**Urban green spaces and suicide mortality in Belgium (2001-2011): a census-based longitudinal study**

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**Abstract**

Background

Exposure to green spaces is associated with improved mental health and may reduce risk of suicide. Here, we investigate the association between long-term exposure to residential surrounding greenness and suicide mortality.

Methods

We used data from the 2001 Belgian census linked to mortality register data (2001-2011). We included all registered individuals aged 18 years or older at baseline (2001) residing in the five largest urban areas in Belgium (n=3,549,514). Suicide mortality was defined using the tenth revision of the World Health Organisation International Classification of Diseases (ICD-10) codes X60-X84, Y10-Y34, and Y870. Surrounding greenness was measured using the Normalized Difference Vegetation Index (NDVI) within a 300m and 1,000m buffer around the residential address at baseline. To assess the association between residential surrounding greenness and suicide mortality, we applied Cox proportional hazards models with age as the underlying time scale. Models were adjusted for age, sex, living arrangement, migrant background, educational attainment, neighbourhood socio-economic position. We additionally explored potential mediation by residential outdoor nitrogen dioxide (NO2) concentrations. Finally, we assessed potential effect modification by various socio-demographic characteristics of the population (sex, age, educational attainment, migrant background, and neighbourhood socio-economic position). Associations are expressed as hazard ratios and their 95% confidence intervals (CI) for an interquartile range (IQR) increase in residential surrounding greenness.

Results

We observed a 7% (95%CI 0.89-0.97) and 6% (95%CI 0.90-0.98) risk reduction of suicide mortality for an IQR increase in residential surrounding greenness for buffers of 300m and 1,000m, respectively. Furthermore, this association was independent of exposure to NO2. After stratification, the inverse association was only apparent among women, and residents of Belgian origin, and that it was stronger among residents aged 36 or older, those with high level of education, and residents of most deprived neighbourhoods.

Conclusion

Our results suggest that urban green spaces may protect against suicide mortality, but this beneficial effect may not be equally distributed across all strata of the population.

**Key words**: Suicide mortality; Greenspace; surrounding greenness; urban health; longitudinal study

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**Ethical considerations**

This research makes use of secondary administrative data. Data management and linkage were executed according to the Belgian privacy legislation and were approved by the Belgian Commission for the Protection of Privacy.

**Introduction**

According to the World Health Organisation (WHO), approximately 703,000 suicide deaths occurred worldwide in 2019, representing an annual global age-standardized suicide rate of 9.0 per 100,000 (WHO, 2021). In 2019, the WHO estimated an age-standardized suicide rate of 13.9 per 100,000 in Belgium; representing one of the highest rates in Europe (Belgium, 2021; WHO, 2021).

Socio-demographic, psychological factors, lifestyle factors, and the availability of mental health services are well known associated factors for suicide mortality (Bauwelinck et al., 2016; Franklin et al., 2017). However, findings are also mounting that environmental factors related to urbanicity could potentially influence suicidal motives (Casas et al., 2017; Helbich et al., 2017; Seltenrich, 2018). Among others, urban green spaces are suggested to reduce the incidence of mental health disorders such as depression (Gascon et al., 2015). More than half (60%) of committed suicides in Europe are due to depression (EU, 2008). Consequently, the reduction in occurrence of depression could in turn reduce the risk of suicide mortality.

Diverse pathways have been suggested to explain the association between green spaces and suicide mortality. Firstly, green spaces have been shown to have a mental restoration effect through the reduction of stress(Høj et al., 2021; Liu et al., 2022). Secondly, green spaces foster social interactions (de Vries et al., 2013; Maas et al., 2009; Seeland et al., 2009; Ward Thompson et al., 2016), and suicide ideation and mortality have been associated with isolation (Helm et al., 2020; Roma et al., 2013). Thirdly, green spaces are linked with higher physical activity engagement (Knobel et al., 2021; van den Berg et al., 2019) , and physical activity has been associated with improvement in mental health (Creese et al., 2021; Pearce et al., 2022). Lastly, green spaces aid in the attenuation of air pollution (Beckett et al., 1998; Nowak, 1994a; Nowak et al., 2000), and long term exposure to air pollutants such as fine particulate matter, and nitrogen dioxide (NO2) might be related with suicide mortality (Min et al., 2018).

To date, the scientific evidence regarding the effects of green spaces on suicide mortality is limited, and results of studies published so far are not conclusive. Whereas some studies reported an inverse association between green spaces and suicide mortality (Helbich et al., 2018; Jiang et al., 2021; Min et al., 2017) others did not find statistically significant associations (Bixby et al., 2015; Mitchell & Popham, 2008). However, all these studies are cross-sectional, and most were ecological. Thus, they were limited in terms of evaluating causality. To the best of our knowledge, only one case-control study has been published that revealed a protective effect of green spaces against suicide mortality among women in areas with a low level of urbanicity (Helbich et al., 2020). There is thus need for more longitudinal based study designs. Furthermore, the study by Helbich et al. (2020) did not consider the role of outdoor air pollution as a mediator in the association between green spaces and suicide mortality. Investigating this pathway could provide insights into the mitigation of air pollutants by green spaces as a potential underlying protective mechanism of green spaces.

Previous studies have reported a difference in risk estimates of mental health outcomes such as depression and green spaces between population groups (van den Berg et al., 2015). As a result, there is a potential as well for such differences to exist in associations between suicide mortality and green spaces. However, such potential modification effects in the association between green spaces and suicide mortality are underexplored. Helbich et al. (2020) only examined effect modifications by sex. Consequently, there is need for more examination of potential effect modification by other factors such as age, and social-economic position. Understanding such potential modification effects can better inform action on which population groups may benefit most from green spaces.

Belgium is one of Europe’s most urbanized countries. Approximately 98% of Belgium’s total population resides in urban areas (Bank, 2020). As a result of the rapid urbanization, the amount of green spaces in the urban environments may be limited. Here, we present a prospective cohort study that assesses the association between long-term exposure to residential surrounding greenness and suicide mortality among residents of the five largest urban areas of Belgium. We also assess potential effect modification by sex, age, educational attainment, migrant background, and neighbourhood social economic position. Finally, we investigate the role of residential outdoor NO2 concentrations as a mediator in the association between residential surrounding greenness and suicide mortality.

1. **Methods**

*2.1 Study Design and Population*

Our analyses are based on a prospective cohort study design with a follow-up period between 1st October 2001 and 31st December 2011 (10.25 years of follow-up). To conduct this study, we used several administrative data sources. The 2001 Belgian census dataset was linked to register data on mortality and emigration during the follow-up period (2001-2011). The 2001 Belgian census dataset contains detailed information on the socio-demographic characteristics of the population. The data on mortality and emigration contains information on the causes of death, dates of death, and dates of emigration (if any). Data on causes of death are coded using the tenth revision of the WHO International Statistical Classification of Diseases and Related Health Problems (ICD-10) (WHO, 2016). Furthermore, environmental indicators (residential surrounding greenness and air pollution) were linked to the 2001 Belgian census using the residential address for each individual at baseline (2001). In this study, we included individuals aged 18 years and older at baseline and officially residing in one the five largest urban areas in Belgium (Antwerp, Ghent, Brussels, Liège, and Charleroi) at the time of the 2001 Belgian Census. These urban areas have at least 250,000 residents and include the city and the commuting zone (Luyten & Van Hecke, 2007). We excluded individuals who resided in care homes (n=74,593; 2.05%) and those with missing covariate information (n=722,853; 16.92%).

*2.2 Suicide Mortality*

Suicide events were defined as original mortality causes with ICD-10 codes namely: X60-X84 (intentional self-harm), Y10-Y34 (event of undetermined intent), and Y870 (sequelae of intentional self-harm) (WHO, 2016). Events of undetermined intent were also included because suicide mortality may be underreported and some suicides are classified as undetermined intent instead of intentional self-harm (WHO, 2014). Nevertheless, in sensitivity analyses, we used a second definition of suicide deaths that excluded deaths classified as “event of undetermined intent” category to consider a potential misclassification of suicide events.

*2.3 Residential Surrounding Greenness*

Residential surrounding greenness was measured using the Normalised Difference Vegetation index (NDVI). NDVI captures the density of green vegetation within a circular buffer of the participant’s residential address. NDVI values range from -1 to 1, with very low NDVI values (0.1 and below) corresponding to barren areas of rock, sand, and water; moderate values (0.2 to 0.3) corresponding to shrub and grassland; while high NDVI values (above 0.6) correspond to temperate and tropical rainforests (NASA, 2000). Negative values representing water surfaces were set to zero to avoid outweighing the presence of green spaces when calculating the indicator. The NDVI average index measures were obtained from Landstat-5 satellite images for the period 2004-2006 at 30m resolution. A detailed explanation of the obtention of NDVI measures can be found elsewhere (Bauwelinck et al., 2021). Mean NDVI values were assessed in 300m and 1,000m buffers within the residential addresses. A small buffer of 300m was chosen to reflect the immediate surroundings within a walkable distance, while a 1,000m buffer was chosen to reflect the wider surroundings. In addition, for sensitivity analyses we used information from Urban Atlas to estimate green spaces surrounding the residential address, also within 1,000m and 300m buffers. Further details are provided elsewhere (Bauwelinck et al., 2021).

*2.4 Outdoor air pollution*

Data on outdoor NO2 concentrations were obtained from the Belgian Interregional Environment Agency (*Belgian Interregional Environment Agency (IRCEL - CELINE)*, 2021). NO2 is a major air pollutant in urban areas owing to the high traffic density in such areas and has been shown to be associated with an increased risk of suicide mortality (EEA, 2020; Min et al., 2018). A comprehensive description of procedures involved in obtaining outdoor concentrations of NO2 in Belgium are explained elsewhere (Hooyberghs et al., 2006; Wouter Lefebvre & Vranckx, 2013). Briefly, concentrations of NO2 are continuously measured through a wide network of stationary monitoring stations. These data are then used in spatial-temporal interpolation models and combined with a Gaussian dispersion model based on emissions from traffic and industrial sources and including meteorological data to calculate the pollutant concentrations for the whole country. In our study, we used 2005 and 2010 annual mean concentrations (µg/m3) of NO2 at 25m resolution to obtain an average concentration of outdoor NO2 incorporated in our analyses.

*2.5 Potential confounders and effect modifiers*

Potential confounders and modifiers were identified *a* priori based on previous literature (Helbich et al., 2020; Rojas-Rueda et al., 2019). Information on confounders and effect modifiers was obtained from the 2001 Belgian census. These included sex, age, living arrangement (single/separated/divorced vs married/cohabiting), individual socio-economic position, neighbourhood socio-economic position, and migrant background. Individual socio-economic position was approximated using educational attainment (Galobardes et al., 2006). Education was categorised according to the International Standard Classification of Education (ISCED) (UNESCO, 2012): lower secondary education or less (ISCED 0-2) was considered as “low”, upper secondary education (ISED 3-4) was considered as “mid” and tertiary education (ISCED 5-6) was considered as “high”. Neighbourhood socio-economic position was measured using the unemployment rate per census tract (i.e., for privacy reasons, the smallest geographical unit for which information on residence is available) of residence at baseline. Last, migrant background captured information on the family history of migration based on the parents’ country of origin. We used the 2001 World Bank classification of countries by income (Bank, 2001) resulting in three categories namely, residents of Belgian origin, residents of other high-income country (HIC) origin, and residents of low- and middle-income country (LMIC) origin.

*2.6 Statistical analyses*

We used Pearson correlation coefficients to present associations between environmental indicators and neighbourhood socio-economic position included in our study.

We performed survival analyses utilising Cox proportional hazards models with age as the underlying time scale to investigate the association between suicide mortality and residential surrounding greenness, for 300m and 1,000m buffers. Individuals were right censored if they emigrated before the end of the study period or if they died due to a cause of death other than suicide. We included the variable (urban areas) as a shared frailty term (random effect) in the model to account for the unobserved between-urban area heterogeneity and the clustered nature of environmental and socio-demographic characteristics in each urban area. We tested the proportional hazards assumption for all covariates using the Chi-Squared Goodness of Fit Test (Schoenfeld, 1980). For migrant background, the proportional hazards assumption did not hold, therefore, we included a strata term for this variable in the main model to allow for differential baseline hazards distributions according to migrant background. We constructed our main model using a stepwise approach, which involved cumulatively adjusting for potential confounders in successive models. Model one (M1) was stratified by migrant background and included the frailty term. Model two (M2) adjusted for the covariates in M1 and individual-level confounders (living arrangement, sex, and educational attainment). Model three (M3) was M2 further adjusted for neighbourhood socio-economic position (percentage of unemployed per statistical ward). We computed the variance inflation factors (VIFs) for each of our variables in the main model (M3) to check for multi-collinearity. We found no indications of multi-collinearity as all the VIFs of our variables were below 10. We presented effect estimates as hazard ratios (HR) with their 95% confidence intervals (CI) for an interquartile range (IQR) increase in residential surrounding greenness.

We tested for the linearity of the exposure-response associations by comparing our main model (M3), including the linear term of the exposure, with a model where natural splines with two degrees of freedom were specified for both NDVI buffers of 300m and 1,000m (Supplementary Figure S1). We compared the improvement in the goodness of fit of a model specifying splines with 2-degrees of freedom versus specifying 3-degrees of freedom, and we observed no improvement when using a higher degree of freedom. We used several methods to compare both models, including the likelihood ratio test (LRT) method, the Akaike Information Criterion, and the Bayesian Information Criterion.

We observed a statistically significant deviation from linearity in the models assessing the association between residential surrounding greenness and suicide mortality (Supplementary Figure S1). In brief, the curves show a non-linear association with an overall linear decrease in the HR, followed by a slight increase in hazard ratios (HR) for individuals exposed to the highest residential surrounding greenness. Consequently, we repeated the analyses for the main models categorising the continuous indicators of NDVI into quintiles of exposure.

In additional analyses, we explored the role of residential outdoor NO2 concentrations in the association between residential surrounding greenness and suicide mortality. NO2 was considered as a potential mediator for which we performed mediation analyses as described by Imai and colleagues (Imai et al., 2010). In brief, we first specified two models: the “exposure-mediator-outcome model”, through survival regression, and the “exposure-mediator model”, through linear regression. Both models were adjusted for the covariates included in the main model. The two models were then fitted to obtain the average direct effect (ADE), often referred to as the total effect, and the average causal mediation (ACME) effect often referred to as the indirect effect. Finally, we obtained the proportion mediated, which is a ratio between the indirect effect and the total effect [ACME/(ACME+ADE)]. Proportions mediated were reported with their respective 95% Quasi-Bayesian confidence intervals.

We explored potential effect modification by including interaction terms into our main models between NDVI and sex, educational attainment, age (18-35 years, 36-65 years, and >65 years), migrant background, and neighbourhood socio-economic position (quartiles of percentage of unemployed per statistical ward). The goodness of fit of these models was tested by evaluating the statistical significance of the LRT comparing the model with and without interaction term. Furthermore, we stratified our main models for the potential effect modifiers.

Finally, we performed several sensitivity analyses to assess the robustness of our findings. First, we included only non-movers, i.e., those who did not move to a different census tract during the 10 years prior to baseline (from 1991 to 2001). Assuming that there were no major changes in the greenness of the statistical sectors between 1991 and 2001, non-movers were exposed to a similar living environment for at least 10 years prior to the start of the follow-up. Second, we used Urban Atlas to assess green spaces instead of NDVI. Third, we restricted our analyses to individuals older than 30 years because they probably completed their educational career and have attained their highest level of formal education. Education among this subgroup may thus better reflect the achieved socio-economic position. Fourth, we excluded individuals residing in suburban areas and commuting zones as such areas are characterized by an extensive land use in both housing and commercial activities (Luyten & Van Hecke, 2007). Fifth, to account for individuals with missing covariate data, we conducted multiple imputation by chained equations to generate five complete datasets and our main model was as well rerun on the full imputed population. Sixth, we restricted our analysis to individuals who did not either die or emigrate from the beginning of the study (1st of October 2001) until the year of measurement of the indicator of surrounding greenness (1st of January 2006). This was done to minimize the temporal mismatch between the measurement of exposure and outcome in our study. Seventh, we calculated the E-values to ascertain the magnitude residential confounding would have to nullify our observed associations between residential surrounding greenness and suicide mortality. Last, we excluded suicide mortality within the “event of undetermined intent” category (ICD-10 codes: Y10-Y34) to examine potential misclassification of suicide events. Data analyses were performed using R statistical software (version 4.0.5) (R, 2019) (R packages survival (Therneau & Grambsch, 2000), mice (Stef van Buuren & Groothuis-Oudshoorn, 2011), and mediation (Dustin et al., 2014)).

1. **Results**

At baseline, 3,549,514 individuals were at risk. The total person-years at risk amounted to 33,997,785 with a mean follow-up of 9.6 years. Table 1 presents the distribution of the suicide deaths during follow-up (2001-2011), the environmental, and socio-demographic characteristics at baseline (2001) for the total population and the five largest urban areas in Belgium. A total of 8,577 suicide deaths occurred during the study period, leading to a risk of suicide mortality of 0.24 cases per 100 individuals. The risk was slightly higher in Charleroi (0.26%) and Liège (0.31%), compared to the other urban areas. The median value of residential surrounding greenness within the 300m and 1,000m buffers were 0.60 (IQR=0.23) and 0.65 (IQR=0.23), respectively. For both buffers, the lowest median value was observed in Antwerp, that also showed the highest yearly averages of NO2 outdoor concentrations. The mean age at baseline was 46.9 years (standard deviation=±17.8), 43.15% of the total population had low education and 81.38% was of Belgian origin. By urban area, the percentage of individuals with low education was highest in Charleroi, while Ghent had the highest percentage of individuals of Belgian origin. A detailed description of the socio-demographics at baseline and environmental indicators among those who died of suicide and the survivors from suicide is provided in Supplementary Table S1. In brief, suicide deaths were most common in men, in the population of Belgian origin and the population with a low education level. We observed slightly lower median residential surrounding greenness (NDVI 300m) among those who died of suicide (0.59, IQR: 0.24) compared to those who did not die of suicide (0.60, IQR: 0.23) (p-value<0.05).

All included environmental indicators were moderately to strongly correlated with each other (Supplementary Figure S2). NDVI measures of residential greenness (300m and 1,000m) were strongly correlated with each other (r=0.93), and negatively correlated with residential NO2 outdoor concentrations (r=-0.75 and r=-0.82 for 300m and 1,000m buffers, respectively). With the percentage of unemployed per statistical ward the correlations were moderate (r=-0.49 and r= -0.52 for 300m and 1,000m buffers of residential greenness, respectively, and r=0.34 with NO2 concentrations).

Figure1 illustrates the HRs and their 95% CIs for the association between residential surrounding greenness (NDVI 300m) and suicide mortality, with stepwise cumulative adjustment for potential confounders. The exact values of the HRs and 95% CIs are reported in Supplementary Table S2. Adjustment for both individual and neighbourhood confounders (M2 and M3) attenuated the associations considerably. Results of our main model (M3) showed that the risk of suicide mortality decreased by 7% (HR=0.93, 95%CI 0.89-0.97) for an IQR increase in surrounding greenness within 300m buffer. Similar HRs were observed for NDVI within a 1,000m buffer (Supplementary Table S2). As the results of the linearity tests suggested non-linearity, we additionally categorised residential surrounding greenness into quintiles (Supplementary Table S3). The results confirm what we observed on Figure S1: a linear trend for the second to the fourth quintiles relative to the first (least green quintile) and a slight reduction in the strength of the association for the fifth quintile (greenest quintile). Nevertheless, for the four highest quintiles relative to the first (least green quintile), the association was inverse and statistically significant, with overlapping 95% CI.

*Table 1: Suicide deaths during follow-up (2001-2011), and environmental and socio-demographics characteristics at baseline (2001), for total study population and stratified by the five largest urban areas in Belgium.*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Total**  **(n= 3,549,514)** | **Antwerp**  **(n= 783,020)** | **Brussels**  **(n=1,602,248)** | **Ghent**  **(n= 396,001)** | **Charleroi**  **(n= 315,394)** | **Liège**  **(n= 452,851)** |
| **Suicide deaths (2001-2011),** n (%) | 8,577 (0.24) | 1,534 (0.20) | 3,856 (0.24) | 987 (0.25) | 812 (0.26) | 1,388 (0.31) |
| **Residential surrounding greenness NDVI 300m,** median (IQR) | 0.60 (0.23) | 0.56 (0.22) | 0.61 (0.25) | 0.62 (0.22) | 0.62 (0.18) | 0.63 (0.20) |
| **Residential surrounding greenness NDVI 1,000m,** median (IQR) | 0.65 (0.23) | 0.62 (0.21) | 0.66 (0.25) | 0.67 (0.22) | 0.66 (0.19) | 0.66 (0.21) |
| **Air pollution,** median (IQR)  NO2 (µg/m3) | 26.88 (12.38) | 30.55 (12.91) | 27.03 (13.80) | 23.47 (12.47) | 25.30 (8.91) | 24.88 (7.68) |
| **Sex,** n (%)  Men  Women | 1,707,389 (48.10)  1, 842,125 (51.90) | 382,508 (48.85)  400,512 (51.15) | 766,878 (47.86)  835,370 (52.14) | 193,590 (48.89)  202,411 (51.11) | 149,373 (47.36)  166,021 (52.64) | 215,040 (47.49)  237,811 (52.51) |
| **Age,** mean (SD) | 46.85 (17.76) | 47.25 (17.71) | 46.65 (17.77) | 46.71 (17.67) | 46.61 (17.69) | 47.21 (17.89) |
| **Living arrangement,** n (%)  Single  Married | 1,487,762 (41.91)  2,061,752 (58.09) | 311,380 (39.77)  471,640 (60.23) | 683,153 (42.64)  919,095 (57.36) | 155,124 (39.17)  240,877 (60.83) | 137,067 (43.46)  178,327 (56.54) | 201,038 (44.39)  251,813 (55.61) |
| **Educational attainment,** n (%)  Low  Mid  High | 1,531,679 (43.15)  1,015,151 (28.60)  1,002,684 (28.25) | 325,262 (41.54)  257,598 (32.90)  200,160 (25.56) | 649,638 (40.55)  435,702 (27.19)  516,908 (32.26) | 171,619 (43.34)  110,991 (28.03)  113,391 (28.63) | 167,919 (53.24)  86,081 (27.29)  61,394 (19.47) | 217,241 (47.97)  124,779 (27.55)  110,831 (24.47) |
| **Migrant background,** n (%)  Residents of Belgian origin  Residents of other HIC origin  Residents of LMIC origin | 2,888,566 (81.38)  430,101 (12.12)  230,847 (6.50) | 694,550 (88.70)  51,176 (6.54)  37,294 (4.76) | 1,256,689 (78.43)  201,683 (12.59)  143,876 (8.98) | 370,655 (93.60)  12,506 (3.16)  12,840 (3.24) | 233,564 (74.05)  67,225 (21.31)  14,605 (4.63) | 333,108 (73.56)  97,511 (21.53)  22,232 (4.91) |
| **Percentage of unemployed per statistical ward,** median (IQR) | 10.90 (10.52) | 8.33 (4.20) | 10.94 (8.56) | 7.17 (4.27) | 23.59 (12.56) | 18.73 (12.08) |

SD: Standard Deviation; HIC: High-Income Country; LMIC: Low- and Middle-Income Country

**Fig. 1.** Hazard ratios (HR) and 95% confidence intervals (CI) with increasing degree of adjustment for the association between suicide mortality and NDVI 300m.

Chart, box and whisker chart

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Note: **M1**: stratified by migrant background and accounted for between-area variability by including a shared frailty term; **M2**: adjusted for M1 and for individual-level confounders (living arrangement, sex, and educational attainment); **M3**: adjusted for M2 and for neighbourhood socio-economic position (percentage of unemployed by statistical ward).

In additional analyses, we explored outdoor N02 concentrations as a potential mediator of the association between residential surrounding greenness and suicide mortality. The results of the mediation analyses are presented in Supplementary Table S4. We observed that the proportions of the associations mediated by NO2 in this study were small and not statistically significant.

Regarding effect modification, Table 2 shows the association between residential surrounding greenness (NDVI 300m and NDVI 1,000m) and suicide mortality stratified by sex, age (18-35 years, 36-65 years, and >65 years), education, migrant background, and quartiles of percentage of unemployed per statistical ward as a measure of neighbourhood socio-economic position. By sex, inverse and significant associations were observed for women (NDVI 300m=HR: 0.81, 95%CI: 0.75-0.87 and NDVI 1,000m=HR: 0.78, 95%CI: 0.73-0.85) but not for men. In addition, effect estimates (hazard ratios) for women were stronger than those for the total population (Figure 1). With regards to age, stronger inverse associations were observed for older adults’ group (36-65 years) as compared to their younger counterparts (18-35 years). We observed a trend across education categories and quartiles of percentage of unemployed per statistical ward. For education, there was an increasing protective effect of green spaces against suicide mortality with increasing level of education, while for neighbourhood social economic position, the protective effect of green spaces against suicide mortality becomes stronger with increasing levels of unemployed individuals per statistical ward. Lastly, inverse associations were observed for individuals of Belgian origin (NDVI 300m= HR: 0.92, 95%CI: 0.88-0.97 and NDVI 1,000m= HR: 0.93, 95%CI: 0.89-0.97) but not for those from other origins.

Finally, the results of the sensitivity analyses conducted in specific population subgroups are presented in Table S5 of the supplementary material. After excluding individuals who moved to a different statistical ward between 1991 and 2001 for NDVI 300m, and suicide deaths classified as undetermined event, the association estimates were not statistically significant. Nevertheless, in all sensitivity analyses (including the latter) the HR were overall in line with the ones presented in Figure 1 and Table S2 (i.e., adjusted HR ranged from 0.91 to 0.98).

Table 2: Adjusted associations (HR and 95%CI) between residential surrounding greenness and suicide mortality, stratified by sex, age, educational attainment, migrant background, and percentage of unemployed per statistical ward

|  |  |  |
| --- | --- | --- |
|  | **Hazard Ratios1** | |
| **NDVI 300m** | **NDVI 1,000m** |
| **Sex**  Women (n=1,842,125)  Men (n=1,707,389)  LRT p-value2 | 0.81 (0.75-0.87)  0.99 (0.94-1.04)  <0.001 | 0.78 (0.73-0.85)  1.01 (0.96-1.06)  <0.001 |
| **Age categories**  18-35 (n=1,094,813)  36-65 (n=1,803,212)  >65 years (n=651,489)  LRT p-value2 | 0.97 (0.91-1.04)  0.93 (0.88-0.99)  0.92 (0.84-1.03)  0.04 | 0.99 (0.92-1.06)  0.94 (0.89-0.99)  0.90 (0.81-1.00)  0.11 |
| **Educational attainment**  Low (n=1,531,679)  Mid (n=1,015,151)  High (n=1,002,684)  LRT p-value2 | 0.96 (0.90-1.01)  0.94 (0.87-1.02)  0.88 (0.86-0.96)  <0.001 | 0.95 (0.89-1.01)  0.93 (0.86-1.01)  0.93 (0.86-1.02)  <0.001 |
| **Migrant background**  Residents of Belgian origin (n=2,888,566)  Residents of other HIC origin (n=430,101)  Residents of LMIC origin (n=230,847)  LRT p-value2 | 0.92 (0.88-0.97)  1.04 (0.93-1.16)  1.02 (0.83-1.27)  <0.001 | 0.93 (0.89-0.97)  1.04 (0.94-1.16)  1.05 (0.84-1.30)  <0.001 |
| **Quartiles of percentage of unemployed per statistical ward**  Q1 [0,7.37] (n=892,003)  Q2 (7.37,10.9] (n=884,435)  Q3 (10.9,17.9] (n=888,368)  Q4 (17.9,64.6] (n=884,708)  LRT p-value2 | 1.03 (0.92-1.16)  0.97 (0.88-1.06)  0.94 (0.88-1.03)  0.89 (0.83-0.96)  <0.001 | 1.05 (0.92-1.20)  0.96 (0.87-1.06)  0.95 (0.88-1.03)  0.91 (0.85-0.98)  <0.001 |

1 stratified by migrant background, accounted for between-area variability by including a shared frailty term, adjusted for individual-level confounders (living arrangement, sex, and education level), and neighbourhood socio-economic position (percentage of unemployed by statistical ward)

2 LRT p-values derived from the model fit comparing the main model with and without interaction term

1. **Discussion**

In this study, we investigated the association between long-term exposure to residential surrounding greenness and suicide mortality between 2001 and 2011 among residents from the five largest urban areas in Belgium. Our findings reveal that increasing surrounding greenness around the residence is associated with a reduced risk of suicide mortality. However, this beneficial effect may not be equally distributed across all strata of the population. The protective effect of green spaces on suicide mortality was only apparent for women and for residents of Belgian origin. The protective effect was stronger among those aged 36 or older, individuals with a high level of education, and residents of deprived neighbourhoods. Finally, we did not find evidence of mediation by NO2 in the association between residential surrounding greenness and suicide mortality.

Our finding of an inverse association between residential surrounding greenness and suicide mortality is in line with previous ecological and cross-sectional studies in the Netherlands (Helbich et al., 2018) and Asia (Japan and Korea) (Jiang et al., 2021; Min et al., 2017). With regards to comparison with similar prospective studies, a longitudinal register based case-control study conducted in the Netherlands found an inverse association between green spaces and suicide mortality for women residing in areas with low levels of urbanicity but not in the total population (Helbich et al., 2020). A potential reason for the difference in these results may be in methods of assessment of suicide mortality. In our main analyses, we included deaths of undetermined intent (ICD-codes: Y10-Y34) whereas the study by Helbich et al. 2020 did not include these deaths. When we excluded deaths of undetermined intent in our sensitivity analyses, we as well observed statistically insignificant inverse associations between green spaces and suicide mortality. However, we believe that inclusion of deaths of undetermined intent as suicide deaths is justified, particularly in the Belgian context. A study investigating the relationship between suicide deaths and deaths of undetermined intent among European Union countries revealed a statistically significant negative correlation between the two forms of death in Belgium (Birt et al., 2003). This may imply a potential for misclassification of suicide mortality as deaths of undetermined intent.

We did not find evidence of residential outdoor NO2 concentrations being a potential mediator in the association between residential surrounding greenness and suicide mortality. Similar results were obtained in a study in China, where measures of air pollution did not mediate the association between NDVI and psychological well-being (Wang et al., 2020). However, our finding contradicts that of an ecological study conducted in Taiwan (Shen et al., 2022) and cross-sectional studies conducted in Barcelona (Spain) and Bulgaria (Dzhambov et al., 2018; Gascon et al., 2018). A potential reason for the inconsistent results may reside in the diverging study designs of these studies and our longitudinal study design. Our study findings may imply that other protective mechanisms of green spaces contribute to the inverse association between residential surrounding greenness and suicide mortality. Previous studies have reported statistically significant proportions of suicide mortality related outcomes (depression and stress) mediated through mechanisms such as stress reduction (Liu et al., 2019), physical activity engagement in parks (Bojorquez & Ojeda-Revah, 2018), and social interactions (de Vries et al., 2013).

We found indications of effect modification by sex and observed inverse associations for residential surrounding greenness and suicide mortality for women only. This is consistent with the longitudinal study in Netherlands (Helbich et al., 2020). It has been hypothesized that women may spend more time in their immediate living environments, including green spaces, since they are often primary caregivers who supervise children and work part-time more often than men do (Ruijsbroek et al., 2017).

We observed stronger inverse associations between residential surrounding greenness and suicide mortality for individuals with high levels of education. Due to the lack of similar studies, we compare our results with studies analysing mental health outcomes (depression and anxiety) in relation to exposure to green spaces, although we are aware of the potential differences of these outcomes with respect to suicide mortality. This finding is inconsistent with an explorative study conducted in Spain (Ruijsbroek et al., 2017) observing a positive association between neighborhood green space and general mental health among low-educated residents. Individuals with high levels of education may have healthier lifestyles (higher levels of physical activity), better health care access and greater social and economic support as compared to their counterparts of low education levels. As a result, this could as well be reflected in the use, availability, and access to residential green spaces and could potentially explain the observed differential patterns by education level.

With regards to age, our associations are stronger for those aged 36 years or older. A study conducted in Australia corroborates this finding (Astell-Burt et al., 2013), showing stronger mental health benefits among physically active middle to older aged adults. Although, in our study we were unable to assess physical activity of the individuals, the study by Astell-Burt et al. (2013) suggested increased physical activity among this age category as a probable explanation for the observed inverse association.

We also observed stronger inverse associations between surrounding greenness and suicide mortality with residents of the most socio-economic deprived neighbourhoods. This is line with a study that observed a stronger reduction in the risk of all-cause mortality for increasing quintiles of greenness among individuals who resided in the most income deprived areas (Mitchell & Popham, 2008). We postulate for such individuals, green spaces such as parks may be their only source for health promoting activities which may improve their mental health and in turn reduce the risk of suicide mortality as compared to individuals residing in wealthy neighbourhoods that even in the absence of residential green spaces can rely on alternatives of improving their mental health.

With regards to migrant background, we only observed statistically significant inverse associations for individuals of Belgian origin. This is a novel finding as to the best of our knowledge, no study has assessed the potential effect modification by migrant background in the association between green spaces and suicide mortality. We did not observe statistically significant associations for individuals of non-Belgian origin.It should be noted that we observed flipped directions in the associations (hazards ratio estimates greater than one) for individuals with non-Belgian origin. A probable explanation for this may be related to utilisation of green spaces by individuals of non-Belgian origin. Previous literature has shown that urban green spaces are seen as insecure places where migrants feel unwelcome (Kloek et al., 2013). Such factors in turn may inhibit utilisation of green spaces and may also increase the risk of suicide mortality. However, based on our results, we cannot conclude that green spaces may increase the risk of suicide mortality in this specific population group because of the wide confidence intervals. Consequently, there is need for more research to understand the role of the migrant background in the association between green spaces and suicide mortality.

Our study has some limitations that should be taken into consideration when interpreting our results. First, our study relied on registry data which had limited information on individual health-life-style behaviours. Lifestyle factors such as illicit drug use, and alcohol consumption have been shown to be associated with suicide ideation and mortality (Li et al., 2012; Motsa et al., 2021). In addition, these life-style factors may affect the utilisation of green spaces. Consequently, there is a potential for residual confounding in our study, However, studies on depression that adjusted for these lifestyle behaviours did not observe a significant change in the associations (Abraham Cottagiri et al., 2022; Klompmaker et al., 2019). Furthermore, we calculated E-values as part of our sensitivity analyses and our results showed that a residual confounder would have to a minimum magnitude of 1.36 (for NDVI 300m) and 1.32 (for NDVI 1,000m) on the risk ratio scale with both residential surrounding greenness and suicide mortality to explain away our observed associations. However, to the best of our knowledge, there is no literature assessing the association between green spaces and suicide mortality controlling for lifestyle factors to evaluate the potential effect of such adjustment in our estimates. Moreover, it is unclear whether lifestyle factors (e.g., smoking, alcohol consumption) are linked to exposure to green spaces. Health-behaviour covariates may additionally be strongly correlated with socioeconomic position, for which we adjusted in our study.

Secondly, NDVI is a quantitative and unspecific measure of all types of green (private or public green). It does not capture qualitative components such as types of green spaces available. However, we used Urban Atlas, as an alternative exposure measurement of green spaces in our sensitivity analyses and we observed similar effect estimates.

Thirdly, our study did not include time-varying information on residential surrounding greenness throughout the follow-up period. We only had one measure of residential surrounding greenness for the year 2006, close to the middle of the follow-up period, which is another limitation of our study. We assumed that, although the quantity of green spaces may vary across time, their spatial distribution remains relatively stable. However, no other exposure information was available for other years to test this. Moreover, exposure assessment was based on the geocoded residential address at baseline (2001), and we lacked information on residential mobility during the follow-up period. Nevertheless, we were able to conduct sensitivity analyses over a subsample of individuals who had not moved during the 10 years prior to baseline (non-movers). We assumed that these individuals were exposed to a similar amount of green space and air pollution for at least 10 years. For non-movers, the HR obtained were in line with the ones obtained for the full study population, but not statistically significant for NDVI 300m. We believe that the loss of statistical significance is most likely related to the reduction in the number of individuals when including only non-movers.

Lastly, our study solely focussed on urban areas, thus our study findings cannot be generalised to residents of rural areas. Emerging evidence suggests a rural-urban inequality in relation to suicide mortality risk, with higher suicide mortality risk in rural areas, and the mechanisms involved are still unknown. (Casant & Helbich, 2022; Hagedoorn & Helbich, 2022).

Despite these limitations, our study presents important strengths. First, we included a large number of individuals at risk (n=3,549,514), we had a long follow-up period (10 years) and included five large urban areas in Belgium. In addition, we had detailed information on several socio-demographic factors both at individual and neighbourhood. These characteristics are well known risk factors for suicide mortality and strong determinants of the availability and quality of green spaces in the neighbourhood of residence (Kabisch, 2019; Rigolon, 2016). Therefore, we believe that potential residual confounding related to lack of information on socio-economic factors is minimal in our study. In addition, owing to the large sample size, we could conduct a number of stratifications in representative subgroups of our population to assess potential effect modification by several socio-demographic factors suggested to be relevant in the assessment of the associations between green spaces and suicide mortality (Helbich et al., 2020). Finally, we would like to highlight that our results were robust to most of the sensitivity analyses conducted. After excluding individuals who moved to a different statistical ward between 1991 and 2001, and suicide deaths classified as undetermined event, the association estimates were not statistically significant. We believe that the loss of statistical significance is most likely related to the reduction in the number of individuals when including only non-movers and under-reporting of suicide deaths.

**Conclusion**

Our findings suggest that the availability of urban green spaces may help reduce suicide deaths. Some specific population groups may be more susceptible to suicide mortality due the lack of urban green spaces in the environment namely, women and residents of Belgian origin. Also, residents of most deprived neighbourhoods, older adults, and individuals with a high level of education may benefit most of the availability of urban green spaces. In the context of climate change, with mental health being one of the main health consequences (IPCC, 2022), introducing green spaces in cities may be an important adaptation strategy.

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1. **Appendix A: Supplementary data**

Supplementary data to this article has been attached as a supplementary file.

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