**Long-term exposure to objective and perceived residential greenness and diabetes mortality: a census-based cohort study**

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***Science of the Total Environment***

**Received Date:** 15 October 2021

**Received in Revised Form:** 17 January 2022

**Accepted:** 22 January 2022

**Available Online:** 29 January 2022

**This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the published version in the journal. Please cite this article as:**

<https://doi.org/10.1016/j.scitotenv.2022.153445>

**Highlights**

* Mortality cohort study over 2.3 million adults in largest Belgian urban areas
* Surrounding greenness not associated with diabetes mortality after full adjustment
* Potential confounding by neighbourhood socioeconomic characteristics
* Perceived greenness independently associated with lower diabetes mortality risk
* Most beneficial for women, low-educated and individuals residing in wealthiest areas

**Author statement**

Lucía Rodríguez Loureiro: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Visualization

Lidia Casas: Conceptualization, Writing – Review & Editing, Supervision, Funding acquisition

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**Abstract**

Background: Residing close to green spaces might reduce diabetes mellitus (DM) risk; however, evidence for diabetes mortality is limited. Moreover, individual and neighbourhood social factors may determine DM risk. Exposure to green spaces may also depend on socioeconomic position (SEP). This study examined the associations between residential greenness and diabetes-related mortality, and the role of the social environment in these associations.

Methods: We used the 2001 Belgian census linked to mortality register data for the period 2001-2014. We included individuals aged 40-79 years old and residing in the five largest Belgian urban areas at baseline. Exposure to residential greenness was assessed with surrounding greenness using the Normalized Difference Vegetation Index (NDVI) within 500-m of residence (objective indicator), and perceived neighbourhood greenness (subjective indicator). We conducted mixed-effects Cox proportional hazards models to obtain hazard ratios (HR) for diabetes-related mortality per interquartile range (IQR) increments of residential greenness. We assessed effect modification by social factors through stratification.

Results: From 2,309,236 individuals included at baseline, 1.2% died from DM during follow-up. Both residential greenness indicators were inversely associated with diabetes-related mortality after adjustment for individual social factors. After controlling for neighbourhood SEP, the beneficial association with surrounding greenness disappeared [HR 1.02 (95%CI:0.99,1.06)], but persisted with perceived neighbourhood greenness [HR 0.93 (95%CI:0.91,0.95)]. After stratification the inverse associations with perceived neighbourhood greenness were strongest for women, the lowest educated, and individuals residing in least deprived neighbourhoods.

Conclusions: Our findings suggest that an overall positive perception of neighbourhood green spaces reduces independently the risk of diabetes-related mortality, regardless of the neighbourhood social environment. Nevertheless, neighbourhood SEP may be a strong confounder in the associations between diabetes-related mortality and greenness indicators derived from satellite images. Perception factors not captured by objective measurements of green spaces are potentially relevant in the association with DM, especially among disadvantaged groups.

**Keywords:** Diabetes mellitus; Mortality; Green spaces; Built environment; Perception; Social factors.

1. **Introduction**

Diabetes mellitus (DM) is of major public health concern worldwide. In Europe, DM prevalence was around 9% in adults aged 20 to 79 in 2019 and is projected to rise even further in the next decades (International Diabetes Federation (IDF), 2019). Individuals with DM have two to three-times higher death risk compared to the general population (Salehidoost et al., 2020; Soedamah-Muthu et al., 2006), and one in three deaths due to DM occur in people under 60 years old (IDF, 2019).

Previous studies suggest that the built environment composition in the residential area might be associated with DM morbidity (Bilal et al., 2018; Gary-Webb et al., 2014). The built environment of a neighbourhood is crucial, as it lays the physical foundations that may influence the lifestyles and social dynamics of its residents, representing barriers or opportunities for well-being (Leal and Chaix, 2011). For instance, urban density and land availability could determine the presence of green spaces in urban areas (Yang et al., 2020). Green spaces may improve health outcomes by providing opportunities for physical activity and social cohesion, inducing physical and attention restoration, and mitigating exposure to environmental hazards (Hartig et al., 2014; Nieuwenhuijsen et al., 2017). In this regard, residential green spaces have been associated with a reduction of both DM prevalence (Astell-Burt et al., 2014; Bodicoat et al., 2014; Klompmaker et al., 2019; Müller et al., 2018; Ngom et al., 2016) and incidence (Dalton et al., 2016; Paquet et al., 2014). However, few studies have evaluated the association between green spaces and diabetes mortality (Crouse et al., 2017; James et al., 2016; Richardson et al., 2012; Xu et al., 2017), and only two applied a longitudinal study design using individual data (Crouse et al., 2017; James et al., 2016). Moreover, all these studies used objective measures of green spaces, while the subjective perception of the built environment may be key in the associations with DM (Dendup et al., 2019).

Individual and neighbourhood social factors are closely related to DM morbidity (Bilal et al., 2018; Hill-Briggs et al., 2020; Kivimäki et al., 2018). Patterns of residential segregation by socioeconomic position or migrant background and the unequal allocation of resources in the neighbourhoods reinforce each other in producing health inequalities (Diez-Roux and Mair, 2010) and potentially affect exposure to green spaces (Rigolon, 2016). To our knowledge, studies investigating the role of social factors in the relation between green spaces and DM are scarce and have shown mixed results (Astell-Burt et al., 2014; Dalton et al., 2016; Müller et al., 2018; Xu et al., 2017).

In this study, we investigate the associations between objective and perceived residential greenness and diabetes-related mortality among 40 to 79-year-old adults residing in Belgian urban areas between 2001 and 2014. In addition, we examine the role of social factors at both the individual and the neighbourhood level in these associations.

1. **Methods**
   1. **Study population and design**

We conducted a longitudinal study using administrative data from the 2001 Belgian census (baseline) linked with register data on mortality and emigration during the follow-up period from October 1, 2001, until December 31, 2014. The 2001 Belgian census includes detailed individual information on sociodemographic and socioeconomic characteristics of the total population officially residing in Belgium that year. This dataset is linked to environmental variables (i.e., information on exposure to green spaces and air pollution concentrations) using the residential addresses at baseline. Our study population consisted of all non-institutionalized individuals officially residing in the five largest Belgian urban areas (Antwerp, Ghent, Brussels, Charleroi, and Liège) in 2001 and aged 40 to 79 years old at baseline. The urban area is defined as a functional geographical unit –independent of administrative boundaries– in terms of living, working, trade, education, cultural experience, and leisure. Each of the five urban areas are divided in four sub-areas: the city core, the urban periphery, the banlieue and the commuter residential zone (Luyten and Van Hecke, 2007), resulting in 20 clusters of urban areas.

* 1. **Diabetes-related mortality**

Mortality data included the causes of death issued from the death certificates, coded using the 10th revision of the International Classification of Disease (ICD-10) (World Health Organization (WHO), 2016). Diabetes-related mortality was defined using the ICD-10 codes E10-E14, including both type 1 (insulin-dependent) and type 2 (non-insulin-dependent) DM. Diabetes is under-reported in death certificates as the underlying cause of death, as individuals with DM usually die from related health complications (e.g., cardiovascular disease or renal failure) (IDF Diabetes Atlas Group, 2015). Thus, we included all death certificates with any mention of DM (i.e., if DM was listed as an underlying, immediate, intermediate, or additional cause of death). This approach has been recommended to capture the actual burden of DM in the population (McEwen et al., 2011; Romon et al., 2008). A description of the registration of DM mortality events in death certificates can be found in Table S1.

* 1. **Residential greenness**

We used one objective (surrounding greenness) and one subjective (perceived neighbourhood greenness) indicator. **Surrounding greenness** was measured with the Normalized Difference Vegetation Index (NDVI), a green density metric, to obtain the average density of green vegetation within a circular buffer around the residential address. Two different buffer sizes were available: 500-m and 1,000-m. This indicator was calculated over a set of atmospherically corrected satellite images from the Landsat-5 for the summer period of 2006, with a 30 m spatial resolution. Negative NDVI values representing water surfaces were set to zero (Bauwelinck et al., 2021). Therefore, surrounding greenness included values from 0 to 1, ranging respectively from no green to highest green density. More methodological details are provided elsewhere (Bauwelinck et al., 2021). **Perceived neighbourhood greenness** was derived from the 2001 census, which inquired each household about their satisfaction regarding neighbourhood provision of green spaces. Possible answers included “Poorly equipped”, “Normally equipped” or “Very well equipped”. Perceived neighbourhood greenness was calculated at the level of the census tract (i.e., the smallest administrative unit available, similar to neighbourhoods: N=8,485), and defined by the percentage of households reporting the provision of neighbourhood green spaces as “very well equipped”.

* 1. **Covariates**

We included age, gender, household living arrangement (cohabiting with a partner, single, or other), and migrant background [Belgian, other high-income country (HIC), and low and middle-income countries (LMIC)] to assess the individual sociodemographic characteristics. Individual socioeconomic position (SEP) was operationalized through educational attainment (tertiary, higher secondary, lower secondary, low or no education, and missing), and housing tenure (owner, tenant, and missing). Missing observations were included as separate categories, as they are likely not randomly distributed across the population.

Neighbourhood socioeconomic position (SEP) was approximated by four indicators at the level of the census tract: percentage of unemployment in the working population, percentage of houses with very low comfort (i.e., no toilet nor bathroom), percentage of residents from LMIC, and median net taxable household income. All indicators were retrieved from the 2001 census, except for the latter which was made available by Statistics Belgium (<https://statbel.fgov.be/en>) for the year 2005. We used principal component analysis (PCA) applying varimax rotation over these variables to obtain an index of neighbourhood SEP accounting for most of their variance (σ2=78.8%). Census tracts with less than 200 inhabitants were excluded beforehand to avoid measurement error derived from low N, which could result in an over- or underestimation of the SEP index in those areas (32% of census tracts, N=2,707; 4.4% of observations, N=108,159).

In additional analyses we considered annual mean concentrations (µg/m3) of ambient air pollutants PM2.5 and NO2 at the residential address [the estimation procedure of ambient pollution data in Belgium has been described in detail elsewhere (Rodriguez-Loureiro et al., 2021)], and population density (number of inhabitants/km2) at the level of the census tract in 2001.

* 1. **Statistical analyses**

Spearman correlation was used to estimate the strength of the linear association between residential greenness indicators and the neighbourhood SEP index. To assess the associations between residential greenness and diabetes-related mortality, we conducted multilevel, mixed-effects Cox proportional hazards to obtain Hazard Ratios (HR) and the 95% confidence intervals (95%CI), using age as the underlying time scale. Each individual was followed until censored at the age of emigration, age of death from other causes, or end of the follow-up. We used mixed-effects models to account for the underlying hierarchical data structure and to avoid violation of the independency of observations assumption when clustered (Austin, 2017). We defined the following hierarchal structure: individuals (level 1) were nested within the census tracts (level 2), which were nested within the urban residential areas (level 3). To account for cluster-specific random effects we specified two shared frailty terms (Austin, 2017): one for the clusters of urban areas (N=20) and one for the census tracts (N=5,778) nested within the urban areas.

We defined our main model by applying stepwise regression: model 1 (M1) adjusted for gender and age and accounted for random effects including the two shared frailty terms; model 2a (M2a) added to M1 the individual social dimensions (migrant background, educational level, housing tenure and household living arrangement); model 2b (M2b) added to M1 the index of neighbourhood SEP; and model 3 (M3) was defined as the main model including all the individual and the neighbourhood variables. We fitted separate models for both residential greenness indicators (surrounding greenness 500-m buffer and perceived neighbourhood greenness). We assessed the linearity of the exposure-response relationship by fitting natural splines with two degrees of freedom and compared it to the model with the linear term by using a likelihood-ratio test (LRT). Model comparisons did not reveal significant improvements of the models with natural splines (Figure S1). The HRs for diabetes-related mortality therefore accounted for one interquartile range (IQR) increment in each residential greenness indicator.

In additional analyses we explored the potential role of air pollution in the associations under study (Figure S2). We therefore adjusted our main models for air pollution (PM2.5 and NO2, separately), and for air pollution combined with population density as done in prior studies (Crouse et al., 2017).

Furthermore, we investigated effect modification by the individual and neighbourhood social stratification dimensions (gender, migrant background, educational level, and neighbourhood SEP). First, we included a multiplicative interaction term between each of the dimensions and each residential greenness indicator in separate models. These models were then compared to the main model through a likelihood ratio test (LRT). Second, we stratified our main models by the categories of the effect modifiers; for the neighbourhood index of SEP, we used quartiles.

We conducted several sensitivity analyses by repeating the stepwise adjustment of the associations with diabetes-related mortality as follows: (a) using a larger buffer size of surrounding greenness (1,000-m buffer); (b) including only mortality related to DM type 2 (ICD-10 code E11); (c) including only individuals who at baseline reported (very) good self-perceived health status and not having longstanding illnesses or disabilities (i.e., healthy subpopulation), selected following the methodology from a previous study (Rodriguez-Loureiro et al., 2021); (d) conducting a complete case analyses (i.e., excluding missing observations in educational level and housing tenure); (e) excluding individuals aged 65 years or older; (f) including only individuals who reported living in the same census tract in 1991 and in 2001 (non-movers); (g) excluding individuals with a private garden; (h) excluding individuals living in the banlieue and the commuting zones, as they present a rural appearance (Luyten and Van Hecke, 2007).

We used the statistical software Stata release 16 (StataCorp, 2019) to create the dataset and we conducted all statistical analyses in R/4.0 (R Core Team, 2020), using the packages coxme (Therneau, 2020), ggplot2 (Wickham, 2016), and splines (R Core Team, 2020).

1. **Results**

After excluding individuals with no information on residential address at baseline (2001) (N=25,795; 1.0%), the population at risk was 2,309,236 individuals aged 40 to 79 years. The description of the study population, in total and by quartiles of the neighbourhood index of SEP, is displayed in Table 1. During follow-up (2001-2014), 1.2% (N=26,928) of the population died with any mention of diabetes in their death certificates. The percentage of diabetes-related mortality followed a gradient across quartiles of neighbourhood SEP, being lowest in the wealthiest areas (0.7%) and highest in the most deprived areas (1.7%). The mean age at baseline was 56.8 ± 11.3 years. Most of the study population were Belgians, owners and cohabited with their partner. The median exposure to surrounding greenness was 0.62 (IQR: 0.22). The median proportion of households reporting very good provision of neighbourhood green spaces in the census tract (i.e., perceived neighbourhood greenness) was 22.5% (IQR: 21.3). The residential greenness metrics followed a gradient according to neighbourhood SEP, with residents in most deprived areas presenting the lowest exposure to green spaces. A detailed description of the environmental variables is shown in the Supplemental Material (Table S2).

**Table 1.** Description of the total study population by quartiles of the neighbourhood index of socioeconomic position. Five largest Belgian urban areas, 2001-2014.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Total population** | **Quartiles of neighbourhood socioeconomic position** | | | |
|  | **(aged 40-79 years)** | **Q1 (least deprived)** | **Q2** | **Q3** | **Q4 (most deprived)** |
|  | **n=2,309,236** | **n=578,102** | **n=576,605** | **n=577,775** | **n=576,754** |
| **Death certificates registering diabetes (ICD-10: E10-E14) as any cause of death during follow-up, N (%)** | 26,928 (1.2) | 4,322 (0.7) | 5,814 (1.0) | 7,235 (1.3) | 9557 (1.7) |
| **Emigrations during follow-up, N (%)** | 74,239 (3.2) | 12,065 (2.1) | 13,886 (2.4) | 20,549 (3.6) | 27739 (4.8) |
| **Age at baseline, mean ± SD** | 56.8 ±11.3 | 56.0 ± 10.9 | 57.1 ± 1.4 | 57.4 ± 11.5 | 56.8 ± 11.5 |
| **Women, N (%)** | 1,205,500 (52.2) | 293,962 (50.8) | 300,313 (52.1) | 308,768 (53.4) | 302457 (52.4) |
| **Migrant background, N (%)** |  |  |  |  |  |
| Belgian | 1,938,852 (84.0) | 539,306 (93.3) | 528,694 (91.7) | 487,561 (84.4) | 383291 (66.5) |
| Other HIC | 240,057 (10.4) | 32,393 (5.6) | 36,636 (6.4) | 64,845 (11.2) | 106183 (18.4) |
| LMIC | 130,327 (5.6) | 6,403 (1.1) | 11,275 (2.0) | 25,369 (4.4) | 87280 (15.1) |
| **Educational level** a**, N (%)** |  |  |  |  |  |
| Tertiary education | 465,930 (20.2) | 147,067 (25.4) | 120,474 (20.9) | 120,010 (20.8) | 78379 (13.6) |
| Higher secondary education | 481,495 (20.9) | 143,820 (24.9) | 127,802 (22.2) | 118,102 (20.4) | 91771 (15.9) |
| Lower secondary education | 564,831 (24.5) | 135,204 (23.4) | 142,129 (24.6) | 148,939 (25.8) | 138559 (24.0) |
| Low/No education | 572,488 (24.8) | 117,483 (20.3) | 140,840 (24.4) | 133,105 (23.0) | 181060 (31.4) |
| Unknown | 224,492 (9.7) | 34,528 (6.0) | 45,360 (7.9) | 57,619 (10.0) | 86985 (15.1) |
| **Housing tenure** a**, N (%)** |  |  |  |  |  |
| Owner | 1,661,899 (72.0) | 499,385 (86.4) | 452,373 (78.5) | 408,122 (70.6) | 302019 (52.4) |
| Tenant | 524,225 (22.7) | 61,243 (10.6) | 101,077 (17.5) | 137,590 (23.8) | 224315 (38.9) |
| Unknown | 123,112 (5.3) | 17,474 (3.0) | 23,155 (4.0) | 32,063 (5.5) | 50420 (8.7) |
| **Household living arrangement, N (%)** |  |  |  |  |  |
| Cohabiting | 1,608,406 (69.7) | 467,449 (80.9) | 425,688 (73.8) | 384,134 (66.5) | 331135 (57.4) |
| Single | 596,345 (25.8) | 88,792 (15.4) | 124,249 (21.5) | 166,095 (28.7) | 217209 (37.7) |
| Other | 104,485 (4.5) | 21,861 (3.8) | 26,668 (4.6) | 27,546 (8.4) | 28410 (4.9) |
| **Residential UGS indicators, median (Q1 - Q3)** |  |  |  |  |  |
| Surrounding greenness (500-m buffer) | 0.62 (0.50 - 0.72) | 0.70 (0.63 - 0.75) | 0.66 (0.57 - 0.74) | 0.60 (0.48 - 0.71) | 0.45 (0.33 - 0.58) |
| Perceived neighbourhood greenness (%) | 22.5 (13.0 - 34.3) | 30.2 (22.0 - 40.7) | 25.1 (17.3 - 34.7) | 20.3 (12.7 - 32.9) | 11.1 (6.2 - 21.4) |
| a Educational level and housing tenure containing active missing categories. | | | | | |

The Spearman correlations between residential greenness and neighbourhood SEP are shown in Figure S3. The correlation between surrounding greenness and perceived neighbourhood greenness was moderately positive (ρ=0.40). Both indicators were negatively and moderately correlated with neighbourhood SEP, although stronger for surrounding greenness (ρ=-0.54) than for perceived neighbourhood greenness (ρ=-0.46).

The stepwise adjustment of multilevel Cox models on the associations between residential greenness and diabetes-related mortality are presented in Figure 1, and the exact estimates in Table S3 in supplemental material. For surrounding greenness, model 1 (adjusted by age and gender) showed that one IQR increase in surrounding greenness was associated with 22% decreased risk of diabetes-related mortality (HR 0.78; 95%CI: 0.76, 0.81). In model 2a, after including the individual sociodemographic and socioeconomic variables, the association estimate was weaker but inverse and significant (HR 0.88; 95%CI: 0.86, 0.91). In models 2b and 3, adding the neighbourhood index of SEP resulted in non-significant associations close to the null. For perceived neighbourhood greenness, in models 1 and 2a we obtained similar results as for surrounding greenness (e.g., for M2a: HR 0.86; 95%CI: 0.84, 0.88). Nevertheless, in models 2b and 3, after adjusting for neighbourhood SEP, the association estimate remained inverse and significant (e.g., for M3: HR 0.93; 95%CI: 0.91, 0.95).

**Figure 1.** Associations [Hazard ratios (HR) and 95% confidence intervals] between surrounding greenness within a 500-m buffer and perceived neighbourhood greenness and diabetes-related mortality in the five largest Belgian urban areas, 2001-2014. HRs are expressed for one interquartile range (IQR) increment in surrounding greenness (IQR 0.22) and perceived neighbourhood greenness (IQR 21.3). Results from multilevel Cox regression models using age as the underlying time scale. M1 adjusted by age and gender and included two shared frailty terms for the urban areas and for the census tracts within the urban areas; M2a = M1 + migrant background, educational level, housing tenure and household living arrangement; M2b = M1 + neighbourhood index of SEP; M3 = fully adjusted model.



In additional analyses we further adjusted main models for air pollution (PM2.5 and NO2, one at a time) and air pollution combined with population density. Observed HRs of our main models did not change after such adjustments (Table S4).

The results for the effect modification analyses by individual and neighbourhood social stratification dimensions are shown in Figure 2, and the exact estimates are shown in the supplemental material (Table S5). The interaction terms for both residential greenness indicators with gender, neighbourhood SEP, and additionally for perceived neighbourhood greenness with migrant background were statistically significant. We found no significant interactions with educational level. For surrounding greenness, we observed positive (HRs > 1) and significant associations with diabetes-related mortality among women, residents from Belgium, and individuals with secondary education. Across quartiles of neighbourhood SEP, the HRs for the least and most deprived areas were below one, while those for the intermediate quartiles were above one. Nevertheless, none of these associations were statistically significant. For perceived neighbourhood greenness, the association estimates were inverse and statistically significant except for individuals from LMIC and for individuals with higher secondary education. The strongest associations were found for women (HR 0.90; 95%CI: 0.87, 0.93), and residents from other HIC (HR 0.85; 95%CI: 0.80, 0.92). We observed a gradient by educational level, being the beneficial associations stronger the lower the educational level. The strongest associations were observed for individuals in the lowest educational category. Last, stratification by quartiles of neighbourhood SEP showed a trend with slightly stronger associations observed in the least deprived neighbourhoods (HR 0.89; 95%CI: 0.84, 0.93) compared to the most deprived (HR 0.93; 95%CI: 0.90, 0.97).

**Figure 2.** Associations [Hazard ratios (HR) and 95% confidence intervals] of diabetes-related mortality with IQR increments of surrounding greenness within a 500-m buffer and perceived neighbourhood greenness in the five largest Belgian urban areas, 2001-2014. Stratified by gender, migrant background, educational level, and quartiles of the neighbourhood SEP. Models adjusted by age, gender, migrant background, educational level, housing tenure, housing living arrangement and neighbourhood SEP. *p*-values resulting from likelihood ratio tests comparing the main model to the model with the interaction term (*p*-value < 0.05 indicates significant interaction).



We conducted several sensitivity analyses to evaluate the robustness of our findings (Table S6). For surrounding greenness, we observed that the estimates for models adjusting by neighbourhood SEP became statistically significant above the unity when using the 1,000-m buffer of greenness, T2DM, doing complete case analyses, and excluding individuals with private garden. When limiting the analyses to the younger population (40-64 years old) the associations in all models were inverse (HRs < 1), although non-significant after full adjustment (M3). For perceived neighbourhood greenness, the results were robust to all sensitivity analyses conducted, unless when excluding individuals with private garden after adjusting for the neighbourhood SEP index (M2b and M3). In this case, the associations were null.

1. **Discussion**

We observed that, after adjustment for an index of neighbourhood SEP, the associations between residential greenness and diabetes-related mortality only remained inverse and significant for perceived neighbourhood greenness (i.e., living in census tracts where a greater proportion of households reported very good provision of green spaces), but not for the objective indicator of residential greenness derived from satellite images. In stratified analyses using surrounding greenness, we observed positive significant associations (HRs > 1) in women, Belgians, and individuals with secondary education. The strongest beneficial effect of increased perceived neighbourhood greenness was observed in women, individuals originating from high-income countries other than Belgium, the lower educated and those living in the least deprived neighbourhoods.

Several mechanisms could explain the association between green spaces and the risk of mortality due to diabetes mellitus (DM). First, green spaces offer opportunities for physical activity, which has been associated with reduced risk of DM (Aune et al., 2015) and decreased risk of premature death among individuals with this condition (Sluik et al., 2012). Second, they could induce restoration and reduce stress, potentially lessening the risk of DM (Golden et al., 2008) and its complications, including mortality (Lin et al., 2010, 2009). Furthermore, greener neighbourhoods may enhance social cohesion, which in turn has been associated with lower incidence of DM (Gebreab et al., 2017). Finally, green spaces could contribute to the mitigation of environmental hazards, e.g., air pollution, associated with DM (Eze et al., 2015; Thiering and Heinrich, 2015). In our study, the associations between green spaces and DM mortality did not change after further adjustment for air pollution, nor for air pollution combined with population density. Hence, the role of aforementioned indicators seemed to be negligible in our study associations. Findings from a similar study in Canada – when adjusting for air pollution and population density – were in line with ours, although observed associations were stronger (Crouse et al., 2017).

As mentioned in the introduction, previous studies assessing the association between residential greenness and diabetes-related mortality are scarce. Crouse et al. (2017) found an inverse but non-significant association between urban residential surrounding greenness and diabetes and cardiovascular disease mortality after adjusting for individual and area-level covariates. An ecological cross-sectional study found no associations between the population-weighted proportion of green space land cover and age-standardized rates of diabetes mortality in the 49 largest US cities (Richardson et al., 2012). Finally, a study in Hong Kong using small-area analysis found an inverse association between median area-level NDVI values and diabetes mortality at the individual level (Xu et al., 2017). Each of these studies adjusted their analyses by individual and neighbourhood socioeconomic characteristics, except for the ecological study by Richardson et al. (2012), that controlled for city-level sociodemographic indicators. Only the study by Xu et al. (2017) controlled for the cluster effects of the studied areas. Moreover, all aforementioned studies assessed diabetes mortality using the underlying cause of death, while we considered all death certificates with any mention to diabetes, which might be a better estimation of the actual burden of diabetes in the population (McEwen et al., 2011).

In our study, adjusting for neighbourhood SEP reduced the association with surrounding greenness to unity, and comparatively had a smaller effect with perceived neighbourhood greenness. Prior studies conducted in the Belgian context also found that the neighbourhood social environment was key in the association between objective measures of green spaces and cardiovascular outcomes, i.e., medication sales (Aerts et al., 2020) and mortality (Bauwelinck et al., 2021). This may also apply to metabolic disorders. A possible reason is the presence of residual confounding when not controlling for the area socioeconomic characteristics. Surrounding greenness measured with satellite images is potentially unequally distributed in the population, i.e., concentrated in wealthier areas, showing a misleading beneficial effect of green spaces on health. A second explanation could be the lower quality of green spaces in more deprived areas (Rigolon, 2016), which can be related to perceptions of physical disorder and lack of safety, both sources of psychological distress and barriers for green spaces’ use (Knapp et al., 2019; Knobel et al., 2021).

The effect of positive perceived neighbourhood greenness was found to be independently associated to a decreased risk of diabetes-related mortality. This subjective measure could capture qualitative features of green spaces related to beneficial health effects, such as accessibility (Dadvand et al., 2016), bird biodiversity (Knobel et al., 2021) or perceived safety (Knapp et al., 2019; Knobel et al., 2021). Moreover, neighbourhoods with positive perceptions of nearby green spaces might identify areas additionally concentrating other health promoting services, such as physical activity resources or high-quality food environments, which are important determinants of DM (Hill-Briggs et al., 2020). Hence, the subjective indicator may partially include aspects of neighbourhood SEP, as it was aggregated at the level of the census tract. Subjective measures of residential greenness have been associated with improved mental health (Sugiyama et al., 2008) and with increased recreational walkability and physical activity (Sugiyama et al., 2014; Van Dyck et al., 2013), potentially influencing DM. Furthermore, two prior studies observed an overall mortality risk reduction among individuals residing in areas where large shares of individuals reported a good provision of green spaces (Bauwelinck et al., 2021; Takano et al., 2002). A possible limitation of using subjective indicators is that positive perceptions of the residential living environment might be the result of residential self-selection, as people would choose to live in areas they find pleasant. This bias is presumably minimized in our study, as the sociodemographic and socioeconomic characteristics included are considered predictors of residential self-selection (Dendup et al., 2019). Moreover, we aimed at reducing reverse causation (i.e., healthier individuals reporting positive perceptions of neighbourhood greenness) by using an aggregated measure of this indicator.

We found positive associations between surrounding greenness and DM mortality among women. This is inconsistent with the results of a nationwide cohort study of female nurses, where the association between residential surrounding greenness and diabetes mortality was inverse but non-significant (per 0.1-unit increase: HR 0.85, 95%CI: 0.52, 1.39) (James et al., 2016). This discrepancy may be explained by different uses of green spaces due to dissimilar population characteristics; the study population in James et al. (2016) was strongly homogeneous and was mainly composed by White non-Hispanic women, while our study population comprised the entire population residing in Belgium in 2001. A potential explanation for our findings is that women may experience feelings of insecurity in low-quality green areas, leading to stronger detrimental effects (Richardson and Mitchell, 2010). Although we could not test this hypothesis, women may be more susceptible to factors related to their immediate built and social environment. In this line, our results with perceived neighbourhood greenness in women showed that, the better perception of neighbourhood green spaces, the lower the risk of DM-related mortality. Their exposure to green spaces might be greater, as they usually spend more time in the home surroundings, and they may rely to a greater extent on local resources and nearby social contacts (Maas et al., 2009; Rodriguez-Loureiro et al., 2021; Stafford et al., 2005). We additionally observed a strong protective effect of perceived neighbourhood greenness among individuals originating from other HIC. In our study, around 40% of individuals in this migrant group originated from Italy (results not shown). On one hand, they might a priori present a diabetes-related mortality advantage due to their high adherence to the traditional Mediterranean low-fat diet, mainly driven through lower body mass index (BMI) (Deboosere and Gadeyne, 2005; Wild and Byrne, 2006). In addition, the cultural background from individuals originating from Southern European countries, strongly interdependent from a particular place or community, might motivate outdoor recreation (Gentin, 2011). Hence the importance of the residential living environment for this group. Regarding educational level, the lower educated seemed to benefit more from living in a neighbourhood with an overall positive perception of green spaces. Previous studies assessing the association between residential green spaces and DM incidence (Dalton et al., 2016) and prevalence (Müller et al., 2018) did not find interactions with individual SEP measured with occupation (manual vs. non-manual) and education, respectively. Green spaces may be key health promoting features in the living environment from which all residents could benefit. Individuals with lower SEP generally have worse health outcomes, one of the reasons being having fewer resources to compensate poor living conditions. This might be partially counterbalanced when residing in greener areas compared to socioeconomically deprived individuals who are not exposed to green spaces (Mitchell and Popham, 2008). Finally, when stratifying our models by quartiles of neighbourhood SEP the inverse associations were slightly stronger in individuals residing in wealthier areas. This is in disagreement with a cross-sectional study that found no effect modification by neighbourhood SEP in the beneficial association between green spaces and type 2 DM (Astell-Burt et al., 2014), and with the study by Xu et al. (2017) that found a stronger association between median area-level NDVI and diabetes mortality for individuals living in areas with lower median household income. Our findings are consistent with previous studies using mortality cohorts reporting strongest beneficial associations in wealthier areas (Crouse et al., 2017; Vienneau et al., 2017; Villeneuve et al., 2012). Our findings suggest that the qualitative features of perceived neighbourhood greenness leading to a decreased risk of diabetes-related mortality might be slightly better in wealthier areas.

Our study presents some limitations. First, because of the use of administrative data, we were unable to control for lifestyle risk factors, such as BMI or smoking status. Although the prevalence of risk factors in the population might be determined by the social dimensions considered, we cannot rule out residual confounding. A nationwide cohort study of women that controlled for these factors found inverse but non-significant associations between surrounding greenness and diabetes mortality (James et al., 2016). Other studies have found an independent beneficial association between green spaces and DM after adjusting for lifestyle factors (Astell-Burt et al., 2014; Dalton et al., 2016; Klompmaker et al., 2019). However, given the differences regarding study design, population characteristics, or exposure assessment, it remains a challenge to ascertain the effect and direction that this adjustment would have in our estimates. Second, we lacked information on important covariates, such as physical activity, which could have explained the different mechanisms at play in the association between each metric of exposure to green spaces and DM mortality (Yang et al., 2020). Third, the indicator for residential surrounding greenness was only available at one single time point (2006), selected halfway of the follow-up period (2001-2014). We assumed that although quantitatively surrounding greenness may change over time, the spatial patterns of greenspace distribution remained relatively stable. Fourth, information on the geocoded residential address was only available at baseline (2001). We were able to select a subsample of non-movers during the 10 years prior to baseline to account for long-term exposure to residential greenness, which confirmed our main results. Still, we might have incurred in exposure misclassification due to unavailability of information on residential mobility during the follow-up period (2001-2014). Fifth, no indicators on the quality of the residential green space were available. However, our indicator on perceived neighbourhood greenness might partially account for qualitative characteristics of residential greenness. Sixth, assessing greenspace exposure exclusively in the residential address is potentially also a source of exposure misclassification, as it ignores mobility patterns. Moreover, information on socioeconomic and sociodemographic characteristics was also only available at baseline. However, our study population only included adults, which tend to have a relatively stable SEP. Another limitation of our study is that we did not have information on diagnoses of diabetes and/or related disorders at baseline. However, in sensitivity analyses we were able to confirm our results in a healthy population subgroup. Finally, albeit including all death certificates with any mention to diabetes, the actual burden of diabetes in the population might still be under-estimated and its reporting highly related to cardiovascular disease as the underlying cause of death (McEwen et al., 2011).

The strengths of our study are the large size of the study population (N=2,309,236) and the long follow-up (13.25 years), together with the richness of the environmental database. This database allowed us to have a high-resolution individual exposure assessment at the residential address of each person officially residing in the five largest Belgian urban areas at baseline. Additionally, we could use an objective and a subjective indicator of the living environment to capture different green spaces’ characteristics. Furthermore, we accounted for cluster effects at both the level of the census tract and of the urban area. Finally, our large representative dataset allowed us to conduct stratification analyses to assess effect modification by social dimensions.

1. **Conclusions**

We found evidence that residing in areas with an overall positive perception of neighbourhood green spaces reduced the risk of diabetes-related mortality after adjusting for individual and neighbourhood social factors. Neighbourhood socioeconomic position (SEP) appeared as a strong confounder in the models with surrounding greenness. For the subjective indicator, the strongest beneficial effects were found in women, residents from high-income countries other than Belgium, the lower educated and in individuals living in the wealthiest areas. The burden of DM is increasing in the population (IDF, 2019; WHO, 2016). Environmental characteristics are key, as they affect large shares of the population. Thus, it is important to reinforce DM prevention by identifying the objective and perceived environmental elements that might help decreasing the risk of developing DM, especially among disadvantaged population groups. Future research is needed to contrast our results and should consider the mechanisms linking residential greenness to diabetes-related mortality, including confounding for neighbourhood SEP and effect modification by individual and neighbourhood social determinants of health.

**Funding**

Lucía Rodríguez Loureiro is funded by the Brussels Institute for Research and Innovation (INNOVIRIS) [project number: 2019-ANTICIPATE-26100]. Mariska Bauwelinck is funded by an individual PhD grant supported by the Research Foundation-Flanders (FWO) [grant number 11A9718N].

**Acknowledgements**

The authors would like to recognize the important role of Statbel in this study (Directorate-general Statistics – Statistics Belgium) for geocoding the census data and easing data linkages. The resources and services used in this work were provided by the VSC (Flemish Supercomputer Centre), funded by the Research Foundation – Flanders (FWO) and the Flemish Government. The icons used for the graphical abstract were made available by the Noun Project (<https://thenounproject.com>) under a Free Creative Commons (CC) license [attributions: Population by Susannanova; Belgium by Fien Robbe; Research by ibrandify; Park by Andrew Nolte; Forest by Aneeque Ahmed; Garden by Template; perception by Vectors Point; GPS by Turkkub; coding by iconnut; poverty, demographic and mortality by Nithinan Tatah; Income by Becris; Multi ethnic by Olena Panasovska; icd file document by IYIKON].

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