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A protective role of urban greenspace on the association between night-time heat and suicide in Seoul, South Korea

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Abstract

Suicide, a leading cause of death among the youth, has shown a positive association with high temperatures. However, few studies have explored the association between tropical nights and suicide and the potential role of greenness on this association. We investigated the association between suicide and two hot night indices: hot night duration (HNd) and hot night excess (HNe), representing heat duration and excess heat during night-time. We also explored whether the association was modified by urban greenspace, measured by satellite-derived normalized difference vegetation index (NDVI), across 25 districts in Seoul, South Korea from 2000 to 2020. Based on the multi-district daily time-series data, we performed a space-time-stratified case-crossover analysis with a distributed lag linear model with lags of up to 7 d for HNd and HNe, adjusting for daily mean temperature and relative humidity. We added an interaction term between the hot night index and NDVI to assess the effect modification of greenness. In total, 14 693 suicides were included in this study. The relative risk (RR) of suicide per a 10% increase in HNd was 1.059 (95% CI: 1.017–1.103) in low NDVI areas and 1.031 (95% CI: 0.988–1.075) in high NDVI areas. The RR per a 1 °C increase in HNe was 1.011 (95% CI: 0.998–1.024) and 1.005 (95% CI: 0.992–1.018) in low and high NDVI areas, respectively. Greenspaces have expanded over time in all districts of Seoul, and the risk of suicide for night-time heat decreased over time in both low and high NDVI areas. Our findings suggest that exposure to night-time heat is associated with an increased risk of suicide, but this risk may be mitigated by greater greenspaces in urban areas. Prioritizing development and maintenance of urban greenspaces will be a critical co-benefit strategy for promoting public mental health in changing climates.

1. Introduction

Climate change has been widely acknowledged to be one of the most serious global threats to human health (Woodward *et al* 2014, Masson-Delmotte *et al* 2018). In recent decades, warming temperatures have been observed and hot extremes have become more frequent and intense across most land regions (Masson-Delmotte *et al* 2021). Increasing warm days and heat waves are more likely to cause high night-time temperatures, leading to heat stress and heat-related illnesses (Murage *et al* 2017, Roye *et al* 2021, He *et al* 2022). Numerous epidemiological studies have found that non-optimal temperatures are associated with adverse health outcomes such as higher risks of mortality and cardiovascular, respiratory, and neurological diseases (Bhaskaran *et al* 2009, Lian *et al* 2015, Mciver *et al* 2016, Gasparrini *et al* 2017, Zhao *et al* 2018). Mounting evidence suggests that high temperatures have impact on adverse mental health outcomes, including suicide (Kim *et al* 2019, Frangione *et al* 2022).

Suicide is the leading cause of death among young adults (WHO 2021). In South Korea (hereafter, Korea), suicide is the number one cause of death among teens, 20 s, and 30 s (Office 2021). Suicide is complex because various factors such as biological, social, psychological, and stressful life events may increase its risk (Nock *et al* 2008). Some epidemiological studies have reported that weather conditions, especially temperature, are a risk factor, as the risk of suicide increases with high temperatures in the summer (Kim *et al* 2011, 2019, Lehmann *et al* 2022). Several mechanisms of the association between high temperature and suicide have been proposed based on biological, social, and stressor perspectives (Coryell and Schlesser 2001, Carballo *et al* 2009, Tiihonen *et al* 2017, Popovska-Perčinić *et al* 2021, Lehmann *et al* 2022). However, most previous studies have focused on the harmful effects of daily mean or maximum temperatures on suicide; yet, evidence of the hazardous effect of night-time heat on suicide is limited. The hazardous effects of night-time heat have only been studied for total and cause-specific mortality, such as cardiovascular, respiratory, and mental health diseases (Murage *et al* 2017, Roye *et al* 2021).

Exposure to greenspaces is known to improve mental health and may reduce the risk of suicide (Mendoza *et al* 2023) by reducing stress (Liu *et al* 2022), stimulating physical activity (De Vries *et al* 2013), and fostering social interactions (De Vries *et al* 2013). However, the potential interplay between greenspace and high temperatures during the night-time on suicide remains to be explored. Thus, to resolve this knowledge gap, this study examined the association between night-time heat and suicide and the potential modifying effects of urban greenspace on the association based on 20 year multi-district daily time-series data in Seoul, Korea. We also investigated whether the associations differed by sex and age, and whether they were modified by other district-level indicators besides greenspace, and changed over time in Seoul, where greenspaces have increased.

2. Method

2.1. Data

We collected data on suicide mortality, meteorological variables, urban greenspace, and district-level indicators for each of the 25 districts ('gu') in Seoul, Korea. Death certificates issued from 2000 to 2020 between the 1st of June and the 30th of September, representing the warmest season, were retrieved from statistics Korea (Korea 2021). We aggregated death certificates into daily suicide counts for each district. Suicide was defined as intentional self-poisoning and self-harm based on the International Classification of Diseases, Tenth Revision (ICD-10) codes X60–X84 (WHO 2016).

Daily mean temperature (°C) and mean relative humidity (%), calculated from dew point temperatures, were collected using the Google Earth Engine (GEE) with ERA5-Land dataset from 2000 to 2020 as hourly averages (Muóoz Sabater 2019), and aggregated to the daily district level. Urban greenspace data were also collected as a monthly mean normalized difference vegetation index (NDVI) through GEE with the MOD13A2.061 Terra Vegetation Indices 16-Day Global 1 km dataset between the warm months (May–October) from 2000 to 2020 (Didan 2021). NDVI is estimated from the vitality and density of vegetation at a pixel based on different intensities of reflected sunlight because plant leaves absorb a specific spectrum of light (Schmid 2017). NDVI values range from 0.1 (stone, sand, and snow), 0.3 (sparse vegetation), and 0.6 (temperate forests) to 1.0 (highest possible density of vegetation/leaves), and below zero, indicating the presence of water. The raw data extracted from the GEE ranged from −2000 to 10 000. We aggregated it at the monthly district level and multiplied a scale factor (0.0001) by the monthly aggregated district-level value.

Additionally, we collected eight district-level indicators (annual indicators) for use as potential effect modifiers, including the air conditioner (AC) penetration rate (%), number of hospital beds per 1000, sleep hours (hours), number of basic livelihood security recipients per 1000, residential area per person (persons m^{-2}), population density (persons km^{-2}), subjective city danger perception, and the occurrence and arrest of five major crimes per 1000 (no. of people). Detailed information such as the definition, data source, and collection periods of each district-level indicator are summarized in the supplementary materials (table S1).

2.2. Hot night indices

We used two hot night indices proposed in a previous study (Roye 2017), which were calculated using the hourly temperature data extracted from the GEE, as mentioned above. It relies on the hourly temperature data during hour i on day j (T_{ij}). The hot night duration (HNd) index (%), describing the duration of the heat effect, was calculated as the sum of hours during the night-time (time between sunset and sunrise) for which the temperature threshold (T_{thr}) was exceeded. A second index, hot night excess (HNe) in °C, allowing for the evaluation of the excess nocturnal thermal stress, was obtained through the sum of excess

heat during the period with temperatures greater than T_{thr}. We defined T_{ths} as 25 °C, which is Korea's hot night standard temperature (Korea Meteorological Administration 2022).

2.3. Statistical modeling

We used a space-time-stratified case-crossover design with distributed lag nonlinear functions to examine the association between the hot night index and suicide. We fitted a conditional quasi-Poisson regression model considering overdispersion (Armstrong *et al* 2014, Wu *et al* 2021). We designed a stratum by a four-way interaction term of the district, calendar year and month, and day of the week to compare the exposure levels between case and control days matched within the stratum. The stratum was not only defined with time but also with space for multi-location time-series data, allowing for the application of a one-stage analysis across 25 districts based on the assumption that there are no random or systematic effects between districts (Armstrong *et al* 2014). When we examined the assumption, I^2 estimates for HNd and HNe were 7.0% and 17.2%, respectively, indicating not substantial heterogeneity in the exposure-response association across districts. Strata with no suicide events were excluded from the analysis.

The distributed lag linear function for the association between hot night index and suicide was obtained by combining two functions for the linear exposure-response and additional nonlinear lag-response associations (Gasparrini *et al* 2010). Specifically, we used a linear function for the association between hot night index (HNd or HNe) and suicide, and for lag-response, a natural cubic spline (NCS) with three internal knots placed at equal intervals on the log scale of lags up to seven days. We assumed linear exposure-response associations for the hot night index based on the quasi Akaike's information criterion (QAIC) values and exposure-response patterns (figure S1).

We adjusted for the daily mean temperature and relative humidity in the model. For temperature, we applied a distributed lag nonlinear function, allowing for both nonlinear temperature-suicide association and nonlinear lag-response functions (Gasparrini *et al* 2015). We used the NCS for the dimension of temperature-suicide association with two internal knots placed at the 55th and 90th percentiles of temperature distributions across 25 districts and the same parameters for lag response over a lag of seven days as those for the hot night indices described above. Daily relative humidity was adjusted using an NCS with three degrees of freedom.

We added an interaction term between the hot night index and a binary indicator of greenness (i.e. low vs. high, defined as below or above the median of 20 years average NDVI) for each district to examine whether urban greenspace could mitigate the risk of suicide associated with hot nights. In addition, greenness was replaced with other district-level potential effect modifiers. We dichotomized the district-level indicators based on the median of the long-term averages for each variable and added an interaction term with the hot night index. The differences in estimates within each group (both the total study population group and subpopulation group) by binary indicators, that is, low and high NDVI or district-level indicators regions, were measured using the Wald test.

Additionally, we performed a stratified analysis by subpopulations and subperiods. We estimated the associations between hot nights and suicide by greenness in three age groups (younger than 30 years, middle-aged between 30 and 64 years, and older than or equal to 65 years) and sex (males and females). As NDVI has increased over time in Seoul, we divided the study period into two, i.e. the 2000s (2000–2009) and the 2010s (2010–2020), and estimated changes in the association between hot nights and suicide by greenness.

2.4. Sensitivity analysis

We performed several sensitivity analyses to assess the results' robustness. First, we extended the analysis period from June–September to May–September. Next, we altered the T_{thr} for the hot night indices from 25 °C to 24 °C or 26 °C. Third, we fitted a reduced model without temperature adjustment to see how the pattern of the lag-response associations between hot nights and suicide changed in the models with and without temperature adjustment. Finally, we applied two different approaches for examining the effect modification by greenspace: a stratification analysis instead of the interaction model and a conventional two-stage time-series quasi-Poisson regression analysis. For the stratification approach, we divided the dataset into two groups defined as below or above the median of the 20 year average NDVI. In the conventional two-stage design, we estimated the exposure-response association for each district and then pooled the district-specific overall cumulative association estimates using meta-regression analysis incorporating the NDVI groups as a meta-predictor (Sera and Gasparrini 2022). The details of model design and parameter specification are described in the supplementary materials (p 3).

Additionally, we considered other greenspace-related variables, such as total urban forest area ratio and total urban forest area per person within each district, instead of NDVI in the sensitivity analysis.

Table 1. Summary statistics by urban greenspace rank.

Variable		NDVI low	NDVI high	Total
# of districts		13	12	25
Suicide[a]	Total #	7380	7313	14 693
	Daily mean	2.9	2.9	5.7
	Male (%)[b]	68.5	66.4	67.4
	<30 yr (%)[c]	14.8	15.3	15.1
	30–64 yr (%)[c]	60.7	60	60.3
NDVI[d]	Mean (SD)	0.33 (0.06)	0.49 (0.09)	0.40 (0.11)
	Median (min, max)	0.33 (0.11, 0.48)	0.50 (0.15, 0.64)	0.39 (0.11, 0.64)
HNd (%)[a]	Mean (SD)	28.2 (25.3)	27.6 (24.6)	27.9 (25.0)
	Median (min, max)	27.3 (0, 100)	27.3 (0, 100)	27.3 (0, 100)
HNe (°C)[a]	Mean (SD)	7.3 (9.7)	7.2 (9.6)	7.2 (9.6)
	Median (min, max)	3.4 (0, 69.6)	3.3 (0, 67)	3.3 (0, 69.6)
Temperature (°C)[a]	Mean (SD)	22.7 (2.8)	22.6 (2.8)	22.7 (2.8)
Relative humidity (%)[a]	Mean (SD)	80.7 (9.9)	80.3 (10.1)	80.5 (10)

[a] The number of suicides, HNd, HNe, temperature, and relative humidity are defined between June to September from 2000 to 2020.

[b] Proportion of suicides in men over the total number of suicides during the study period.

[c] Proportion of suicides in each age group (<30 years and between 30 to 64 years) of the total number of suicides during the study period.

[d] NDVI was defined as the monthly mean between May to October from 2000 to 2020.

NDVI = normalized difference vegetation index; HNd = hot night duration; HNe = hot night excess; SD = standard deviation.

All statistical analyses were performed using R (version 4. 1. 2; R development Core Team) with the package 'gnm' for a space-time-stratified case-crossover analysis design and the packages 'dlnm' and 'tsModel' for a distributed lag nonlinear or linear function.

3. Results

Overall, there were 14 693 suicides between June to September from 2000 to 2020 in Seoul. The summary statistics of the meteorological variables and mortality counts depending on NDVI levels are shown in table 1, and district-level values are shown in tables S2–S4. The young group (aged <30 years) accounted for 15.1% and the middle-aged group (aged 30–64 years) accounted for 60.3% of the total suicides. Suicides in males accounted for 67.4% of all cases. A total of 50.2% of suicides occurred in low NDVI districts. The mean yearly NDVI for 20 years (2000–2020) of each district ranges from 0.26–0.55, 5–48.7 for total urban forest area ratio (%), and 4.8–51.3 for total urban forest area per person (persons m^{-2}).

The mean daily HNd (%) was 27.9 (standard deviation [SD]: 25.0) and the mean HNe (°C) was 7.2 (SD: 9.6) for all districts. The median NDVI for all 25 districts in Seoul was 0.40 (range 0.11–0.65), and it was 0.33 (range 0.11–0.48) and 0.50 (range 0.16–0.65) in low NDVI districts ($n = 13$) and high NDVI districts ($n = 12$), respectively. Figure 1 shows the spatial distribution of suicide per 100 000 persons, mean NDVI, mean HNd (%), and mean HNe (°C) over the study period. Figure 2 shows the gradual increase in the annual mean NDVI by district to varying extents. Overall, the median NDVI increased from 0.34 in 2000 to 0.40 in 2020.

Figure 3 depicts the estimated associations between hot night indices (HNd or HNe) and suicide by urban greenspace level after adjusting for daily mean temperature and relative humidity. Generally, these associations were positive. Low NDVI districts showed a higher risk of suicide on hot nights than high NDVI districts, suggesting that NDVI may play a protective role as an effect modifier of suicide associated with night-time heat exposure. We observed strong evidence of an association between suicide and HNd in low NDVI districts, with a relative risk (RR) of 1.059 (95% confidence interval [CI]: 1.017–1.103) per 10% increase in HNd, whereas the RR for high NDVI districts was 1.031 (95% CI: 0.988–1.075). The RR per 1 °C increase in HNe in low and high NDVI districts was 1.011 (95% CI: 0.998–1.024) and 1.005 (95% CI: 0.992–1.018), respectively. However, the difference in RR between the low and high NDVI districts was statistically insignificant (p-values for interaction of 0.246 for HNd and 0.373 for HNe).

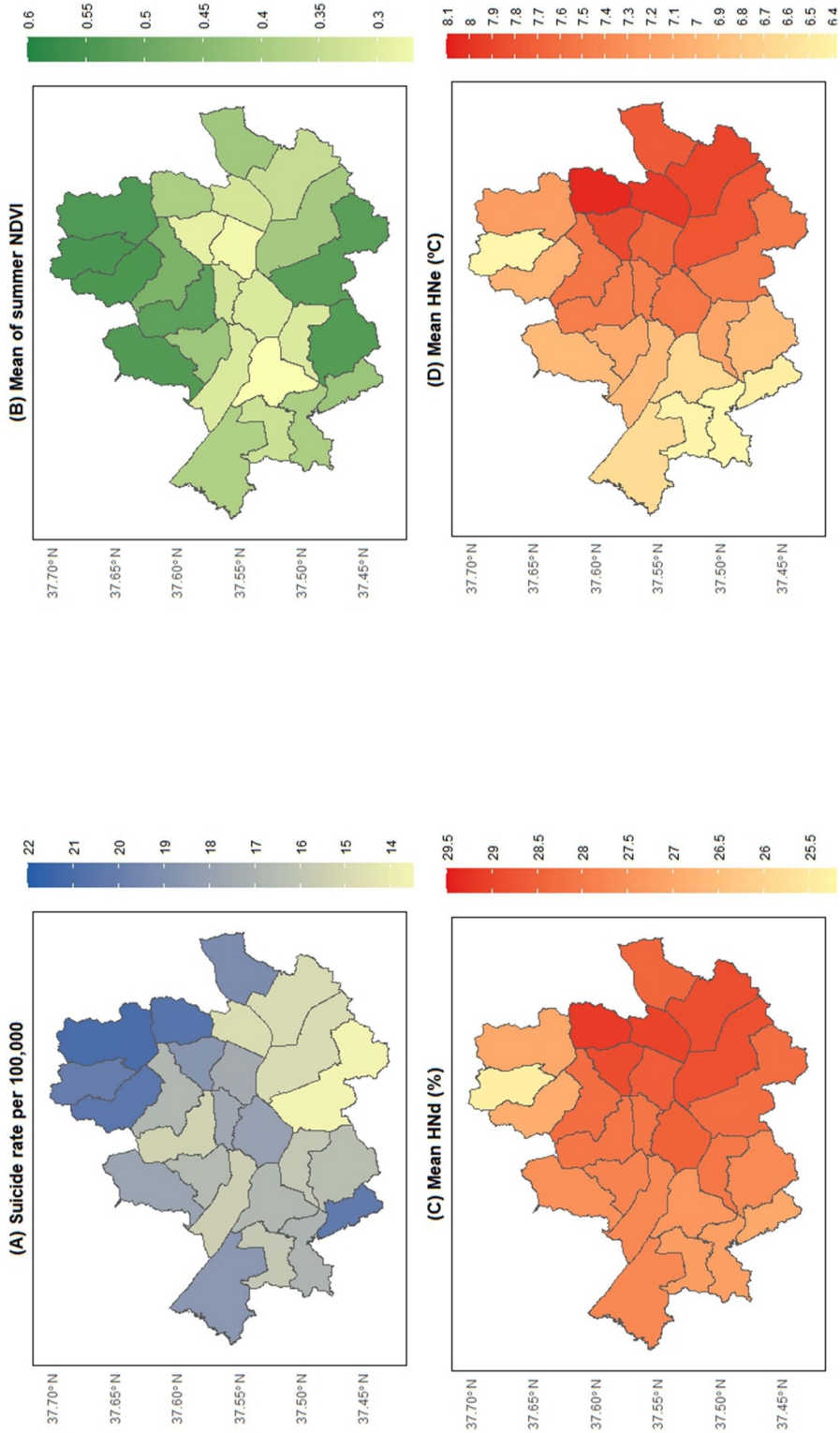

Figure 1. The study area includes 25 districts in Seoul, South Korea, and the location-specific suicide rate per 100 000 (defined as the yearly average number of suicides between June to September from 2000 to 2020 over the yearly average population size of each district), summer greenspace (estimated with NDVI between May to October from 2000 to 2020), HNd, and HNe (defined between June to September from 2000 to 2020). NDVI = normalized difference vegetation index; HNd = hot night duration; HNe = hot night excess.

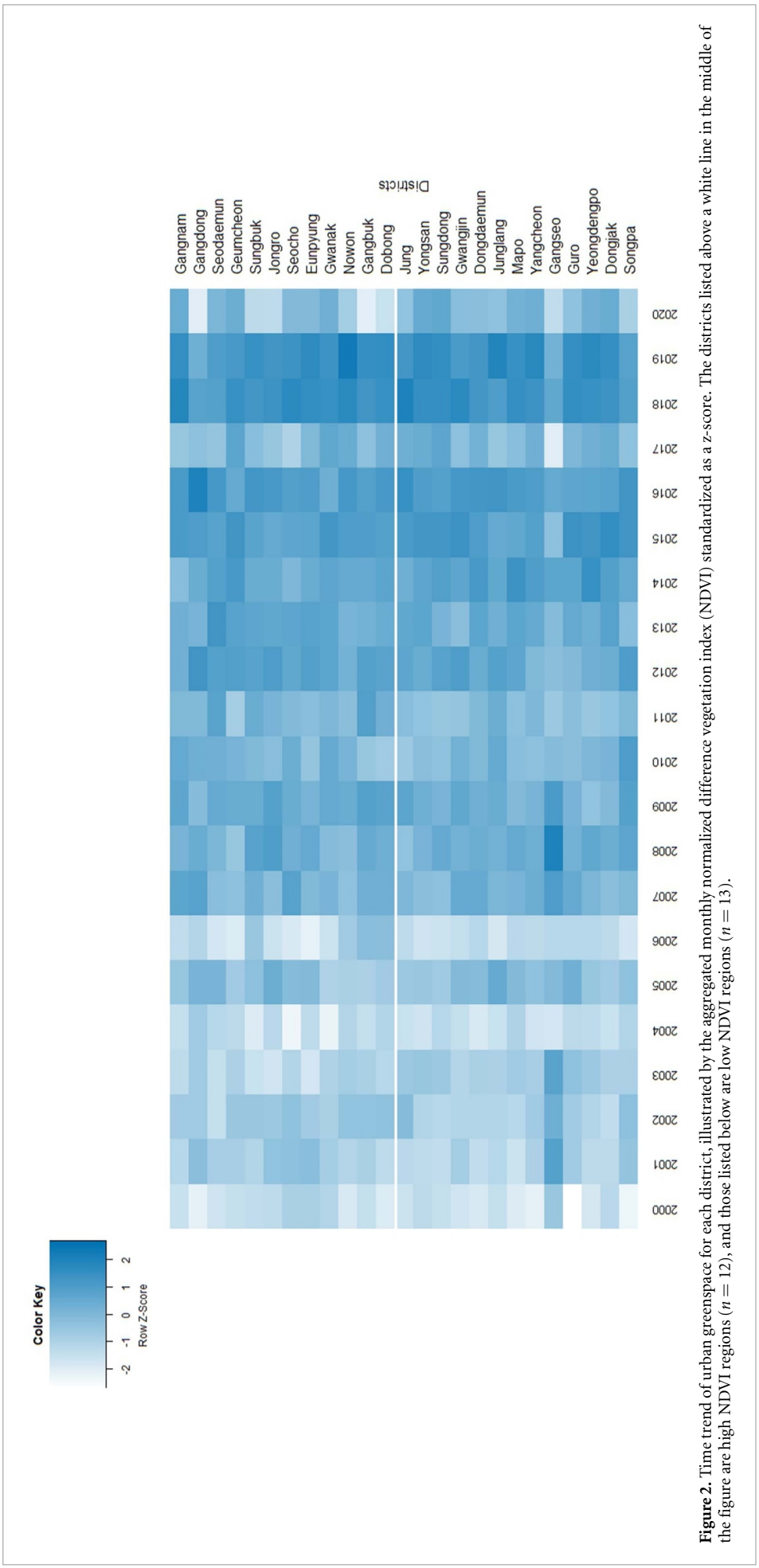

Figure 2. Time trend of urban greenspace for each district, illustrated by the aggregated monthly normalized difference vegetation index (NDVI) standardized as a *z*-score. The districts listed above a white line in the middle of the figure are high NDVI regions ($n = 12$), and those listed below are low NDVI regions ($n = 13$).

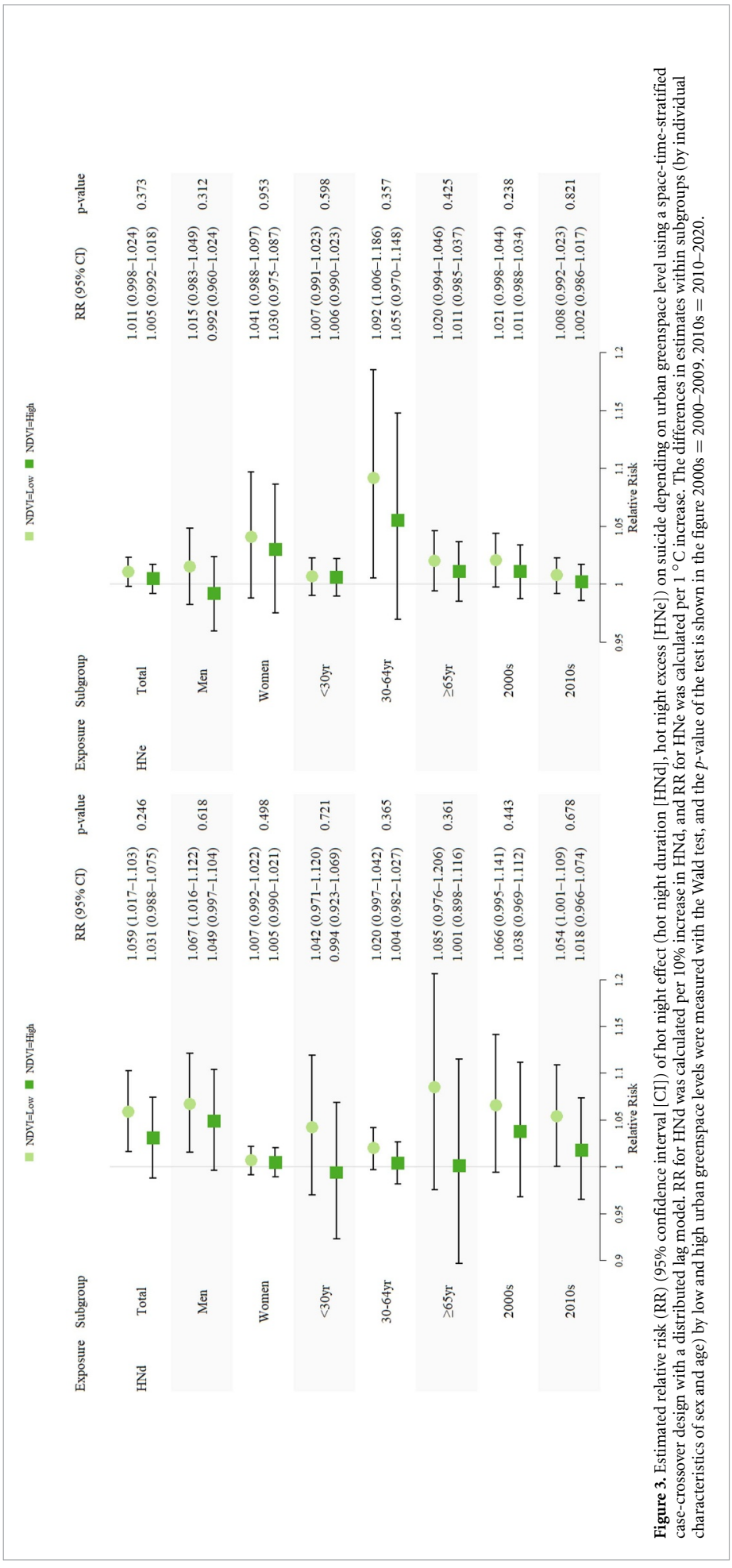

Figure 3. Estimated relative risk (RR) (95% confidence interval [CI]) of hot night effect (hot night duration [HNd], hot night excess [HNe]) on suicide depending on urban greenspace level using a space-time-stratified case-crossover design with a distributed lag model. RR for HNd was calculated per 10% increase in HNd, and RR for HNe was calculated per 1 °C increase. The differences in estimates within subgroups (by individual characteristics of sex and age) by low and high urban greenspace levels were measured with the Wald test, and the *p*-value of the test is shown in the figure 2000s = 2000–2009. 2010s = 2010–2020.

Figure 3 also shows the sex- and age-specific associations between hot nights and suicide by the urban vegetation level. The patterns of the protective effects of NDVI were broadly similar in all subgroups—males, females, young, middle-aged, and old. However, the association between hot nights and suicide varied by the type of hot night index. We also analyzed the association between night-time heat and suicide without the interaction term between the hot night index and a binary indicator of greenness (low vs. high). It was prominent in the male and old-aged groups for HNd and in the female and middle-aged groups for HNe (figure S2).

As urban greenspaces have increased over time, the risk of suicide due to night-time heat decreased in both low and high NDVI districts in the 2000s and the 2010s (figure 3). For example, the risk of suicide per 10% increase in HNd was 1.066 (95% CI: 0.995–1.141) in low NDVI districts in 2000s, while it was 1.054 (95% CI: 1.001–1.109) in 2010s. Similarly, the risk of suicide per 1 °C increase in HNe was 1.021 (95% CI: 0.998–1.044) in low NDVI districts in the 2000s, and 1.008 (95% CI: 0.992–1.023) in the 2010s in low NDVI districts. This pattern of risk reduction was consistent even when the association was analyzed without the interaction term (figure S2).

Figure 4 shows the association between night-time heat and suicide by other district-level indicators. We found no evidence of effect modification on the association (all p values for interaction > 0.05), although the association was more evident in districts where people sleep less (p-values for interaction of 0.130 for HNd and 0.361 for HNe) than in districts where people sleep more. The correlations between sleep hours and other district-level indicators were not strong ranging from −0.31 to 0.26 (figure S3).

The sensitivity analysis showed consistent patterns of the protective effects of urban greenspaces on the association between night-time heat and suicide when we changed the analysis period from June–September to May–September or the cut-off to define the hot night indices from 25 °C to 24 °C or 26 °C (table S5). This protective effect of greenness was also consistent when we changed the analysis model (table S6) or applied the total urban forest area ratio and total urban forest area per person as an indicator of greenness instead of NDVI (table S7). The greenness pattern (i.e. the higher risk of suicide for hot nights in low NDVI districts) remained similar when we removed the daily mean temperature from the model. However, the lag-response patterns differed between models with and without temperature adjustment. The model without temperature adjustment provided narrower 95% CIs over all the lag days and more significant RR estimates at short lag days (1–2 d) than the CIs from the model with temperature adjustment (figure S4). In contrast, the model with temperature adjustment provided more significant RR estimates for 2–3 lag days. The lowest RR estimates were observed on non-lag days (0 d) commonly.

4. Discussion

In this study, we estimated the association between night-time heat and suicide based on 20 year multi-location time-series data, including 14 693 suicide deaths in Seoul, Korea, and observed suggestive evidence of effect modification by urban greenspace. The risk of suicide for both increases in HNd and HNe, representing the duration of heat and excess heat during night-time, respectively, were more prominent in low greenness districts than in high greenness districts, although the difference in the risks was not statistically significant. The risk of suicide due to night-time heat exposure decreased over time as greenness has increased in Seoul. Our findings suggest that urban greenspaces play a protective role in mitigating the increased risk of suicide associated with night-time heat exposure.

To the best of our knowledge, no previous epidemiological study has focused on suicide for hot nights, although some studies have reported a positive association between suicide and daily mean temperature (Kim *et al* 2011, 2019, Lehmann *et al* 2022), and between mortality and hot nights (Roye *et al* 2021). A previous multi-country study in southern Europe showed positive associations between the risk of nonaccidental, respiratory, and cardiovascular mortality and hot night exposure (both HNd and excess) (Roye *et al* 2021). In their study, the risk estimates for excess were consistently higher than those for duration across many cities, whereas our estimated risk was higher for the duration (1.047 (95% CI: 1.008–1.089)) than for excess (1.008 (95% CI: 0.996–1.020)) (figures 3 and S2).

Several mechanisms have been proposed to explain the association between ambient temperature and suicide from the biological, social, and stress perspectives. The serotonergic system is sensitive to ambient temperature, resulting in increased depression and impulsive-aggressive behavior (Carballo *et al* 2009, Tiihonen *et al* 2017). In addition, higher ambient temperature is linked to the hyperactivity of the hypothalamic-pituitary-adrenal (HPA) axis, which is also associated with suicide risk (Coryell and Schlesser 2001, Popovska-Perčinić *et al* 2021). At the social level, activities tend to differ depending on weather conditions, and decreased social activities on hot days may trigger depressive episodes and other factors related to suicide (Lehmann *et al* 2022).

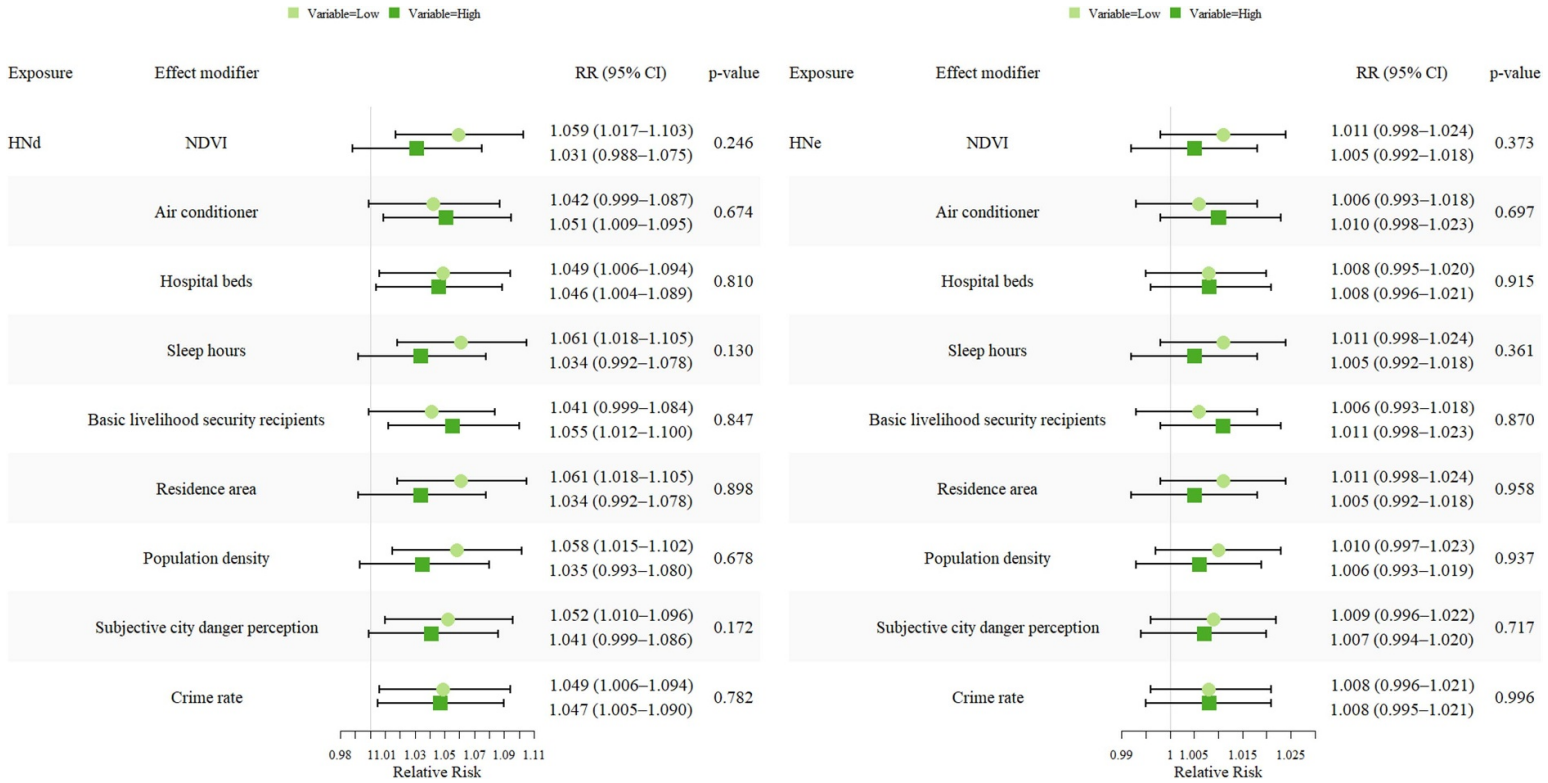

Figure 4. Estimated relative risk (RR) (95% confidence interval [CI]) of hot night effect (hot night duration [HNd], hot night excess [HNe]) on suicide depending on district-level indicators (low vs. high) using a space-time-stratified case-crossover design with a distributed lag model. RR for HNd was calculated per 10% increase in HNd, and RR for HNe was calculated per 1 °C increase. The differences in estimates within regions by low and high district-level indicators were measured with the Wald test, and the *p*-value of the test is shown in the figure.

Many studies have discussed the potential mechanisms explaining the association between hot night–suicide but the exact mechanisms remain unclear. One plausible mechanism is that night-time heat causes sleep deprivation, which could result in increased suicide attempts. As the sleep–wake cycle is sensitive to this temperature-circadian cycle, sleep quality is affected by temperature (Van Someren 2003, Obradovich *et al* 2017, Minor *et al* 2022). In addition, opening windows on hot nights may increase noise-related stress, resulting in reduced quality of sleep (Murage *et al* 2017). Sleep deprivation or being awake at night due to hot nights can increase the use of alcohol or other substances, and social support declines during the night (Perlis *et al* 2016, Roy *et al* 2022). Furthermore, staying awake at night may decrease frontal lobe function, leading to diminished problem-solving abilities and increased impulsive behaviors (Perlis *et al* 2016). These conditions may increase suicide risk.

Our finding of the protective effect of urban greenspaces on the association between night-time heat and suicide is in line with that of previous studies. A census-based longitudinal study in Belgium showed a 6%–7% risk reduction in suicide mortality for an interquartile range increase in residential surrounding greenness (Mendoza *et al* 2023). A study in Seoul in Korea also uncovered the protective effect of urban greenspaces showing higher estimates for the association between total mortality and 1 °C increases in temperature in regions with lower levels of vegetation (Son *et al* 2016).

Several mechanisms have been proposed for the protective effects of greenspaces. In districts with lower greenness, a lack of vegetation can contribute to increased heat retention and reduced cooling effects (Sodoudi *et al* 2018). Exposure to residential greenery spaces or parks is negatively associated with depression (Bojorquez and Ojeda-Revah 2018, Liu *et al* 2019), and offers opportunities for social cohesion and physical activities, which could relieve stress and improve health (De Vries *et al* 2013, Liu *et al* 2019). Thus, districts with lower greenness might experience a lack of social cohesion and limited opportunities for social engagement, potentially exacerbating the negative impact of high night-time temperature on suicide risk.

We investigated whether the association between night-time heat and suicide differed according to sex and age. The male group and people older than 65 years old showed a higher risk of HNd increase; in other words, as they are exposed longer to night-time heat, the risk of suicide increases. Older people are vulnerable to heat exposure, as they lose their capacity for thermoregulation or sweating (Folkerts *et al* 2020). The subgroup analysis results were consistent with those of the previous studies showing strong associations between suicide and ambient temperature in men and the elderly (Gao *et al* 2019, Sim *et al* 2020, Frangione *et al* 2022); however, most studies used temperature itself as an exposure variable (i.e. mean temperature or maximum temperature), unlike the night-time excess heat or duration above the threshold temperature used in this study.

As night-time heat can cause sleep disorders or sleep deprivation (Van Someren 2003), which potentially leads to an increase in the risk of suicide (Perlis *et al* 2016, Roy *et al* 2022), we hypothesized that districts, where people sleep less, have a higher risk of suicide for exposure to night-time heat. We tested this hypothesis by adding an interaction term between the hot night indices and the mean sleep hours (low vs. high) of each district in the model. The results showed a higher risk of suicide in districts with low sleep hours, although the 95% CI overlapped with that in districts with high sleep hours. This finding may be the basis for the mechanism described above.

We also hypothesized that people living in districts with a higher subjective city danger perception or crime rates may be more vulnerable to night-time heat exposure, as they may be less likely to open windows or travel to cooler locations because of safety concerns, especially on hot nights (Gronlund 2014). When we added subjective city danger perception and crime rate as interaction terms with hot night indices, contrary to our expectations, we found no evidence of an effect modification on the association (all p-values for interaction > 0.1).

The association between night-time heat and suicide decreased from the 2000s to the 2010s as urban greenspaces have increased over time. The risk reduction could be explained in part by the adaptation to heat regarding biological or societal factors such as housing (Gasparrini *et al* 2015, Todd and Valleron 2015, Lehmann *et al* 2022) or an increase in AC penetration rate (Kyselý and Kříž, 2008, Ha and Kim 2013). The AC penetration rate in Seoul has increased from 15% to 71% between 1994 and 2009 (Ha and Kim 2013), reaching over 90% in the 2010s. This reduction could also be explained by the protective effect of increased greenspaces over time (Mendoza *et al* 2023). Interestingly, we observed a consistent pattern of higher risk of suicide associated with night-time heat in low NDVI districts for each subperiod. These findings suggest that climate change policies should consider increasing urban greenspaces as an adaptation strategy.

This study has several limitations. First, since we used regional exposure values instead of personal exposure values for hot night indices, temperature, relative humidity, and greenness, the personal exposure levels may have been misclassified, as this is only an aggregated estimate of outdoor exposure. Moreover, we could not consider the local variation in greenspace accessibility and distribution within a district or use a smaller spatial unit due to lack of information on the residence of death data. It could lead to

misclassification of exposure value. However, this misclassification is expected to be non-differential in the outcome of suicide, it rather biases risk estimated toward the null (Rothman *et al* 2008, Loken and Gelman 2017). Second, for district-level indicators, the data could not cover the entire study period, 2000–2020, so the values may represent only a part of the period. Third, because of confidentiality issues, we could not access more detailed information on whether the people who died by suicide had been diagnosed with mental disorders such as depression, or were a state of lack of sleep.

Even though there are some limitations of the study, our findings indicate that night-time heat could increase the risk of suicide, and urban greenspaces could act as a climate adaptation or protection measure. Exposure to greenspaces can promote mental health by promoting recreational and sporting activities, social contact, stress reduction, and mitigation of air pollution, noise, and heat exposure (James *et al* 2015). As climate change continues, it will cause an increase in warm days and heat waves, finally resulting in high night-time temperatures. With an increase in night-time temperature, it is necessary to consider the increased potential risk of suicide attributable to night-time heat. Further studies taking into account individual-level proximity to greenness in different areas would help to better understand the protective effect of urban greenspaces in the hot night-suicide association.

5. Conclusion

Suicide is a complex but preventable event; therefore, public health policies need to consider its epidemiology and related risk factors. This study showed an increased risk of suicide associated with exposure to night-time heat and provided evidence of the protective role of urban greenspaces in this association. Urban greenspaces have increased in Seoul, Korea, at varying levels in different districts. Therefore, night-time heat exposure should be considered when discussing suicide prevention programs, and we need to maximize the co-benefits of residential greenspaces in planning mitigation and adaptation strategies in the present day and under a changing climate corresponding to extreme heat.

Data availability statements

Suicide data used in this study were obtained from the Korean Statistical Office. These data are available upon request from the Korean Statistical Office MicroData Integrated Service website: [https://mdiskostatgokr/indexdo]. Meteorological and greenness data were obtained from the Google Earth Engine website, available at: [https://earthengine.google.com/].

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare no conflicts of interest. All authors have read the manuscript; agreed that the work is ready for submission to a journal, and accept responsibility for its content.

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