated with 12 months of measurements at monitoring sites in 2009 (Eeftens et al., 2011; Schmitz et al., 2019). Annual average $PM_{2.5}$ concentrations were predicted by traffic intensity, distance from transportation infrastructure, land use, etc., resulting in good agreement with measured on-site concentrations (Schmitz et al., 2019). To reduce computational demand, $PM_{2.5}$ concentrations were resampled from a 5 × 5 m to a 25 × 25 m grid employing bilinear interpolation. No time series data were available, but annual mean concentrations are stable over 10–15 years (Eeftens et al., 2011; De Hoogh et al., 2018). As for greenery, for each area-level confounder we computed accumulated exposures per buffer (i.e., 300, 600, and 1,000 m) over people's residential moves.

2.4. Statistical analyses

We used descriptive statistics (i.e., mean [μ] and standard deviation [SD]) to summarize the characteristics of the study population. To assess differences in demographics and exposures between cases and controls, we used Chi^2 tests for categorical variables and Kruskal–Wallis tests for continuous ones. We used Spearman correlation coefficients (ρ) to test for bivariate associations between the exposures.

We fitted conditional logistic regressions to assess associations between suicide mortality and accumulated exposure to greenery (Keogh and Cox, 2014). Such models allow for data structures where cases and the matched controls are not independent but belong to the same strata. Non-linear greenery exposure–response functions are possible, but they are poorly captured through linear effects (May and Bigelow, 2005). We therefore assessed the shape of greenery effects with thin-plate regression splines, whereas the level of smoothing is determined in a data-driven way during model fitting (Wood, 2017). A visual inspection and the effective degrees of freedoms were not indicative of complex non-linear exposure–response functions. To reduce the risk of multicollinearity, we replaced the splines with greenery classified into quartiles. We report the regression coefficients as odd ratios (ORs) together with their 95% confidence intervals (CIs).

Due to distinct gender differences in suicide behavior (Turecki and Brent, 2016), we conducted stratified analyses (Hagedoorn et al., 2020). Our incremental modeling strategy had an increasing level of covariate adjustment. Model 1 included greenery and was minimally

adjusted (per design, only for age, sex, and matching time). Model 2 additionally controlled for area-level confounders (i.e., urbanicity, social fragmentation, and $PM_{2.5}$). Model 3 included greenery and nationality, marital status, household type, employment status, and income. Model 4 was fully adjusted for both individual- and area-level confounders.

As secondary analyses, we assessed whether the greenery–suicide association differed across levels of urbanicity by refitting Model 4 with full adjustment. To have enough statistical power, we considered two strata: high (3rd and 4th quartiles; Model 4a) and low (1st and 2nd quartiles; Model 4b) levels of urbanicity per buffer size. Finally, to test the influence of residential mobility, we fitted fully adjusted models stratified for movers (i.e., those who had changed their place of residence at least once; Model 4c) and non-movers (i.e., those who had never changed their place of residence; Model 4d).

To evaluate the robustness of all models, we conducted sensitivity tests concerning the influence of buffer sizes of 300, 600, and 1,000 m on the greenery–suicide association. All statistical analyses were performed with R software (R Core Team, 2019), version 3.6.2.

3. Results

3.1. Description of the study population

In total, our study population included 105,398 persons. We excluded 3400 suicides due to incomplete individual-level data (Fig. 1).

Of the 9,757 persons who died by suicide, 6,748 were male (69.2%) and 3,009 were female (30.8%), as detailed in Tables S2 and S3 in the Supplementary Materials. The study population's mean age was 46.2 years (SD ± 12.0). For the individual-level characteristics nationality, marital status, household type, employment status, and income, we observed significant differences between cases and controls (all $p < 0.001$). The study population had moved, on average, 1.9 times (SD ± 1.2) and stayed at an address for 5.3 years (SD ± 3.7); 54.5% of the cases and 50.9% controls had moved at least once during their 10-year residential histories (Table S2).

3.2. Exposure distribution and correlations

Fig. 2 shows the mean NDVI between 1997 and 2016 across the Netherlands. The level of NDVI declines with increasing levels of urbanicity across the study population (Fig. S1), as evidenced by negative Spearman correlations ($\rho_{300m} = -0.729, p < 0.001$) (Fig. S2). We also observed moderate inverse Spearman correlations between NDVI and fine particulate matter ($PM_{2.5}$) ($\rho_{300m} = -0.280, p < 0.001$), while correlations between urbanicity and $PM_{2.5}$ were positive ($\rho_{300m} = 0.210, p < 0.001$) (Fig. S2).

Suicide cases were exposed to significantly lower NDVI scores, higher $PM_{2.5}$ concentrations, lower social fragmentation, and higher levels of urbanicity than the controls (Table S4). The differences are statistically significant due to our large sample ($p < 0.001$). Our subgroup analyses showed that male suicide cases and male controls were exposed to higher NDVI scores and lower $PM_{2.5}$ concentrations, and resided in less urbanized areas than women (Table S5).

3.3. Associations between greenery and suicide

Fig. 3 summarizes the associations between accumulated NDVI and suicide mortality across the four models and three buffer sizes for males, females, and total suicide mortality. Tables S6–S8 present all the model results.

The minimally adjusted Model 1—which controlled only for age, gender, and date of suicide—showed for males, females, and the total population, that people who live in neighborhoods with above-average NDVI levels (3rd and 4th quartiles) had a significantly lower suicide risk than those in neighborhoods in the lowest NDVI quartile. Additional adjusting for social fragmentation, urbanicity, and $PM_{2.5}$ in Model 2 showed that the inverse associations were not robust for males, females, or the total population. Only adjusting for individual-level characteristics in Model 3 resulted in partly positive associations in the upper quartiles; these are likely to be biased results arising from the neglect of area-level confounders. Model 4 showed no significant associations between greenery and suicide risk. Different buffer sizes did not alter these results.

3.4. Subgroup analyses

In our secondary analyses (Fig. 4, Tables S9–S11), we examined differences in NDVI–suicide associations by refitting Model 4 for areas with a high (Model 4a) and a low level of urbanicity (Model 4b). Associations differed across both strata; albeit statistical significance was reached only for the 300 m buffers. With increasing buffer sizes, the differences between areas with high and low levels of urbanicity diminished. For females in areas with a low level of urbanicity (Model 4b), the odds for the 2nd to 4th NDVI quartiles showed a significantly larger suicide risk reduction than for those exposed to low NDVI levels (1st quartile). Independent of the buffer size, we did not obtain similar results when considering males or pooling males and females for areas with a low level of urbanicity. For females in the 4th quartile of NDVI levels in areas with a high level of urbanicity, we found an increase in suicide risk. There was no sign of an association for males. Refitting Model 4 with people who had changed their residential location at least once (Model 4c) and those who had never moved (Model 4d) showed no statistically significant associations.

3.5. Associations between individual- and area-level factors and suicide

Independent of gender, we found strong evidence that people who were unemployed or non-working were at high suicide risk (Tables S6–S8). Single parents also had an elevated risk of suicide. Marriage seems to have a protective effect against suicide. We found that males with high incomes had a reduced suicide risk; for females, the association was insignificant. Dutch people were at higher risk than non-Dutch people. We observed that males living in areas with a high level of urbanicity and those in more socially fragmented neighborhoods had a reduced risk. Among the females, $PM_{2.5}$, urbanicity, and social fragmentation were not statistically significantly associated with suicide mortality.

4. Discussion

4.1. Key findings

Our large, nested population-based case-control study in the Netherlands broke new ground by examining for the first time long-term greenery–suicide associations at an individual level. The results of our minimally adjusted models controlling for age, gender, and date of suicide showed that males and females who were exposed to pronounced long-term greenery over their residential life courses had an alleviated suicide risk later in life. However, the inverse greenery–suicide association was rendered not significant once a comprehensive individual- and area-level adjustment was made, thus refuting our initial hypothesis.

Our findings are not in line with stress reduction theory (Ulrich et al., 1991) or attention restoration theory (Kaplan, 1995). Both theories propose that people's psychological and physiological functioning is positively stimulated by greenery, which helps them to cope with stressful life events and emotional pain, relieves stress, supports their reflections on life (Hartig et al., 2014), and therefore makes people less vulnerable to the emergence of suicidal thoughts, as hypothesized (Helbich et al., 2018). However, our findings that social disadvantage (e.g., lack of employment, single parents) appear to account for the

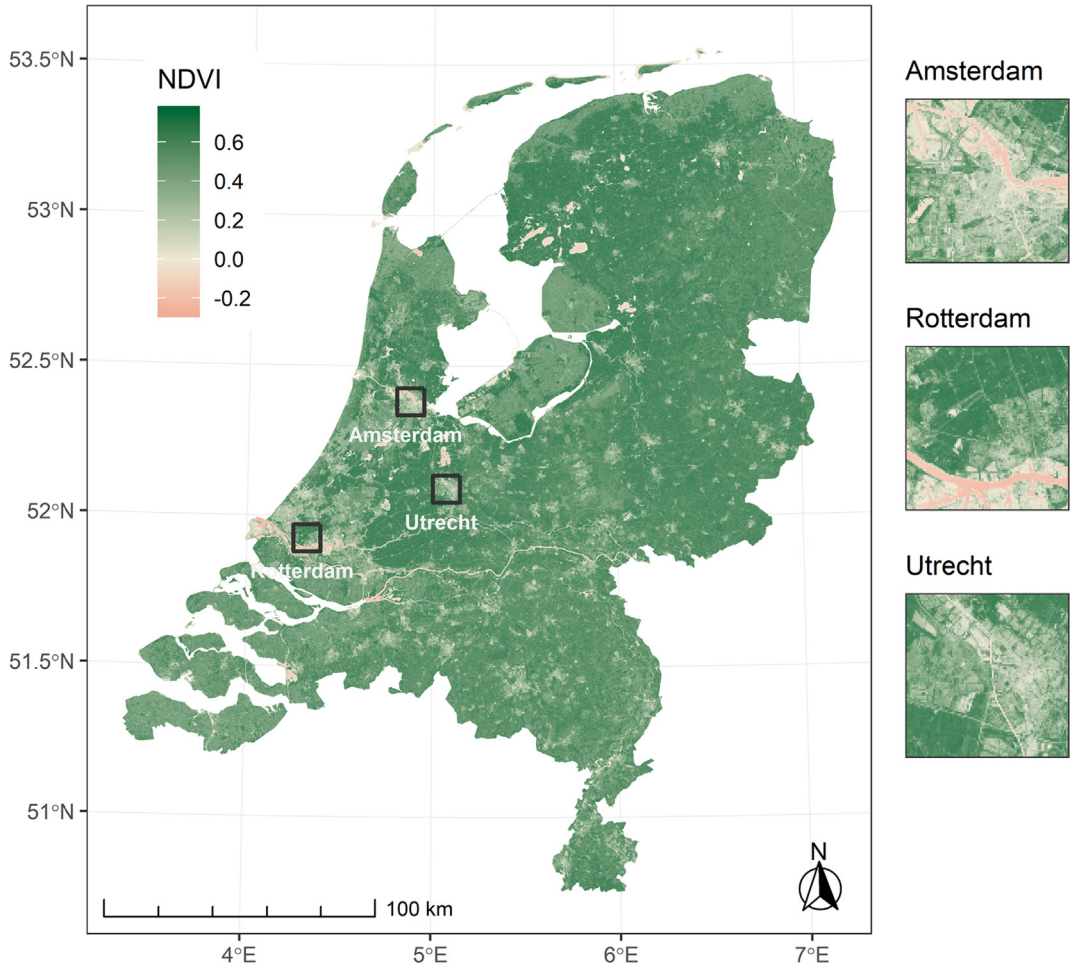

Fig. 2. Mean NDVI scores for the period 1997–2016 across the Netherlands. Panels on the right show the NDVI scores for the country's three major cities, namely Amsterdam, Rotterdam, and Utrecht. Annual mean NDVI maps were computed for May–September based on Landsat 5 MSS, Landsat 7 ETM+, and Landsat 8 OLI data. Higher positive values represent larger amounts of vegetation, lower values represent scarce vegetation, and negative values capture non-biomass (e.g., water).

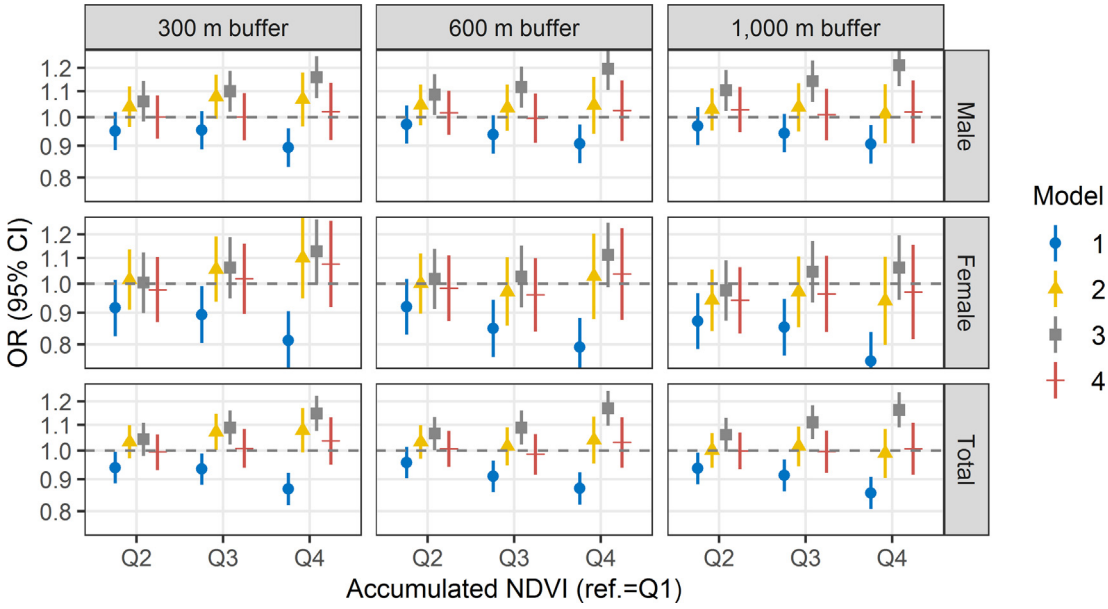

Fig. 3. Odds ratios (ORs) and 95% confidence intervals (CIs) for quartiles of accumulated NDVI scores at the place of residence associated with male, female, and total suicide mortality across a 300, 600, and 1,000 m exposure window (buffer). ORs were estimated with conditional logistic regression models. Model 1 was adjusted for age, gender, and date of suicide through matching. Model 2 was additionally adjusted for area-level confounders. Model 3 included greenery and individual-level confounders. Model 4 included both individual-level and area-level confounders. The area-level confounders were classified into quartiles in our regression analyses to limit multicollinearity. All estimates are relative to the reference category (i.e., the lowest NDVI quartile [Q1]).

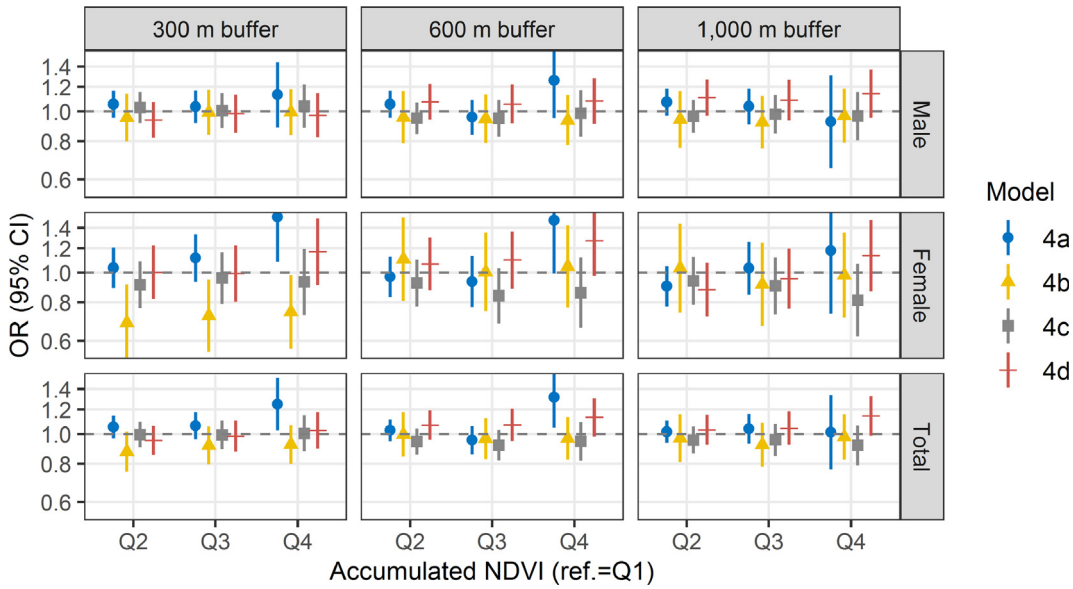

Fig. 4. Odds ratios (ORs) and 95% confidence intervals (CIs) for quartiles of accumulated NDVI scores at the place of residence associated with male, female, and total suicide mortality across a 300, 600, and 1,000 m buffer stratified for areas with a high level of urbanicity (Model 4a), a low level of urbanicity (Model 4b), movers (Model 4c), and non-movers (Model 4d). Models were fully adjusted and estimates are relative to the lowest NDVI quartile (Q1).

relationship between greenery exposure and suicide risk is consistent with the integrated motivational–volitional model of suicide (O'Connor and Kirtley, 2018). According to this theoretical model, distal factors such as environmental exposures mostly affect suicide risk by increasing or decreasing more proximal risk factors, such as mental distress or social connectedness. The present findings therefore emphasize the importance of targeting the social and psychological mechanisms that may account for the environment–suicide risk relationship.

Our finding that a exposure–response relationship is absent is consistent with a study carried out in England (Mitchell and Popham, 2008), but not with an ecological Dutch study that reported a protective correlation between suicide risk and increasing levels of greenery exposure (Helbich et al., 2018). Similarly, larger and less fragmented patches of greenery were protectively associated with suicide in Taipei, Taiwan (Shen and Lung, 2018), while Korean adults living in districts with a low availability of greenery were found to have an 18% higher risk of suicide ideation and a 25% higher risk of suicide attempts (Min et al., 2017). Caution is urged when making comparisons with these earlier studies, however, because we benefited from individual-level data with almost perfect coverage of the entire Dutch population; as a result, the present findings were less susceptible to individual-level confounding (Chang and Gunnell, 2018).

A stratification into areas with high and low levels of urbanicity as well as movers and non-movers also showed no indication of an association between greenery and suicide mortality, for either females or the total suicide mortality. These results corroborate an ecological study in the 50 largest cities in England (Bixby et al., 2015). In contrast, we found—particularly for the 300 m buffer—that females living in highly urbanized areas face a pronounced suicide risk when they are exposed to the highest greenery level. We speculate that this may be because other factors that are not taken into account could be at play. However, females in rural settings faced a significantly lower suicide risk due to increased exposure to greenery. The reasons why greenery is a protective factor in rural but not in urban areas are difficult to establish. We speculate that differences in the quality, distribution, and amount of greenery may play a role—a claim also made elsewhere (Bratman et al., 2019; Ekkel and de Vries, 2017). Urban greenery is usually patchy and small in size. It is composed of artificially installed parks and often solitary street trees, and this impedes both visual and physical access. Conversely, rural greenery with its pronounced diversity (Pett et al., 2016) is primarily composed of agricultural areas and forests, which may be experienced as more natural. When visual greenery, which is known for its health benefits (Ekkel and de Vries, 2017), is the predominant land cover, it may have a particularly calming effect, which in turn possibly reduces suicidal thoughts. Future research is required to tease apart the nature of the direct protective effect of greenery exposure on suicide risk for males residing in rural communities.

4.2. Strengths and limitations

Our study was the first to assess the link between long-term greenery exposure and suicide mortality. A strength of our study was the application of individual-level data from national registers linked with cadastral information and high-resolution time series of remote sensing imagery to capture people's residential greenery exposure histories at an address level (Hagedoorn et al., 2020). Because Dutch register data underwent in-depth validation and were found to be of the highest quality (de Bruin et al., 2004), we can exclude any underreporting or misclassification of suicide cases. The large number of suicide cases provided sufficient statistical power to assess environmental exposures with reduced effect sizes given the adjustment for numerous covariates.

Instead of assigning greenery exposures at a single point in time, our methodologically rigorous long-term greenery exposure assessment considered environmental changes in terms of longitudinal greenery data spanning two decades, as well as exposure variations due to relocation based on the exact moving date, which makes spatiotemporal contextual uncertainties in exposure assessments less likely (Helbich, 2019). Moreover, we took advantage of our georeferenced registers by calculating multiple area-level indicators at an address level.

Although our study broke new ground, we need to emphasize some limitations, many of which are typical of observational studies such as ours. We matched each case to 10 controls, because a full population analysis with >14 million people would have been too computationally demanding. However, it has been shown that such a case–control ratio results in virtually similar estimates as a full population analysis (Essebag et al., 2005; Breslow et al., 1983). Despite our longitudinal study design, it is difficult to infer causation from any observational study.

Register data are intrinsically constrained by the number of available variables. Thus, some variables (e.g., past suicide attempts) were likely to be missing. Moreover, our data did not allow us to assess people's attitudes toward and motives for selecting residential neighborhoods. Thus, residential self-selection—namely that suicidal people tend to reside in residential areas with less greenery—remains an issue, but the bias was found to be marginal (James et al., 2015).

Although there is no universally accepted metric for greenery assessments, ours permitted us to develop 20-year time series for every residential location. The NDVI was not capable of distinguishing different types of greenery, nor did it indicate how people actually made use of it (Ekkel and de Vries, 2017). Finally, even though the residential living environment remains a key anchor in people's lives, our metric omitted other sources of greenery exposure during people's day-to-day activities (e.g., at work) (Helbich, 2018).

5. Conclusions

This longitudinal register linkage study found limited evidence that long-term exposure to greenery along people's residential address histories contributes to resilience against suicide mortality later in life. Whether a protective association between greenery and suicide mortality could be observed was dependent on the level of confounder adjustment. The inverse greenery effect remained significant after full adjustment only for females residing in low urbanized areas. Exposure to greenery may contribute to some extent to suicide prevention for specific population groups, but the effectiveness of such exposure should not be taken as being more important than individual-level risk factors. In order to substantiate our findings, additional life course-based research is warranted.

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Author contributions

MH developed the research idea and developed the study design together with PH. PH prepared and linked the register data. MH carried out the analyses and drafted the manuscript. All authors contributed to the interpretation of the findings. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics statement

Ethical approval (FETC17–060) was obtained from the Ethics Review Board of the Faculty of Social and Behavioral Sciences of Utrecht University.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.105982.

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