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Age-dependent links between urban greenness and suicide in Türkiye: A nationwide ecological study

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Abstract

This nationwide ecological study examined whether the availability of urban green infrastructure (UGI) and its seasonal dynamics are associated with age- and sex-specific suicide mortality rates across Türkiye. We delineated settlement polygons for all provincial and district centers. We paired them with Landsat-8-derived Normalized Difference Vegetation Index (NDVI) to compute annual, summer, and winter mean greenness and intra-annual NDVI variance for 2013-2019. We then assembled age- and sex-stratified suicide rates and nine provincial covariates from the socioeconomic, hydroclimatic, and air quality domains. Analyses included correlations, ordinary least squares with robust errors, optimal-scaling CAT-PCA, pooled PCA with principal-components regression, and canonical correlation analysis. The national mean urban NDVI was 0.124 (whole-province mean: 0.184). Total suicide showed no consistent bivariate association with greenness; however, clear life-course differences were observed between men and women. A higher mean NDVI was associated with lower suicide rates in adolescents and, to a lesser extent, in adults aged 20-39 years. However, the association was positive from age 40 onward. NDVI variance showed a mirror pattern—associated with higher suicide rates in youth but slightly lower rates in older adults—suggesting that both the amount and seasonality of vegetation have age-specific associations with suicide rates in this Turkish setting. Multivariable models supported these gradients: provinces with warmer climates, greater greenness, and seasonally stable vegetation tended to have lower adolescent suicide rates but higher mid-to-late life suicide rates. Temperature variability was the only environmental factor positively associated with suicide across all age-sex strata. These ecological associations are consistent with the age-dependent relationship between UGI and suicide and may help generate hypotheses for age-targeted prevention strategies. However, the cross-sectional, province-level design precludes any causal inference.

Keywords: Suicide, adolescence, aging, urban health, remote sensing, Türkiye

Introduction

Across cultures and centuries, writers, clinicians, and faith traditions have described the restorative effects of contact with nature. Contemporary research provides empirical support: exposure to natural environments, especially green environments, is linked to better cognition, mental health, and several physical outcomes [1,2]. In a public health framework, green spaces can support health-promoting behaviors such as walking, running, and active play, and these pathways are now embedded in models linking parks to physical activity [3]. Observational studies also suggest that greener neighborhoods are often associated with lower obesity and related metabolic risks, including type 2 diabetes [4,5]. Population-based evidence further links residential greenness to healthier birth outcomes, lower cardiometabolic morbidity, and more favorable blood pressure profiles in children [6-8].

Greenness has also been associated with reduced stress reactivity, improved mood, and a lower prevalence of common psychiatric disorders in several reviews [2,9]. Theoretical frameworks offer plausible explanations. Ulrich's affective/stress-reduction perspective proposes rapid psychophysiological calming responses to non-threatening natural scenes [10]. Kaplan's

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attention restoration theory suggests that softly fascinating natural settings replenish directed attention and support mental restoration [11]. Social pathways may also contribute; greener streetscapes can foster informal encounters, social cohesion, and physical co-presence [9]. Because social isolation is a recognized risk factor for suicidal behavior [12], these psychological and social ecosystem services provided by green infrastructure offer coherent pathways through which greenness may be associated with suicide.

Measuring "greenness" is not a straightforward process. Remote-sensing metrics, such as the Normalized Difference Vegetation Index (NDVI), provide spatially and temporally consistent estimates of vegetative cover across large areas and are widely used in health research [2,13]. Other indicators include land-use/land-cover classifications, percentage tree canopy, green-space proportion, street-tree buffers, distance to parks, and the street-level Green View Index (GVI). Perceived neighborhood greenness and in situ environmental audits add a human-scale context [2,13,14]. For urban planning and public health applications, these measures are increasingly combined into urban green infrastructure (UGI) assessments that link land management decisions to ecosystem services and health results.

The evidence linking greenness specifically to suicide is limited and mixed. Ecological studies conducted in Japan have reported inverse associations between green spaces and suicide mortality [15]. However, more recent studies using landscape indices have found complex or null relationships, depending on the metric used [16]. Studies from England, Egypt, and other settings often report weak, absent, or outcome-specific greenness-health links, highlighting the heterogeneity across populations and measurement scales [17-20]. Aggregated mortality studies that include suicide within broader outcome sets also yield inconsistent patterns [19,20]. A key limitation is that most studies adjusted for age or used age-standardized rates instead of modeling age-specific associations. Consequently, the potential life-course heterogeneity remains underexplored.

Seasonal dynamics represent a second gap. Remote-sensing time series allow researchers to characterize not only mean greenness but also intra-annual variability (e.g., phenological amplitude). However, few studies have examined whether suicide-greenness associations differ between locations with seasonally stable and strongly seasonal vegetation types. These dynamics may be important for specific population subgroups in the future. Adolescents might benefit from any available vegetation, whereas the outcomes in older adults could reflect interactions among greenness, climate, mobility limitations and social connectedness.

Türkiye provides an informative setting for this study. The country spans marked climatic and biogeographic gradients from Mediterranean to continental and shows wide provincial variations in socioeconomic conditions and urban form. Using satellite-derived NDVI for urban polygons and full provincial footprints over seven years (2013-2019), we examined whether greenness quantity and intra-annual NDVI variability were associated with age- and sex-stratified suicide mortality across all 81 provinces. We situate these analyses within the literature on urban green infrastructure and ecosystem services to explore how greenness metrics can inform landscape planning and life-stage-sensitive public health strategies. We hypothesized (i) inverse greenness-suicide associations in younger populations, (ii) possible attenuation or reversal in older age groups, and (iii) modifying roles for climatic and socioeconomic covariates.

Material and Methods

Study Area and Design

This nationwide ecological study included all 81 Turkish provinces. We conducted five main steps. First, we delineated urban settlement polygons for every provincial and district center in the country. Second, we extracted greenness metrics—seven-year mean NDVI and intra-annual NDVI variability—within those polygons and within full provincial footprints for 2013-2019. Third, we compiled age- and sex-stratified suicide statistics for this period. Fourth, we assembled nine climatic and socioeconomic covariates. Finally, we tested bivariate and multivariate associations between greenness indicators and suicide mortality.

Delineation of Urban Green Infrastructure

Urban-Polygon Mapping

Because administrative boundaries in Türkiye often extend beyond built-up areas, we manually digitized settlement envelopes in Google Earth Pro (camera height=2500 m; WGS-84, EPSG:4326) using a graphics tablet (Figure 1). The polygons were saved as KML, converted to the shapefile (SHP) format, and uploaded to the Google Earth Engine (GEE). The final dataset included 80 provincial centers, 787 peripheral districts, and 39 district centers in Istanbul, which has no single "central" district. To assess inter-observer error, provincial and district centers were randomly allocated to two independent researchers for blinded digitization of the data. We assessed the agreement on the downstream NDVI summaries using two-sided paired tests (t-test or Wilcoxon signed-rank test for non-normal data), the intraclass correlation coefficient (ICC[2,1]; absolute agreement), and Bland-Altman plots. No statistically significant mean differences were detected; the ICC indicated excellent reliability; and the Bland-Altman plots showed negligible bias with narrow 95% limits of agreement.

Provincial Boundaries

Total-area provincial shapefiles (urban + rural) were obtained from the General Directorate of Mapping of the Turkish Republic [21].

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Figure 1. Workflow for defining urban polygons used for NDVI extraction. Top: Base map of the Aksaray city center. Middle: Corresponding Google Earth satellite image. Bottom: Manually digitized urban settlement boundary (red polygon) superimposed on the satellite layer. This boundary file was exported as KML/SHP and used to clip Landsat-8 imagery for all 81 provincial capitals and 826 districts

Greenness Metrics (NDVI)

Image Collection and Cloud Mask

We used Landsat 8 Collection 2 Level-2 surface reflectance imagery (LANDSAT/LC08/C02/T1_L2) for the analysis. A custom JavaScript in GEE masked the clouds and shadows using the QA_PIXEL bit mask. The images were resampled to 100 m using a median reducer.

Derivation of Mean and Seasonal NDVI Metrics

For each polygon, we computed the monthly mean NDVI from January 2013 to December 2019 and derived the following:

i. **Summer NDVI:** May-October mean

ii. **Winter NDVI**: November-April mean

iii. **Whole-year NDVI:** 12-month mean; and

iv. **NDVI variance:**

The NDVI variance was defined as the statistical variance of the 12 calendar month means and used as an index of intra-annual (seasonal) greenness fluctuations. In practice, for each city and district center polygon and for each full provincial footprint, we first averaged all valid NDVI pixels within each calendar month across the 2013-2019 period to obtain a 12-value monthly NDVI profile for each polygon. Subsequently, we calculated the variance of the 12 values. Higher NDVI variance values indicate stronger seasonal fluctuations between summer and winter greenness, whereas values near zero indicate seasonally stable vegetation. A more detailed description of the NDVI preprocessing workflow and monthly image counts is provided in Supplementary Material A.1-A.3.

Province-level urban NDVI metrics were calculated as population-weighted averages of the city- and district-center NDVI values, with each polygon weighted by its mean mid-year population over the study period so that larger settlements contributed proportionally more to the provincial estimate. The same population-weighting scheme was applied to the summer, winter, annual, and variance-based NDVI metrics. Whole-province NDVI metrics were computed analogously over the total provincial footprint (urban + rural areas).

Suicide Data

Annual female, male, and total suicide counts (2013-2019) and mid-year population estimates were downloaded from the Turkish Statistical Institute (TÜİK) open data portal. Seven-year average incidence rates (per 100,000) were calculated for the total, sex-specific, and four age groups (<20, 20-39, 40-59, and ≥60 y).

Covariates

To reduce residual confounding, we included all provincial variables with complete coverage from 2013 to 2019.

i. **Socioeconomic factors:** divorce rate, unemployment rate, GDP per capita, and mean years of education

ii. **Environmental quality:** 7-year mean PM_{10} concentration (Clean Air Rights Platform/Temiz Hava Hakkı)

iii. **Hydro-climate:** mean daily sunshine, mean air temperature, mean diurnal temperature range, and annual rainy day count

All nine variables were averaged over 2013-2019 and z-standardized before being entered into the multivariate models. These variables were included as standard socioeconomic confounders in ecological suicide research and to construct the integrated "greenness + affluence" factor (F1) used in the PCA/PCR analyses.

Inclusion and Exclusion Criteria

Images flagged as clouds or shadows were excluded from this study. Each polygon required ≥1 valid image per month, and the final image counts per province-month cell ranged from 5 to 121. Image count summaries are provided at Zenodo (DOI: 10.5281/zenodo.15644396).

Data and Code Availability

All shapefiles, monthly NDVI rasters, suicide rate spreadsheets, and complete analysis scripts are openly archived on Zenodo (DOI: 10.5281/zenodo.15644396). The Google Earth Engine code is included in .js file.

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Statistical Analysis

Correlation and Simple Linear Regression

Normality was assessed using the Kolmogorov-Smirnov test, and skewed variables were log-transformed. Pearson or Spearman correlations linked NDVI metrics to suicide rates. Simple ordinary least-squares (OLS) models regressed each suicide outcome on a single NDVI predictor; we report β-coefficients, HC-robust standard errors, R^2, and F-statistics.

Categorical Principal Components Analysis (CAT-PCA)

To reduce dimensionality while respecting mixed measurement levels, we applied optimal-scaling CAT-PCA separately to (i) nine greenness metrics and (ii) ten socioeconomic/climatic variables. All inputs were z-standardized; the coastal dummy was treated as nominal, and the remaining variables as numeric. Under principal normalization and Varimax rotation, two components per block (eigenvalue>1; scree inflection) jointly explained approximately 40% of the inertia. Loadings |≥0.40| were considered salient. CAT-PCA follows the procedure of Çamdeviren et al. [22] and Keskin et al. [23], who recommend factor scores for subsequent regression analyses.

Pooled Conventional PCA and Principal Components Regression (PCR)

All 19 predictors were entered into a single PCA (varimax, eigenvalue>1). Two orthogonal factors emerged: F1, greenness + affluence, and F2, hydro-climatic/socio-environmental stress, which jointly accounted for approximately 60% of the total variance in the model. Age- and sex-specific suicide rates were projected as supplementary variables, and the resulting factor scores were used as covariates in HC3-robust OLS models for total, male, female, and four age-stratified outcomes. This PCR strategy addresses multicollinearity and condenses the predictors into interpretable axes. It also reduces the risk of overfitting, which would occur if all 19 correlated predictors were entered directly into the models with only 81 provinces. In practice, each regression model included at most four orthogonal PCs (F1-F4), yielding an effective sample-to-parameter ratio of approximately 20:1 (81 provinces, ≤4 continuous predictors) and avoiding stepwise variable selection [23,24]. Diagnostics (scree, loadings, and residual plots) and further details are provided in the Supplementary Material.

Canonical Correlation Analysis (CCA)

To examine multivariate associations between the predictor set X (11 climatic-demographic variables) and Y (four age-specific suicide rates), we performed CCA, estimating linear composites

$$U_1=a^TX, \quad V_1=b^TY$$

that maximizes the correlation [25]. All variables were z-standardized, and multivariate normality and variance inflation factors (VIF<5) supported the assumptions. Significance was tested using Wilks' Λ and Bartlett's χ^2 approximation; only the first root was significant ($\Lambda=0.23$, $\chi^2=180.3$, df=44, $p<0.001$). The interpretation relied on the structure coefficients ($|r| \geq 0.30$) and the redundancy indices. Analyses were run in R 4.3 (packages: stats, CCP, yacca) and replicated in Stata 18. Full coefficients and loading plots are provided in Supplements A and B.

Assumption Checks and Multicollinearity Diagnostics

All continuous predictors were z-standardized before the analysis. For correlation, OLS, and principal components regression models, we examined distributional shapes and Q-Q plots to confirm the approximate normality of residuals and inspected residual-versus-fitted and scale-location plots to assess homoscedasticity. Leverage values and Cook's distances were used to identify influential provinces. No single province exerted undue influence, and the HC3-robust standard errors were retained throughout. To evaluate multicollinearity among the original covariates, we computed the variance inflation factors; the largest VIF was below five, indicating no severe collinearity. For the canonical correlation analysis, we checked for multivariate normality. We ensured an observation-to-variable ratio of>7:1. We then tested the significance of the canonical roots using Wilks' Λ and Bartlett's χ^2, following best-practice recommendations for epidemiological applications. Full diagnostics and additional details are provided in the Supplementary Materials (A. 4-A. 5).

Ethics Statement

All data analyzed in this study are publicly available at the provincial level and contain no personal identifiers (TÜİK suicide counts, Landsat-8 NDVI imagery, national socioeconomic, meteorological, and air quality statistics). As no individual-level information was used, this study did not constitute human subjects research and did not require ethics committee approval or informed consent. This study adhered to the principles of the Declaration of Helsinki and the COPE guidelines.

Results

Descriptive Statistics

The population-weighted urban NDVI mean for Türkiye's 81 provinces (2013-2019) was 0.124, and the corresponding whole province NDVI mean was 0.184. Unweighted urban values were: mean 0.131 (median 0.124; min 0.087; max 0.219; SD 0.026), urban-summer NDVI 0.155 (SD 0.033), and urban-winter NDVI 0.108 (SD 0.030). Rize, Düzce, and Ordu ranked highest for average urban greenness, whereas Bayburt, Gaziantep, and Erzurum ranked lowest (Table 1; Figure 2).

For full provincial footprints, the mean NDVI was 0.169 (SD 0.057), 0.209 (SD 0.068), and 0.129 (SD 0.061) in the annual, summer, and winter seasons, respectively. Bartın, Düzce, and Zonguldak showed the greatest provincial greenness, whereas Van, Ağrı, and Hakkâri showed the least (Table 2; Figure 2).

Nationally, the average suicide incidence (2013-2019) was 4.12 per 100,000 (men: 6.16; women: 2.05). The provincial means were 4.34 (total), 7.55 (male), and 2.54 (female) per 100,000 (Table 3; Figures 3-4). Tunceli, Ardahan, and Burdur recorded the highest total incidence; Bayburt, Gümüşhane, and Sakarya the lowest.

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Table 1. Urban NDVI values for all 81 provinces

Province	Urban Average NDVI	Urban Summer NDVI	Urban Winter NDVI	Urban NDVI Variance
Adana	0.115	0.125	0.105	0.004
Adıyaman	0.118	0.134	0.102	0.011
Afyonkarahisar	0.144	0.166	0.122	0.016
Ağrı	0.104	0.157	0.052	0.060
Amasya	0.132	0.154	0.110	0.013
Ankara	0.110	0.130	0.091	0.012
Antalya	0.147	0.149	0.145	0.002
Artvin	0.155	0.189	0.121	0.022
Aydın	0.150	0.151	0.149	0.003
Balıkesir	0.139	0.142	0.135	0.005
Bilecik	0.121	0.142	0.101	0.013
Bingöl	0.115	0.154	0.075	0.037
Bitlis	0.129	0.186	0.072	0.059
Bolu	0.139	0.180	0.097	0.044
Burdur	0.134	0.156	0.112	0.013
Bursa	0.132	0.146	0.118	0.007
Çanakkale	0.144	0.153	0.135	0.008
Çankırı	0.130	0.164	0.096	0.029
Çorum	0.123	0.149	0.098	0.018
Denizli	0.138	0.149	0.126	0.006
Diyarbakır	0.118	0.120	0.116	0.011
Edirne	0.151	0.169	0.133	0.012
Elazığ	0.115	0.130	0.100	0.011
Erzincan	0.115	0.154	0.075	0.032
Erzurum	0.092	0.141	0.043	0.044
Eskişehir	0.118	0.137	0.100	0.008
Gaziantep	0.089	0.092	0.086	0.002
Giresun	0.190	0.228	0.151	0.030
Gümüşhane	0.117	0.151	0.083	0.023
Hakkâri	0.106	0.162	0.050	0.057
Hatay	0.146	0.151	0.141	0.004
Isparta	0.131	0.157	0.105	0.014
Mersin	0.124	0.128	0.119	0.002
İstanbul	0.109	0.120	0.097	0.004
İzmir	0.115	0.111	0.120	0.001
Kars	0.115	0.179	0.052	0.069
Kastamonu	0.141	0.179	0.102	0.029
Kayseri	0.109	0.131	0.088	0.015
Kırklareli	0.166	0.182	0.150	0.012
Kırşehir	0.125	0.154	0.096	0.025
Kocaeli	0.142	0.155	0.130	0.007

Province	Urban Average NDVI	Urban Summer NDVI	Urban Winter NDVI	Urban NDVI Variance
Konya	0.119	0.139	0.098	0.011
Kütahya	0.119	0.142	0.097	0.012
Malatya	0.116	0.138	0.094	0.013
Manisa	0.126	0.130	0.121	0.003
Kahramanmaraş	0.121	0.142	0.100	0.016
Mardin	0.107	0.105	0.110	0.009
Muğla	0.158	0.156	0.160	0.002
Muş	0.116	0.167	0.064	0.056
Nevşehir	0.096	0.118	0.074	0.011
Niğde	0.111	0.130	0.091	0.009
Ordu	0.190	0.229	0.151	0.030
Rize	0.219	0.260	0.178	0.031
Sakarya	0.170	0.198	0.142	0.017
Samsun	0.155	0.179	0.131	0.014
Siirt	0.114	0.123	0.106	0.010
Sinop	0.139	0.137	0.142	0.014
Sivas	0.107	0.137	0.078	0.020
Tekirdağ	0.150	0.157	0.143	0.008
Tokat	0.139	0.165	0.113	0.016
Trabzon	0.173	0.204	0.143	0.020
Tunceli	0.124	0.155	0.094	0.027
Şanlıurfa	0.094	0.092	0.095	0.003
Uşak	0.121	0.136	0.107	0.008
Van	0.116	0.166	0.066	0.045
Yozgat	0.121	0.149	0.092	0.021
Zonguldak	0.167	0.204	0.129	0.025
Aksaray	0.117	0.135	0.098	0.014
Bayburt	0.087	0.128	0.046	0.035
Karaman	0.106	0.122	0.091	0.008
Kırıkkale	0.115	0.140	0.090	0.020
Batman	0.115	0.122	0.107	0.010
Şırnak	0.111	0.108	0.115	0.012
Bartın	0.182	0.225	0.140	0.031
Ardahan	0.124	0.214	0.034	0.122
Iğdır	0.148	0.199	0.098	0.043
Yalova	0.169	0.185	0.154	0.010
Karabük	0.145	0.178	0.113	0.023
Kilis	0.096	0.095	0.097	0.003
Osmaniye	0.161	0.178	0.144	0.009
Düzce	0.202	0.233	0.171	0.024

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Table 2. Provincial border NDVI values for all 81 provinces

Province	Province Average NDVI	Province Summer NDVI	Province Winter NDVI	Province NDVI Variance	Province	Province Average NDVI	Province Summer NDVI	Province Winter NDVI	Province NDVI Variance
Adana	0.176	0.198	0.153	0.001	Konya	0.121	0.145	0.098	0.001
Adıyaman	0.124	0.127	0.121	0.001	Kütahya	0.190	0.215	0.165	0.001
Afyonkarahisar	0.150	0.171	0.129	0.002	Malatya	0.109	0.139	0.078	0.002
Ağrı	0.086	0.165	0.007	0.009	Manisa	0.198	0.209	0.187	0.000
Amasya	0.181	0.199	0.163	0.001	Kahramanmaraş	0.133	0.161	0.104	0.002
Ankara	0.127	0.146	0.107	0.002	Mardin	0.154	0.147	0.162	0.003
Antalya	0.181	0.199	0.163	0.001	Muğla	0.210	0.213	0.207	0.000
Artvin	0.181	0.265	0.097	0.008	Muş	0.106	0.173	0.040	0.008
Aydın	0.220	0.227	0.213	0.000	Nevşehir	0.109	0.129	0.090	0.002
Balıkesir	0.226	0.244	0.208	0.001	Niğde	0.104	0.138	0.070	0.002
Bilecik	0.202	0.236	0.167	0.002	Ordu	0.269	0.355	0.182	0.010
Bingöl	0.117	0.195	0.039	0.008	Rize	0.223	0.318	0.128	0.011
Bitlis	0.110	0.182	0.038	0.007	Sakarya	0.267	0.324	0.211	0.005
Bolu	0.210	0.257	0.162	0.003	Samsun	0.240	0.303	0.177	0.006
Burdur	0.157	0.176	0.139	0.001	Siirt	0.128	0.153	0.104	0.002
Bursa	0.223	0.261	0.186	0.002	Sinop	0.244	0.305	0.182	0.005
Çanakkale	0.235	0.254	0.216	0.001	Sivas	0.112	0.160	0.065	0.004
Çankırı	0.152	0.192	0.112	0.003	Tekirdağ	0.214	0.229	0.198	0.003
Çorum	0.157	0.190	0.123	0.003	Tokat	0.190	0.252	0.128	0.006
Denizli	0.172	0.187	0.156	0.001	Trabzon	0.244	0.339	0.150	0.011
Diyarbakır	0.148	0.149	0.148	0.003	Tunceli	0.119	0.182	0.055	0.005
Edirne	0.205	0.229	0.181	0.002	Şanlıurfa	0.141	0.135	0.147	0.001
Elazığ	0.110	0.130	0.089	0.002	Uşak	0.177	0.187	0.167	0.001
Erzincan	0.095	0.151	0.038	0.004	Van	0.069	0.136	0.001	0.006
Erzurum	0.098	0.179	0.017	0.008	Yozgat	0.132	0.163	0.102	0.003
Eskişehir	0.150	0.168	0.132	0.001	Zonguldak	0.279	0.355	0.202	0.008
Gaziantep	0.137	0.134	0.140	0.001	Aksaray	0.112	0.130	0.095	0.002
Giresun	0.206	0.281	0.130	0.008	Bayburt	0.100	0.178	0.023	0.008
Gümüşhane	0.136	0.207	0.065	0.006	Karaman	0.121	0.146	0.096	0.001
Hakkâri	0.092	0.162	0.022	0.007	Kırıkkale	0.126	0.146	0.107	0.002
Hatay	0.203	0.220	0.185	0.001	Batman	0.137	0.142	0.132	0.002
Isparta	0.143	0.170	0.115	0.002	Şırnak	0.129	0.151	0.108	0.002
Mersin	0.160	0.181	0.139	0.001	Bartın	0.290	0.370	0.209	0.009
İstanbul	0.234	0.273	0.195	0.003	Ardahan	0.146	0.280	0.011	0.021
İzmir	0.218	0.222	0.215	0.000	Iğdır	0.104	0.156	0.053	0.004
Kars	0.110	0.196	0.024	0.010	Yalova	0.269	0.325	0.214	0.005
Kastamonu	0.230	0.291	0.170	0.005	Karabük	0.233	0.295	0.172	0.005
Kayseri	0.106	0.143	0.068	0.003	Kilis	0.129	0.122	0.136	0.001
Kırklareli	0.244	0.290	0.198	0.004	Osmaniye	0.215	0.246	0.184	0.002
Kırşehir	0.121	0.140	0.102	0.002	Düzce	0.289	0.365	0.212	0.008
Kocaeli	0.270	0.318	0.222	0.004					

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Table 3. Suicide rates by province over the 7-year period (2013-2019) for total popula-tion, males, females, and different age groups

Province	TSR	MSR	FSR	<20	20-39	40-59	60<	Province	TSR	MSR	FSR	<20	20-39	40-59	60<
Adana	4.73	7.72	3.32	0.77	2.03	1.43	0.50	**Konya**	4.25	7.26	2.69	0.58	1.84	1.21	0.61
Adıyaman	3.60	6.02	2.36	0.66	1.54	0.91	0.49	**Kütahya**	4.21	7.88	2.01	0.32	1.29	1.34	1.24
Afyonkarahisar	5.21	8.87	3.33	0.86	2.10	1.32	0.94	**Malatya**	3.51	6.08	2.13	0.48	1.57	0.84	0.62
Ağrı	4.31	5.79	4.21	1.66	1.81	0.50	0.34	**Manisa**	4.59	8.23	2.44	0.53	1.64	1.35	1.06
Amasya	3.35	6.92	0.91	0.13	1.18	0.91	1.13	**Kahramanmaraş**	3.27	5.36	2.22	0.77	1.37	0.62	0.51
Ankara	3.79	6.94	1.94	0.35	1.67	1.20	0.57	**Mardin**	3.26	4.85	2.74	0.89	1.74	0.48	0.16
Antalya	4.46	7.77	2.59	0.41	1.90	1.44	0.72	**Muğla**	5.94	10.87	2.82	0.51	2.14	2.04	1.25
Artvin	3.12	5.66	1.58	0.08	1.01	1.18	0.84	**Muş**	5.91	7.59	6.15	2.48	2.41	0.59	0.42
Aydın	6.84	12.52	3.46	0.58	2.30	2.29	1.67	**Nevşehir**	3.57	6.23	2.15	0.49	1.32	1.17	0.59
Balıkesir	5.00	9.29	2.39	0.36	1.86	1.68	1.11	**Niğde**	5.03	9.36	2.37	0.85	2.11	1.18	0.89
Bilecik	5.42	10.41	1.93	0.26	1.72	1.98	1.45	**Ordu**	3.56	6.02	2.29	0.38	0.92	1.29	0.96
Bingöl	5.52	8.53	4.25	1.58	2.42	0.68	0.84	**Rize**	2.61	5.60	0.50	0.43	0.77	0.85	0.56
Bitlis	3.13	4.70	2.52	1.29	1.38	0.33	0.13	**Sakarya**	2.51	4.72	1.13	0.16	0.98	0.79	0.57
Bolu	4.02	8.34	1.11	0.48	1.58	0.91	1.05	**Samsun**	4.16	7.58	2.18	0.58	1.64	1.19	0.76
Burdur	7.07	12.07	4.42	0.82	2.39	1.96	1.90	**Siirt**	3.85	5.81	3.08	1.55	1.68	0.49	0.13
Bursa	4.19	7.97	1.80	0.28	1.53	1.56	0.83	**Sinop**	5.60	9.60	3.47	0.62	1.84	1.57	1.57
Çanakkale	4.89	8.75	2.58	0.38	1.69	1.78	1.04	**Sivas**	4.60	8.55	2.17	0.91	1.52	1.27	0.89
Çankırı	3.14	5.52	1.74	0.22	1.12	1.27	0.52	**Tekirdağ**	4.26	7.67	2.13	0.18	1.59	1.62	0.87
Çorum	4.56	8.88	1.81	0.57	1.67	1.43	0.89	**Tokat**	4.17	7.28	2.47	0.78	1.61	0.76	1.02
Denizli	6.09	11.27	2.98	0.57	2.38	2.11	1.04	**Trabzon**	3.76	6.16	2.65	0.57	1.59	1.06	0.55
Diyarbakır	4.40	6.37	3.86	1.52	1.90	0.73	0.25	**Tunceli**	8.40	13.70	4.81	0.34	3.53	1.51	3.02
Edirne	6.14	12.16	2.00	0.18	2.26	2.29	1.41	**Şanlıurfa**	2.98	3.98	2.96	0.88	1.36	0.49	0.25
Elazığ	4.85	8.38	2.97	0.52	2.22	1.21	0.91	**Uşak**	4.06	7.27	2.22	0.52	1.75	1.12	0.68
Erzincan	3.70	6.17	2.38	0.31	1.63	0.94	0.82	**Van**	4.59	6.25	4.41	1.58	2.14	0.66	0.21
Erzurum	3.63	5.93	2.53	0.86	1.50	0.80	0.47	**Yozgat**	3.39	6.10	1.79	0.64	0.87	1.31	0.57
Eskişehir	5.83	10.86	2.76	0.41	2.34	1.86	1.22	**Zonguldak**	4.32	7.21	2.92	0.33	1.34	1.34	1.31
Gaziantep	3.58	5.84	2.49	0.75	1.75	0.81	0.28	**Aksaray**	2.95	5.31	1.59	0.61	1.01	0.97	0.36
Giresun	2.97	5.31	1.67	0.23	1.57	0.82	0.36	**Bayburt**	1.57	2.85	0.84	0.35	1.05	0.17	0.00
Gümüşhane	1.80	3.16	1.08	0.45	0.90	0.27	0.18	**Karaman**	6.17	12.10	2.31	1.11	2.33	1.98	0.76
Hakkâri	3.87	5.76	2.99	0.83	2.06	0.72	0.26	**Kırıkkale**	4.38	8.64	1.56	0.46	1.65	1.54	0.72
Hatay	2.71	4.84	1.46	0.45	1.27	0.66	0.33	**Batman**	3.41	5.11	2.84	0.89	1.76	0.57	0.20
Isparta	5.86	10.41	3.25	0.77	2.40	1.36	1.33	**Şırnak**	3.72	5.96	2.51	1.23	1.77	0.46	0.26
Mersin	5.03	8.40	3.36	0.65	2.09	1.34	0.95	**Bartın**	5.03	8.55	3.24	0.52	1.40	1.18	1.92
İstanbul	3.22	5.82	1.67	0.25	1.56	0.97	0.43	**Ardahan**	7.78	13.61	4.17	1.15	3.31	1.87	1.44
İzmir	5.04	9.31	2.47	0.35	1.97	1.63	1.09	**Iğdır**	3.97	6.82	2.30	0.74	1.91	0.88	0.44
Kars	5.68	8.93	4.14	1.42	2.11	1.47	0.69	**Yalova**	2.93	5.46	1.37	0.06	1.47	1.00	0.41
Kastamonu	4.84	8.42	2.92	0.61	1.49	1.49	1.26	**Karabük**	3.63	6.89	1.54	0.42	0.83	1.25	1.13
Kayseri	4.98	8.17	3.45	0.67	2.15	1.49	0.67	**Kilis**	4.79	7.33	3.75	1.60	2.02	0.96	0.21
Kırklareli	4.96	9.73	1.65	0.28	1.18	2.03	1.46	**Osmaniye**	4.15	6.86	2.78	0.77	1.59	0.88	0.91
Kırşehir	4.32	8.23	1.86	0.74	0.99	1.42	1.17	**Düzce**	3.62	6.82	1.62	0.27	1.16	1.23	0.96
Kocaeli	3.31	5.77	1.91	0.17	1.44	1.16	0.54								

TSR: Total Suicide Rate; MSR: Male Suicide Rate; FSR: Female Suicide Rate; <20: Total Suicide Rate Under the Age of 20; 20-39: Total Suicide Rate for Ages 20 to 39; 40-59: Total Suicide Rate for Ages 40 to 59; 60<: Total Suicide Rate for Ages 60 and over

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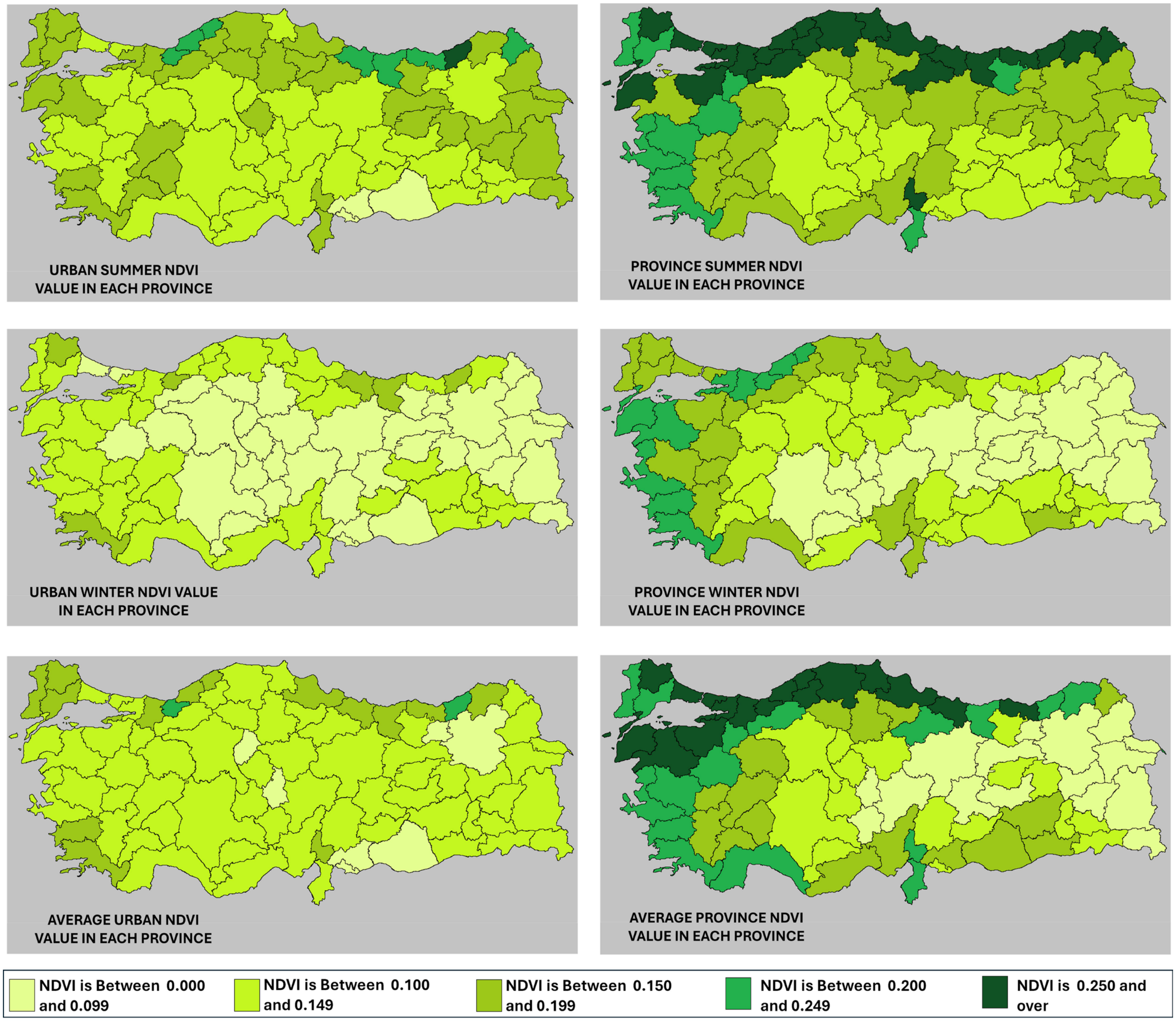

Figure 2. Spatial distribution of NDVI metrics in Türkiye from 2013 to 2019. Left column: urban polygons; right column: entire province footprints. Rows depict summer (May-October), winter (November-April), and annual mean NDVI values. The shading classes correspond to quintiles, with darker green shades indicating higher vegetation density

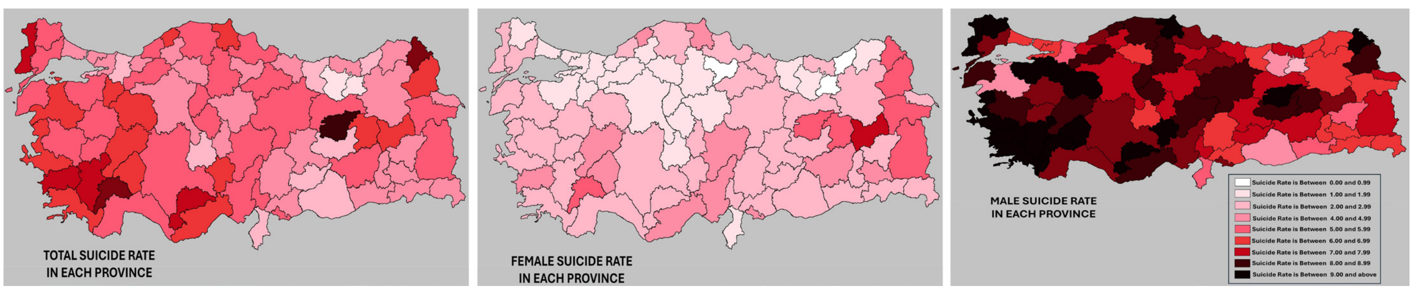

Figure 3. Provincial suicide incidence (per 100,000 population) averaged over 2013-2019. Top: total population. Middle: females. Bottom: males. The color scale progresses from light pink (lowest decile) to black (highest decile); class breaks are shown in the legend

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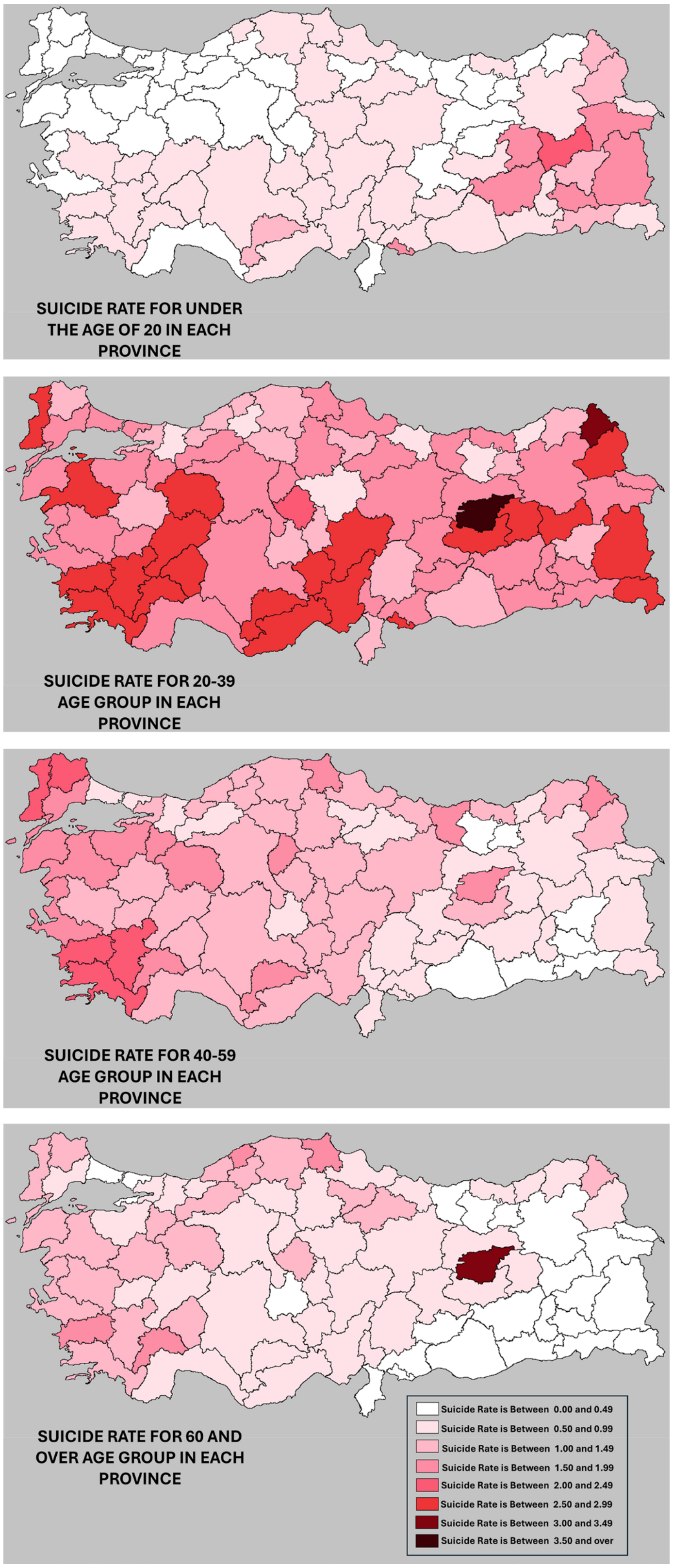

Figure 4. Age-specific suicide incidence (per 100,000 population) by province. The panels show rates for (i)<20 years, (ii) 20-39 years, (iii) 40-59 years, and (iv) ≥ 60 years. Color ramps are identical across panels to facilitate visual comparison; legends denote equal-interval classes of 0.5 per 100,000

Correlations

Bivariate tests revealed no association with total suicide; however, clear sex- and age-specific patterns were observed. Female suicide was weakly and negatively correlated with several mean-NDVI metrics ($r \approx 0.24$), and male suicide showed no consistent links, except for a modest inverse correlation with provincial NDVI variance, which is defined as the variance of the 12 monthly mean NDVI values and is thus an index of intra-annual (seasonal) greenness variability.

Age group results diverged sharply. High vegetation was strongly associated with low suicide rates in adolescents and young adults (r down to −0.56) but was positively associated with suicide from age 40 onward (r up to +0.47). The NDVI variance showed the opposite pattern, being associated with higher suicides in youth and slightly lower rates later in life. The full correlation matrices are presented in Supplement B.1.

Simple Linear Regression

Univariate OLS models confirmed these trends. A one-SD increase in provincial winter NDVI was associated with a 0.55-SD lower suicide rate in those aged <20 years, yet with a 0.39-SD higher rate in the 40-59 year group. Mean greenness was inversely associated with suicide among women and younger individuals but showed neutral or positive associations among mid- and late-life adults. NDVI variance showed the opposite slope, suggesting that both greenness quantity and seasonal dynamics (low vs. high intra-annual variability) have age-specific statistical associations with suicide rates. Eight full regression tables are provided in Supplementary Material B.2.

Multivariate Analyses

Pooled Principal-Components Ordination of Greenness, Climate, And Socio-Economic Predictors

Pooled principal component ordination (Figure 5) located the total, male, and female suicide vectors in a two-dimensional space defined by F1 (greenness + affluence, 34%) and F2 (hydroclimatic/seasonal variability stress, 25%). Total mortality was located near the origin, but the male vector was pulled toward the high-unemployment/air pollution quadrant, whereas the female vector aligned with the warm-green, affluent pole. The underlying pooled component loadings and joint maps for environmental and socioeconomic predictors, together with the locations of the total, male, and female suicide vectors, are provided in Supplementary Materials B.3-B.5.

Age-stratified maps (Figure 6) revealed a life course inversion in the direction of this association. Suicide <20 y clusters in vegetation-scarce, high-variability provinces (far left of F1). The 20-39 y vector shifted slightly to the right, and the mid- and late-life vectors moved toward greener, seasonally uniform, and affluent settings. These patterns foreshadow the multivariate results, in which a higher mean NDVI is inversely associated with suicide in youth but shows neutral or positive associations after mid-life, whereas seasonal NDVI variability displays a mirror pattern.

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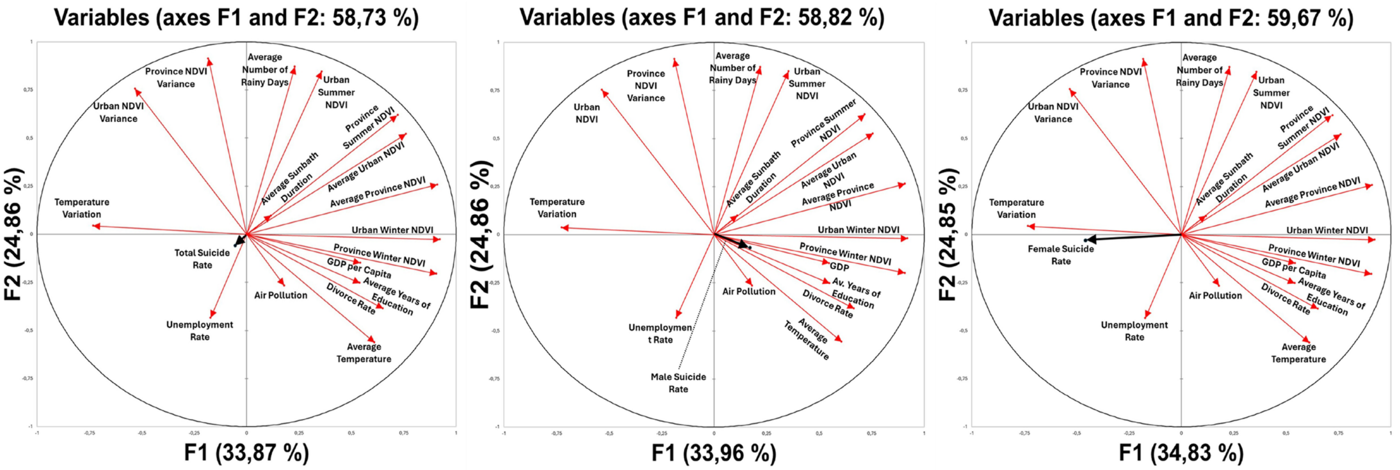

Figure 5. Pooled PCA correlation circles (axes F1 and F2) for male, female, and total populations. Red arrows: predictors; black arrow: outcomes (total, male, female,<20, 20-39, 40-59, ≥ 60 y). The percentage of variance explained is noted. F1=greenness + affluence, and F2=hydrological stress

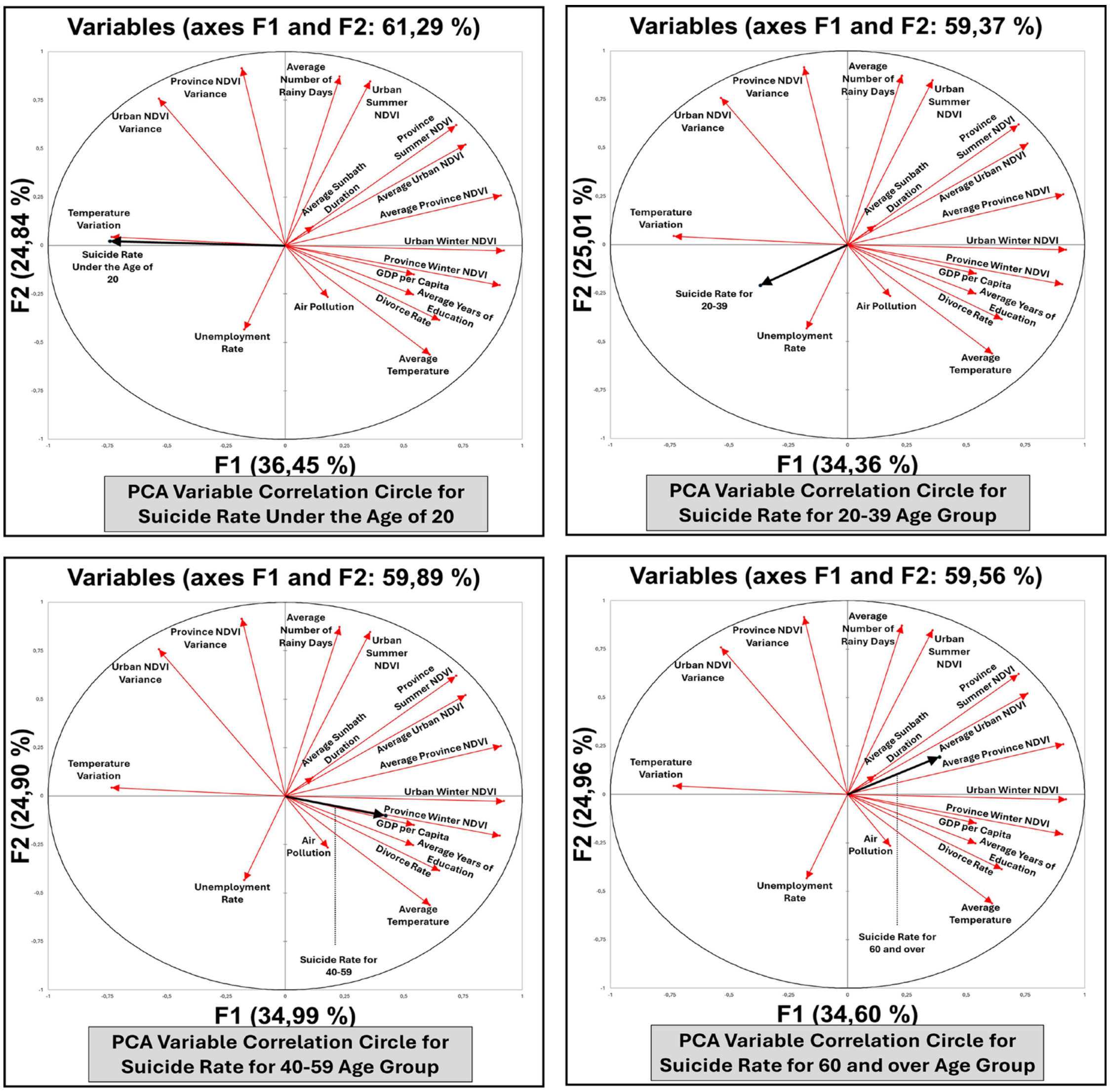

Figure 6. Pooled-PCA correlation circles (axes F1 and F2) for different age groups. Red arrows: predictors; black arrow: outcomes (total, male, female,<20, 20-39, 40-59, ≥ 60 y). Variance explained (%). F1=greenness + affluence and F2=hydro-climatic stress

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CAT-PCA and Pooled PCA

Optimal-scaling CAT-PCA extracted two components from the nine greenness metrics and two from the ten climate-socio-economic variables (joint inertia ≈40%). A pooled PCA on all 19 predictors yielded two orthogonal factors: F1=greenness + affluence (warm, seasonally stable provinces with low NDVI variance) and F2=hydro-climatic/socio-environmental stress (wet, seasonally variable provinces). Age- and sex-specific suicide rates were projected as supplementary variables. Detailed component loadings, variable correlation circles, and the positioning of age- and sex-specific suicide vectors relative to the socio-economic and hydro-climatic covariates are presented in Supplements B.3-B.6, respectively.

Principal-Components Regression

Four rotated PCs explained 78% of the predictor variance: F1 and F2, plus PC3 (affluence without labor market pressure), and PC4 (air pollution under low sunlight). Total suicide was not predicted by any PC; however, life course gradients were evident:

i. **Adolescents (<20 years):** suicide rates declined as F1, F2, and PC3 increased (R^2=0.59).

ii. **Young adults (20-39 years):** chiefly protected by F1 individuals.

iii. **Mid-life (40-59 years) and late-life (≥60 years)**: suicide increased with PC3 and, for seniors, with F2 (seasonally variable provinces).

iv. **Sex strata:** Male suicides increased with PC3, whereas female suicides decreased with F1 and PC3.

Across all models, temperature variability (negative on F1) was the only factor associated with higher suicide rates in all age and sex categories. Its association shifted from higher rates in vegetation-scarce settings during youth to higher rates in seasonally stable and greener settings after age 40. The loadings and coefficients are detailed in Supplement B.10 and Table 4, while the multivariate structure of the socioeconomic and hydroclimatic covariates underlying F1-F4 for total, male, female, and age-specific suicides is illustrated in Supplement B.3-B.6.

Table 4. Results of principal components regression analysis (n=81)

	Predictor	β	SE	95% CI	p-value
MODEL 1 TOTAL SUICIDE RATE	PC1	-0.149	0.111	[-0.370, 0.072]	0.183
	PC2	-0.012	0.111	[-0.233, 0.209]	0.914
	PC3	0.166	0.111	[-0.055, 0.387]	0.139
	PC4	0.093	0.111	[-0.128, 0.314]	0.405
MODEL 2 MALE SUICIDE RATE	PC1	-0.086	0.105	[-0.295, 0.123]	0.415
	PC2	0.037	0.105	[-0.172, 0.246]	0.726
	PC3	0.382	0.105	[0.173, 0.591]	<0.001*
	PC4	0.099	0.105	[-0.110, 0.308]	0.349
MODEL 3 FEMALE SUICIDE RATE	PC1	-0.212	0.102	[-0.415, -0.009]	0.041*
	PC2	-0.126	0.102	[-0.329, 0.077]	0.221
	PC3	-0.377	0.102	[-0.580, -0.174]	<0.001*
	PC4	0.064	0.102	[-0.139, 0.267]	0.532
MODEL 4 SUICIDE RATE<20 YEARS	PC1	-0.346	0.073	[-0.491, -0.201]	<0.001*
	PC2	-0.171	0.073	[-0.316, -0.026]	0.022*
	PC3	-0.663	0.073	[-0.808, -0.518]	<0.001*
	PC4	0.060	0.073	[-0.085, 0.205]	0.414
MODEL 5 SUICIDE RATE 20-39 YEARS	PC1	-0.264	0.108	[-0.479, -0.049]	0.017*
	PC2	-0.195	0.108	[-0.410, 0.020]	0.075
	PC3	-0.025	0.108	[-0.240, 0.190]	0.818
	PC4	0.069	0.108	[-0.146, 0.284]	0.525
MODEL 6 SUICIDE RATE 40-59 YEARS	PC1	0.113	0.088	[-0.062, 0.288]	0.203
	PC2	0.071	0.088	[-0.104, 0.246]	0.422
	PC3	0.624	0.088	[0.449, 0.799]	<0.001*
	PC4	0.105	0.088	[-0.070, 0.280]	0.237
MODEL 7 SUICIDE RATE ≥ 60 YEARS	PC1	0.095	0.100	[-0.104, 0.294]	0.345
	PC2	0.247	0.100	[0.048, 0.446]	0.016*
	PC3	0.412	0.100	[0.213, 0.611]	<0.001*
	PC4	0.005	0.100	[-0.194, 0.204]	0.960

*: p<0.05

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Canonical-Correlation Analysis

The CCA linked 11 climatic-demographic predictors and four age-specific suicide rates. One significant canonical pair emerged (Wilks' Λ=0.23, χ^2=180.3, df=44, p<0.001), with r=0.88 (R^2=0.77). The predictor composite (U_1) described warm, affluent provinces with seasonally stable greenness, low temperature variability, and low unemployment rates. The outcome composite (V_1) loaded negatively on adolescent suicide and positively on the 40-59 and ≥60 y rates. Thus, warm, affluent provinces with seasonally stable greenness show lower adolescent suicide but higher mid- and late-life suicide rates, reinforcing the age-reversal identified in the PCA-regression analyses. The full coefficients and loading plots are presented in Supplement B.11.

In the multivariate models, unemployment and PM_{10} were mainly associated with higher male suicide rates. Female suicide was most strongly associated with unemployment, and greenness had negligible independent effects. Adolescent suicide clustered in cooler, more climatically variable, and less affluent areas. Mid- and late-life suicide increased with the "greenness + affluence" factor, which combines a higher NDVI with a higher GDP and education.

Discussion

This nationwide ecological study shows that the relationship between provincial urban green infrastructure (UGI) availability and suicide is not linear and is not uniformly associated with lower suicide rates. Simple correlations, age-stratified regressions, and multivariate models revealed three patterns. First, vegetation scarcity is strongly associated with higher suicide rates in adolescents and, more modestly, in young adults aged 20-39 years, even after adjusting for climate and socioeconomic factors. Second, from mid-life onward, the direction of the association reverses: greener and more economically affluent provinces with low intra-annual NDVI variability— that is, seasonally stable greenness—have the highest suicide rates, especially among adults aged ≥60 years. Third, temperature variability was the only environmental indicator consistently associated with higher suicide rates across all age and sex groups. In contrast, unemployment and particulate air pollution showed stronger associations with male suicide. Together, these findings suggest that the relationship between green spaces and suicide rates depends on the population age structure and seasonal dynamics of vegetation. Because we did not quantify within-province spatial patchiness, future studies should test whether heterogeneity in access to green spaces modifies these age-divergent patterns.

The biophilia hypothesis proposes an evolved human affinity for nature [1], and empirical evidence shows that contact with green spaces can produce psychophysiological benefits [2]. As urbanization increases and pollutants accumulate, expanding urban green infrastructure (UGI) is viewed as a strategy that can provide multiple ecosystem services, including air filtration, noise reduction, moderation of ambient temperatures, stormwater management, and improved groundwater [26-30]. Reported health benefits range from lower obesity and type 2 diabetes in greener neighborhoods [4,5] to improved cardiometabolic, obstetric, and cognitive outcomes [6-8]. Mechanistically, the UGI may support stress recovery [10], attention restoration [11], and social cohesion [9]. These pathways could buffer suicide risk, given the established link between social isolation and suicidal behavior [12].

Quantifying greenness is not a straightforward process. The NDVI, derived from satellite imagery, is the most widely used metric because it captures both large and small vegetation elements [2,13]. Other approaches include land cover maps, buffers based on distance to parks, perceived greenness questionnaires, and the street-level GVI [13,14]. Each metric reflects a different dimension of UGI. Therefore, our NDVI-based results warrant replication with GVI and perception-based measures to determine whether street-level or experiential greenness modifies the life course patterns observed here.

The suicide-greenness literature is thus heterogeneous. Several ecological studies have reported inverse associations [31-33], whereas others have found null or mixed results [15,19] or positive links for certain landscape configurations [34,35]. A recent systematic review of suicidal ideation and self-harm reported six studies with protective associations and three with null findings [36]. One explanatory gap is age stratification: only one previous study explicitly modelled age-specific associations [37]. Our finding that greenness has a strong inverse association with suicide in youth but weaker, sometimes positive associations in older adults living amid seasonally stable greenness shows how opposite-direction patterns can cancel out in age-aggregated analyses and produce conflicting results. The observed late-life excess is compatible with social isolation mechanisms as a possible explanation. However, because the design is ecological and cross-sectional, and we lack data on social networks or time spent outdoors, this should be viewed as hypothesis-generating rather than as evidence of a causal effect.

Covariate selection also influences ecological inferences. Prior studies have frequently adjusted for sex, age, economic indicators, air pollution, and marital status [18,38]. We included nine province-level covariates—four socioeconomic, four hydroclimatic, and PM_{10}—plus unemployment and divorce to minimize confounding. Temperature variability emerged as a robust correlate of higher suicide rates across the life course, consistent with studies linking thermal stress to suicidal behavior [39]. Its association with greenness reversed after age 40, shifting from higher rates in vegetation-scarce settings for youth to higher rates under seasonally stable greenness for older adults. This pattern suggests that, if confirmed by future causal and individual-level studies, UGI programs aimed at suicide prevention may need to be life-stage specific. Increasing accessible vegetation where it is scarce, for example, in schoolyards and youth recreation areas, could be beneficial for

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adolescents. In greener, seasonally stable, low-density settings, interventions that enhance social connectedness (e.g., age-friendly park programming or green corridor activation) may help address late-life vulnerability.

Socioeconomic and hydroclimatic indicators were not modelled as primary exposures but as contextual determinants that may confound or modify the associations between greenness and suicide. In line with previous ecological studies, the covariate block comprised divorce and unemployment rates, GDP per capita, mean years of education, PM_{10}, mean temperature, temperature variability, sunshine duration, and rainy-day count, all averaged over 2013-2019 [18,38]. Dimension-reduction analyses showed that these variables clustered into an "affluence/greenness" axis and a "hydroclimatic and socio-environmental stress" axis. We then used these axes as orthogonal components in the PCR and canonical correlation analyses. This strategy reduced collinearity, allowed routine adjustment for well-established socioeconomic risk factors, and placed the NDVI-suicide gradients within a broader climatic and labor market context. Detailed age- and sex-specific loading patterns and their alignment with greenness and suicide across provinces are reported in the Supplementary Materials (B. 3-B. 6).

Across the multivariate models, the covariates showed clear but age- and sex-specific patterns. Male suicide was associated with provinces characterized by labor market strain and environmental pollution, reflecting higher unemployment and PM_{10} under warmer, drier, and more thermally variable conditions. Female suicide was more strongly related to unemployment in economically disadvantaged provinces and showed little independent association with greenness. Adolescent suicide clustered in cooler, more thermally variable, and less affluent provinces with scarce vegetation and high NDVI variability. In contrast, mid- and late-life suicides increased in warmer, greener, and more affluent settings with seasonally stable vegetation and, in seniors, additional hydro-climatic stress. Principal component regression and canonical correlation analyses confirmed that temperature variability was the only environmental factor consistently associated with higher suicide rates across all age-sex strata. The age-graded inversion in the greenness-suicide association—from a strongly inverse association in youth to neutral or even positive associations in older adults—persisted after adjusting for socioeconomic and climatic structures.

Limitations include the ecological, cross-sectional design, which precludes causal inference and leaves room for residual confounding, potential exposure misclassification, lack of within-province spatial-configuration metrics, and absence of individual-level confounders, such as mental health service availability or psychiatric morbidity. In addition, the suicide data were obtained from the TÜİK vital registration system and may be affected by under-reporting and misclassification of the cause of death because of stigma, regional differences in certifying practices, and possible changes in coding conventions over time. Such errors are likely to be largely non-differential with respect to greenness and would therefore tend to attenuate rather than inflate the observed associations. However, they may still blur finer age- and sex-specific gradients, particularly in sparsely populated provinces and the youngest age group, where absolute numbers are small. Nevertheless, the nationwide scope, seven-year averaging of suicide rates, and comprehensive covariate set strengthen the generalizability and internal validity of the findings, although some residual model overfitting cannot be entirely excluded, given the modest number of provinces (n=81).

Conclusion

In all 81 provinces of Türkiye, greenness was associated with suicide only when age was considered. The scarcity of vegetation was associated with markedly higher adolescent suicide rates, whereas adults aged ≥40 years had the highest suicide rates in greener, affluent provinces, where vegetation remained seasonally stable. Temperature variability was the only environmental indicator positively associated with suicide in every age and sex group. These ecological findings suggest that the mental health relevance of urban green infrastructure (UGI) may be life-stage specific. However, the cross-sectional, province-level design and potential residual confounding mean that causality cannot be inferred from these results. For public health and planning practices, the patterns observed here may help prioritize hypotheses to be tested in future longitudinal and individual-level studies. For example, future studies could examine whether expanding accessible greenery in youth environments where vegetation is scarce or pairing social-connection programs with year-round green neighborhoods is associated with a lower suicide risk. All data and code have been openly shared to promote replication and season-sensitive UGI designs.

Ethical Approval
Ethics approval and informed consent were not required. This study was based on publicly available, aggregated data and did not involve human participants.

Conflict of Interest
The authors declare no conflict of interest.

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