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Heatwave exposure inequality: An urban-rural comparison of environmental justice

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ABSTRACT

The rapid growth of heatwaves' severity have increasingly endangered citizens' health in the last decade. Evidence points to the environmental injustice of heatwaves: inequal heatwave exposure among socioeconomic groups. Failing to use an adequate indicator of thermal comfort at a large scale, the previous studies have not adequately scrutinized the environmental justice of heatwaves and their variations across a large-scale territory. This study is novel in an unprecedented analysis of psychological equivalent temperature (PET), a comprehensive measure of thermal comfort, across socioeconomic groups and the urban-rural gradient of the Netherlands, as a proxy for factors affecting heatwave vulnerability. The results show that heatwave inequality (measured by the Gini coefficient) is higher in less urbanized areas. It shows that the population aged 25–44, immigrants, tenants, and females are the most heat-exposed groups across all levels of urbanization. However, the population aged 25–44 is more likely to be overexposed in urbanized areas, and immigrants are more likely to be overexposed in rural areas. The results open discussion on the necessity of location-specific policies protecting the most heat-exposed groups in different areas. It also paves the way for future studies using broader PET simulations and expanding their scope to include citizens' daily movements.

1. Introduction

1.1. Heatwave exposure and environmental justice across the urban-rural gradient

The upward trend of heatwaves in Europe in the past four decades has been three to four times faster than in other areas of northern midlatitudes (Rousi et al., 2022). The excess mortality in the July 2022 heatwave was 16 %, the highest ever recorded: 53,000 deaths more than expected (Eurostat, 2022). Various European studies show that extreme heat causes severe damage to citizens' health (see the review by Weilnhammer et al., 2021): the reported related risks for cardiovascular mortality increase on days warmer than certain thresholds (López-Bueno et al., 2019); hospital admissions pick up (Martinez-Solanas & Basagana, 2019); and mortality among senior citizens sharply increases (Green et al., 2016). If no climate adaptation measure is taken, heatwave mortality can be 30 times higher by the end of the century (European Commission, 2022).

The variations in exposure to environmental hazards, among them heatwaves, have brought the concept of environmental justice to the policymakers' agenda in the past two decades. The concept initially originated in the United States as a reflection of racial inequality in exposure to toxic materials. Among the European policymakers, the concept was noted for the first time in 1998 in the Communiqué of the ministerial conference on "Environment for Europe" by underscoring the right of every person from the current and future generation to live in an environment adequate for his/her well-being (Laurent, 2011). In 2018, the European Environment Agency (EEA) reported on "unequal exposure and unequal impacts: social vulnerability to air pollution, noise and extreme temperatures in Europe", urging for integration of environmental justice into the policies (European Environment Agency, 2018). In 2021, the Communiqué on the United Nations' Paris Agreement underscored the importance of "climate justice" in combating climate change (UNFCCC, 2021), and the IPCC report in 2022 referred to "distributive" climate justice as the "the allocation of burdens and benefits among individuals, nations and generations".

Previous studies suggest that heatwave vulnerability differs across socioeconomic groups (Chak Ho et al., 2018; Fan & Sengupta, 2022;

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Goodling, 2020; Kim et al., 2017; Park et al., 2019) and the urban-rural gradient of a territory (Bai et al., 2015; Gabriel & Endlicher, 2011; Hu, Guo, et al., 2019; Sheridan & Dolney, 2003; Yuan et al., 2023). These differences are related to the variations of factors affecting heatwave vulnerability across the urban-rural gradient, among them access to healthcare services (Dong et al., 2020), generation of own photovoltaic energy (Wang, Zheng, et al., 2021), daily time-activities patterns (Matz et al., 2015), buildings' spatial geometry affecting indoor thermal comfort (Sadeghi et al., 2020), and demography and occupation (Li et al., 2023; Sheridan & Dolney, 2003). To prepare for the upcoming rise of heatwaves in the coming decades and to offer location-specific spatial and health plans, geographic understandings -i.e. those taking citizens' socioeconomic characteristics across the urban-rural gradient into account-of heatwave exposure and environmental justice are essential. In the following parts of this section, two knowledge gaps in the previous studies on heatwave exposure inequality are introduced, and the objective and approach of this study are described.

1.2. Previous studies on heatwave exposure: a knowledge gap

Previous studies on variations in socioeconomic groups' thermal exposure could be classified from two perspectives: the environmental indicators used to measure thermal comfort and the studies' geographic scales. Regarding the indicators of thermal comfort, the previous studies could be categorised into four types. The first type of analysis uses air temperature, as recorded at meteorological stations, to analyse heat stress inequality among socioeconomic groups (Fan & Sengupta, 2022; Goodling, 2020), disparities in access to ecosystem services (Herreros-Cantis & McPhearson, 2021), and variations in heat-related hospitalisation (Xu et al., 2020). The second type of analysis uses accessibility to green spaces (Alsahli & Al-Harbi, 2022; Chen et al., 2020; Garrison, 2021; Wu & Kim, 2021; Park & Guldmann, 2020), and trees' cooling and air purification effect (Baró et al., 2019) to analyse heat-exposure inequality among socioeconomic groups. The third type of analysis uses land surface temperature (LST) as a proxy for heat exposure among gender, income, age, education, and ethnic groups (Ghorbani et al., 2022; Zeng et al., 2022a, Sun, Shi, et al., 2022; Hsu et al., 2021; Mashhoodi, 2021a, 2021b; Voelkel et al., 2018). The fourth type of analysis uses psychological equivalent temperature (PET), a measurement based on the human body's energy balance, based on solar radiation, wind speed, air temperature and humidity, to approach thermal inequality (Thach et al., 2015; Yuan et al., 2023; Zhang et al., 2023).

In terms of the geographic scale, four scales have been previously used. The first type of analysis is conducted at the neighbourhood and community scales. Such studies compare thermal comfort in neighbourhoods and communities with different levels of income and education (Adegun & Ayoola, 2022; Goodling, 2020; Park & Guldmann, 2020; Wu & Kim, 2021), related outdoor temperature with energy poverty (Avanzini et al., 2022), energy bills, self-described heat sensitivity, and dehydration (McIntyre et al., 2022). The second type of analysis is conducted at the city scale. Various studies have identified significant city-scale associations between LST and extreme poverty, immigration background, lower levels of education (Voelkel et al., 2018), living in relatively older houses (Zeng et al., 2022a, Sun, Shi, et al., 2022), Zeng et al., 2022b, Sun, Liu, et al., 2022thnicity (Mashhoodi, 2021a), and gender (Mashhoodi, 2021b), or rejected the presence of such associations (Fan & Sengupta, 2022). Various city-scale studies approach thermal inequality based on the variation in access to ecosystem services among income, ethnic, age and educational groups (Alsahli & Al-Harbi, 2022; Garrison, 2021; Herreros-Cantis & McPhearson, 2021), and green spaces' cooling impact (Baró et al., 2019; Ghorbani et al., 2022; Hsu et al., 2021; Mitchell & Chakraborty, 2018; Shih, 2022; Wu et al., 2023; Zhou et al., 2021). Some city-scale studies have identified socioeconomic disparities in heatwave mortality and hospitalisation (Thach et al., 2015; Xu et al., 2020). The third type of analysis is conducted at the regional scale and focuses on disparities among income groups (Chen et al., 2020), temperature-related mortality (Choi et al., 2021; Hu, Guo, et al., 2019), and ethnicity (Renteria et al., 2022). The fourth type of analysis is conducted at the country or global scale. Some studies focused on the inequality of thermal comfort (Zhang et al., 2023) and access to green (Chen et al., 2022) at the global scale, or imbalance of exposure to LST (Mashhoodi, 2021a) and energy expenditure concerning LST (Mashhoodi, 2020) at the country scale.

Two knowledge gaps are evident in the previous studies. Regarding the indicators of thermal comfort, there is no previous study shedding light on the socioeconomic disparities of a heatwave in a large-scale territory using a detailed indicator of thermal comfort. The measurements such as air temperature, LST or access to green only provide a proxy for human thermal comfort, given that thermal comfort is a product of air temperature, radiant temperature, wind, humidity and solar radiation. Among the indicators used in previous studies, PET is the only indicator containing information on all thermal comfort criteria. However, most of the studies using PET are at the scale of neighbourhoods or cities, presumably due to the unavailability of high-resolution data across a large territory. (Even on a small scale, the simulation of PET is a costly and time-consuming exercise that requires a large computational capacity.) The only expectation which uses PET at the global scale (Zhang et al., 2023) understandably lacks detailed information on the demographic characteristics of residents, such as income, household type, and ethnicity, and could not reflect the socioeconomic disparities of heatwave.

The second knowledge gap in the previous studies is the lack of a study at a large geographical scale comparing heatwave exposure disparities across urban-rural gradients using a detailed simulation of thermal comfort, such as PET. Extreme temperatures have different health effects across the urban-rural gradient. Most previous studies investigated cities where the urban heat island effect existed, with higher population density (Bai et al., 2016; Hu, Guo, et al., 2019). However, rural inhabitants are also at risk due to their different socioeconomic composition, e.g., older age, lower education level, agricultural occupations, and poorer access to healthcare services (Li et al., 2023; Sheridan & Dolney, 2003). Some works have investigated the variation in heatwave exposure or mortality across the urban-rural gradient for specific metropolitan areas or sample case study areas (Bai et al., 2015; Gabriel & Endlicher, 2011; Hu, Guo, et al., 2019; Sheridan & Dolney, 2003; Yuan et al., 2023; Zeng et al., 2022b, Sun, Liu, et al., 2022) or for an entire country (Chak Ho et al., 2018; Kim et al., 2017; Park et al., 2019; Wang, Zheng, et al., 2021). While the findings are mixed in terms of the heatwave-mortality relationship in the rural vs urban areas, they indicate differences between the two settings. However, a large-scale analysis must reflect similarities and differences across the urban-rural gradient to offer a broad perspective on the disparities of heatwave exposure. A large-scale country-level analysis with high-resolution data provides a unique opportunity to investigate the spatial variation in heatwave exposure. Unlike smaller-scale studies at the neighbourhood or city level, this level covers the urban-rural gradient, allowing us to test whether exposure to heatwaves is spatially variant across different socio-demographic groups and areas of a territory.

1.3. Objective and approach

To protect at-risk citizens, it is essential to study who is disproportionately exposed to heatwaves and how the highly-exposed citizens are distributed over a territory. This notion is what we refer to as the heatwave exposure socioeconomic geography: the variations of heatwave exposure among gender, age, income and ethnic groups across a territory and between areas with different levels of urbanisation. This provides us with a comprehensive assessment of vulnerability to heatwaves that can inform tailored planning and public health interventions for various areas across the gradient, targeting the most vulnerable groups in each location.

This study aims to feed scientists and policymakers by scrutinizing the environmental justice of heatwave exposure in the Netherlands. The study contributes to the existing body of literature on heatwave exposure inequality through an unprecedented analysis of a country-scale, high-resolution PET database of the 2015 heatwave in the Netherlands (the only available source at the country scale) against high-resolution socioeconomic data. The study is novel as it steps behind the inconclusive proxies of thermal discomfort (such as land surface temperature) used by previous studies and employs a multicriteria measurement of thermal comfort. It is also unique in using PET at the country scale to disclose the socioeconomic disparities of heatwave exposure across the urban-rural gradient as a proxy for factors affecting heatwave vulnerability. To do so, the study put forward three research questions.

a) How severe is a heatwave across the residential zones of the Netherlands? Are there significant differences between urban and rural areas?
b) Does exposure to heatwave vary within and between ethnic, age, gender, income, and housing-tenure groups? Do such inequalities vary across urban and rural areas?
c) What are the most overexposed socioeconomic groups in different residential zones of the Netherlands with varying levels of urbanization?

The study is exploratory. It includes five types of socioeconomic characteristics due to their possible associations with heat exposure.

1. Gender, regarding the unbalanced representation of gender groups in economic sectors, urbanized areas and exposure to urban heat islands (Mashhoodi, 2021b; The World Bank Group, 2020)
2. Ethnicity, regarding the inequality of living environment among ethnic groups (Jesdale et al., 2013; Mitchell & Chakraborty, 2018);
3. Housing tenure, regarding the difference between values of rental and owner-occupied dwellings, which is associated with access to green (Rosenthal et al., 2014; Tan & Samsudin, 2017);
4. Age, regarding lifestyle, employment and home ownership variations across the age groups (Vargo et al., 2016; Madrigano et al., 2015);
5. Income, regarding the segregation of income groups at the city- and regional scales (Nesbitt et al., 2019; Park & Guldmann, 2020).

The next part presents the method employed to find answers to the research questions.

2. Method

2.1. Inequality within socioeconomic groups: population-weighted Gini

In the first step of the analysis, population-weighted Gini index is employed to quantify inequality in heatwave exposure within socioeconomic groups. To do so, initially, the weight of each residential zone in the overall calculation is assigned by equation (1):

$$W_r = P_r \Big/ \sum_{1}^{R} P_r \qquad \text{(Equation 1)}$$

where r (r = 1, …,R) is the rank of the residential zone based on PET value, and P_r and W_r are, respectively, the socioeconomic group population and the residential zone's weight with rank r. Subsequently, the population-weighted value of PET is calculated by use of equation (2).

$$A = \sum_{1}^{R} W_r PET_r \Big/ \sum_{1}^{R} W_r \qquad \text{(Equation 2)}$$

where A and PET_r are respectively weighted-average of PET based on the population of the socioeconomic group and measurements of PET in the residential zone ranked r. Inequality of PET among the socioeconomic group, i.e. Gini weighted by the group's population, is calculated by use of equation (3) (adapted from Lerman & Yitzhaki, 1989).

$$Gini = 2\sum_{1}^{R} W_r (PET_r - A)(\widehat{F}_r - \overline{F}) \Big/ A \qquad \text{(Equation 3)}$$

where $\widehat{F}_r$ is the weighted cumulative distribution of PET (Equation (4)), and its average is denoted by $\overline{F}$.

$$\widehat{F}_r = \sum_{s=1}^{r-1} W_s + W_r \Big/ 2 \qquad \text{(Equation 4)}$$

2.2. Variations between socioeconomic groups: geographically weighted regression

The second part of the analysis methodology, aiming at estimating the variations of PET exposure between socioeconomic groups, is twofold. An ordinary linear least squares regression model (OLS) is employed in the first step. The model estimates the high or low PET among socioeconomic groups. The model does not account for possible spatial variation of PET exposure and offers an average, country-scale perspective. The OLS model estimates the Variance Inflation Factor (VIF), an indicator of dependent variables' independence (see equation (5)):

$$PET_i = \beta_0 + \sum_k \beta_k x_{ik} + \varepsilon_i \qquad \text{(Equation 5)}$$

where PET_i is PET during the heatwave of 2015 (July 1st) between 12:00 and 18:00 in residential zone *i*. x_{ik} is the *k*th socioeconomic characteristics at the residential zone *i*. β_0, β_k, and ε_i are respectively intercept, the estimated coefficient of the *k*th socioeconomic variable, and random error at residential zone *i*. The second step of the analysis is developing a geographically weighted regression model (GWR). The model accounts for spatial variation of high or low PET exposure of socioeconomic groups (equation (6)):

$$PET_i = \beta_0(\mu_i, \nu_i) + \sum_k \beta_k(\mu_i, \nu_i) x_{ik} + \varepsilon_i \qquad \text{(Equation 6)}$$

where (μ_i, ν_i) represents the longitude and latitude of the centroid point of the residential zone *i*, and $\beta_0(\mu_i, \nu_i)$ and $\beta_k(\mu_i, \nu_i)$ are respectively intercept and the estimated coefficient of the socioeconomic variable *k* at residential zone *i*. Equation (7) shows the formulation of the estimated coefficients of the GWR model (equation (7)):

$$\widehat{\beta}(\mu_i, \nu_i) = \left(X^T W(\mu_i, \nu_i) X\right)^{-1} X^T W(\mu_i, \nu_i) y \qquad \text{(Equation 7)}$$

where $\widehat{\beta}(\mu_i, \nu_i)$ is the unbiased estimate of β, and $W(\mu_i, \nu_i)$ is an adaptive bisquare spatial weigh matrix (equation (8)):

$$W_{ij} = \begin{cases} \left(1 - \dfrac{{d_{ij}}^2}{\theta^2}\right)^2, if\ d_{ij} < \theta \\ 0, otherwise \end{cases} \qquad \text{(Equation 8)}$$

where W_{ij} is the weight of zone *j* in the regression model developed for zone *i*. The weight is based on d_{ij}, i.e. the length of the line between the centroids of the zones *i* and *j*. Weights are only assigned to a specific number of nearest zones of zone *i*, θ, or what is called adaptive bandwidth. The optimal number of θ is estimated using the GWR 4.0 tool (Nakaya et al., 2009) to minimise the GWR model's Corrected Akaike Information Criteria (AICc). Ultimately, three performances of the aspatial model (OLS) and spatial model (GWR) are compared: adjusted R^2, AICc, and size and spatial pattern of the residuals (Moran's I).

Two types of spatial analysis are adopted to interpret the GWR model's sheer-size outputs: (1) frequency analysis, i.e. mapping of the locations of and providing descriptive statistics over the zones where socioeconomic groups are significantly over- or underexposed to heatwave PET; (2) most-overexposed analysis, identification and mapping of the socioeconomic group that experiences the highest level of PET at the context of each of the residential zones.

3. Data

3.1. *Case study area, urbanization type and PET, the dependent variable*

The case study areas consist of 2480 residential zones (Wijken), i.e. the geographic boundaries defined by the Dutch Central Bureau of Statistics (CBS). Residential zones are one of the most fine-grained areas where the socioeconomic data on ethnicity, income, age, gender and housing tenure is available to the public. The zones with industrial functions or missing data are excluded from the study. Based on the density of registered addresses per square kilometre, CBS has categorised the zones into multiple "urbanity" categories: high urbanization, i.e.1500 or more addresses per km2; moderate urbanization, i.e.1000-1500 addresses per km2; low urbanization, i.e. 500-1000 addresses per km2; no urbanization, i.e. less than 500 addresses per km2 (CBS, 2015). Fig. 1a represents the study area and the degrees of urbanization at the zone level.

The study's dependent variable is physiological equivalent temperature (PET) during the heatwave of 2015 (July 1st) between 12:00 and 18:00 – based on the only database available at the country scale on heatwave PET. PET is a widely used index to evaluate thermal conditions based on human energy balance. It is the equivalent of an indoor air temperature (i.e. the temperature of an environment with no wind or direct solar radiation) where the core and skin temperature of the human body are in balance (Höppe, 1999). The calculation of PET for outdoor spaces includes various meteorological factors (air temperature, wind, air humidity, solar radiation and altitude angle) and spatial factors (land use, sky view factor, digitally elevated model, vegetation and presence and height of trees). Ultimately, the values of PET are computed by developing a Python-based algorithm, for more details, see the National Heat Felt Temperature report (Goede, A., 2021). The database is available at Climate Atlas Effect (klimaateffectatlas) of the Netherlands (Klimaateffectatlas, 2022), and is illustrated by Fig. 1b.

3.2. *Socioeconomic data*

This study includes five types of socioeconomic characteristics of the inhabitants in the residential zones, using the data published by CBS (CBS, 2015). The first variable type reflects the gender composition of the residential zones: *Women (%)* and *Men (%)*. The second type of variables quantifies the presence of *immigrants (%)*, i.e. inhabitants with at least one non-Dutch parent, according to the CBS definition, and *Natives (%)*. The third type of variables represents *Tenants (%)*, the portion of dwellings in which a non-owner household is registered, and *Homeowners (%)*. The fourth type of variables describes the age structure

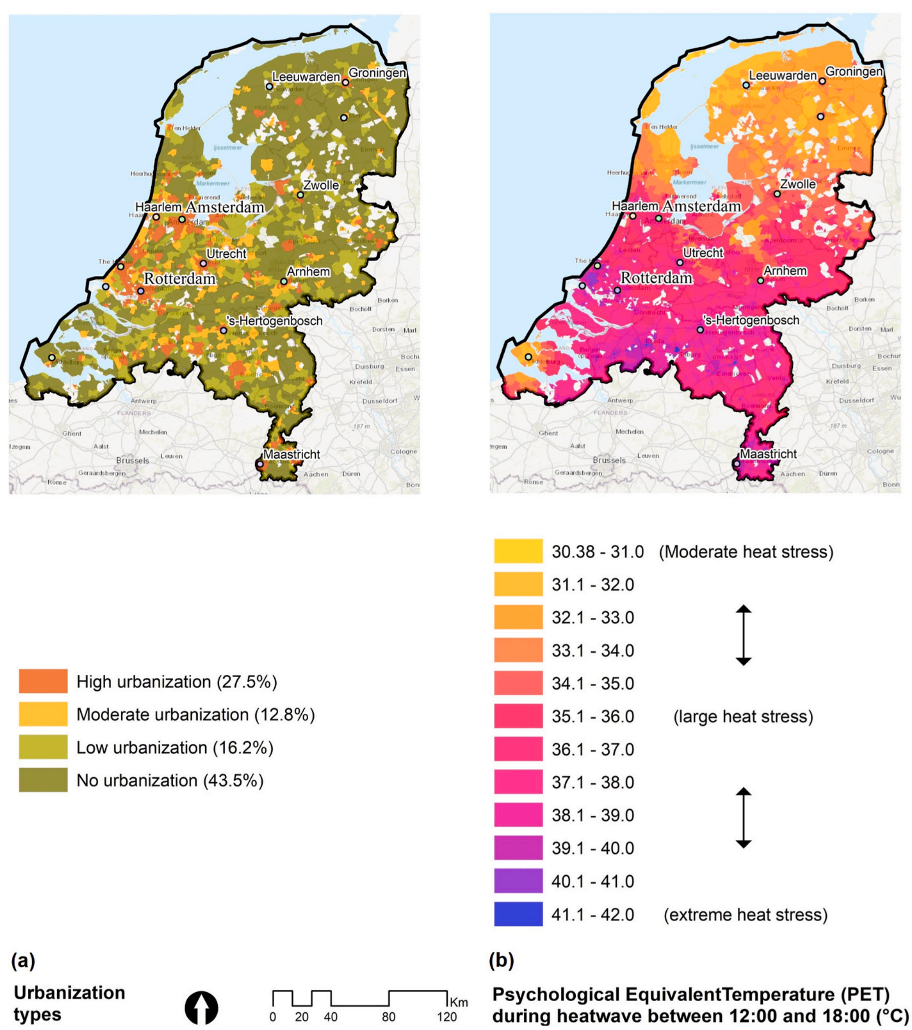

Fig. 1. (a) urbanization types across the zones of the study area, Dutch residential zones, (b) PET measurements during the heatwave of July 1st, 2015, between 12:00 and 18:00, the dependent variable.

of residential zones: *Population aged 14 or younger (%)*, *Population aged 15–24 (%)*, *Population aged 24–44 (%)*, *Population aged 45–64 (%)*, and *Population age 65 or older (%)*. The fifth type of variables identifies income groups: *Low-income (%)*, i.e. the percentage of households among the lowest four income deciles of the Netherlands; *Middle-income (%)*, i.e. the percentage of households from the fifth to eighth income deciles of the Netherlands; *High-income (%)*, i.e. the percentage of households among the two highest income deciles of the country. Table 1 summarises the descriptive statistics of the socioeconomic variables (Table 1).

4. Results

4.1. Heatwave exposure variation across the urban-rural gradient

The first test assesses whether exposure to heatwave PET differs across areas with different levels of urbanity. As PET is not normally distributed (see the results of Kolmogorov-Smirnova and Shapiro-Wilk tests of normality in Appendix 1), a nonparametric ANOVA test (Kruskal-Wallis) is employed. The test rejects the similarity of PET distribution between any pair of urbanity types (see Table 2).

The result shows that the median PET value incrementally increases from the non-urbanized zones (35.6 °C) to highly-urbanized ones (38.1 °C). Measurements of PET in 85 % of highly-urbanized zones indicate a "large heat stress" (i.e. between 36 and 41 °C) and identify 2 % of the zones in "extreme heat stress" (i.e. more than 41 °C). In moderately-urbanized zones, 71 % of areas experience "large heat stress" and 28 % "moderate heat stress" (i.e. between 30 and 36 °C). In low-urbanized and non-urbanized areas, the share of zones with "large heat stress" drops to 58 % and 44 %, with a "moderate heat stress" in the rest of the zones (Fig. 2).

4.2. Urban-rural comparison of heatwave exposure inequality within socioeconomic groups

Fig. 3 shows the Gini coefficient of PET (heatwave exposure) calculated across different urbanization types and socioeconomic groups. Regardless of their socioeconomic characteristics, measurements of inequality among all inhabitants show that higher levels of urbanization are associated with lower inequality among the inhabitants. The inequality incrementally increases from the highly urbanized areas to the non-urbanized areas (Fig. 3a). The results show that inequality among gender groups (Fig. 3b), age groups (Fig. 3c) and home-ownership types (Fig. 3f) are similar and fairly follow the average inequality of each urbanization type. In the case of ethnic groups, there is less inequality among immigrants than native citizens (Fig. 3d). We found that the inequality of heatwave exposure among high-income inhabitants was lower than among other income groups (Fig. 3e). Overall, the patterns of heatwave exposure inequality within socioeconomic groups appear to be more influenced by urbanization than the inhabitants' socioeconomic characteristics.

Table 1
The descriptive statistics of the socioeconomic characteristics analysed in this study.

Variable	Mean	Std. Deviation	Minimum	Maximum
Women (%)	49.86	1.86	28.75	61.29
Men (%)	50.14	1.86	38.71	71.25
Immigrants (%)	14.93	11.14	2.00	92.00
Natives (%)	85.07	11.14	8.00	98.00
Tenants (%)	33.13	15.23	1.00	100.00
Homeowners (%)	66.87	15.23	0.00	99.00
Population aged 14 or younger (%)	16.48	3.60	2.00	38.00
Population aged 15–24 (%)	11.72	2.96	1.00	45.00
Population age 25–44 (%)	22.70	5.07	4.00	49.00
Population aged 45–64 (%)	30.12	4.49	11.00	49.00
Population age 65 or older (%)	18.99	5.88	1.00	66.00
Low-income (%)	39.52	5.30	18.00	68.00
Middle-income (%)	40.05	3.91	17.00	55.00
High-income (%)	20.43	6.67	1.00	55.00

4.3. Heatwave exposure inequality between socioeconomic groups

4.3.1. Diagnoses of OLS and GWR models

Table 3 shows the results of the OLS and GWR models. The dependent variable of the models is the average PET value in the residential zones, the indicator of heatwave exposure. The independent variables of the models comprise the factors from the five socioeconomic dimensions, with one or two factors omitted from each dimension to meet the criteria of independence and low collinearity between the independent variables. Comparing the diagnoses of the OLS and GWR models shows that the latter performs significantly better. This indicates that socioeconomic groups' over- or underexposure to heatwaves varies from location to location. OLS model's estimations of VIF show that socioeconomic characteristics are independent to an acceptable level. Adjusted R-square, the indicator of the goodness of fit, of the GWR model is substantially higher than that of the OLS model: 89 % compared to 25 %, which indicates that spatial variations account for more than 74 % of the associations between PET and socioeconomic characteristics. The AIC estimation of the GWR model is also substantially lower than that of the OLS model, indicating that accounting for spatial variations provides a more informative model. The ANOVA test points out that the size of GWR residuals is significantly smaller than that of the OLS model. The spatial distribution of the models' residuals also indicates that the residuals of the GWR model are more randomly distributed than those of the OLS model, assessed by closer-to-zero absolute values of the Moran's I test (see Table 3).

4.3.2. Geography of socioeconomic groups' over- and underexposure to heat stress

Fig. 4 shows the local coefficients of the GWR model. The red colour indicates a significant (*p-value* < 0.05) positive coefficient, i.e. the overexposure of a socioeconomic group to heatwave compared to other groups. The green colour shows a significant (*p-value*<0.05) negative coefficient, i.e. the underexposure of a socioeconomic group to heatwave compared to other groups. The grey colour indicates that the presence of a socioeconomic is not significantly associated with higher or lower levels of PET.

Five types of over- and underexposure to heatwaves are identified. The first type is overexposure in the vast majority of areas, regardless of urbanization types: women minus men (Fig. 4a) and population aged 25–44 years (Fig. 4e). The second type is overexposure in around 50 % of the areas of all urbanized areas: immigrants (Fig. 4b). The third is the gradual decline of overexposure from 50 % in highly-urbanized areas to about 20 % in non-urbanized areas: the population aged 45–64 years (Fig. 4f). The fourth type is over-, under- and non-significant exposure in roughly equal portions of areas: tenants (Fig. 4c), low-income inhabitants (Fig. 4g), and middle-income inhabitants (Fig. 4i). The fifth type is underexposure in roughly half of the areas in all urbanization types: the population aged 14 or younger (Fig. 4d).

Regarding urbanization and social exposure to heat stress, three patterns are found. The first pattern is the increase of heatwave overexposure in response to a rise in the degree of urbanization. The sharpest increase from the non-urbanized to highly-urbanized areas is observed in the case of women minus men (Fig. 4a) and the population aged 45–64 years (Fig. 4f). To a lesser degree, a similar pattern is observed in the case of low-income (Fig. 4g) and middle-income (Fig. 4i) inhabitants. The second pattern is the increase of overexposure in less urbanized areas, observed in the case of immigrants (Fig. 4b). The third is a sine-wave pattern across the urbanization gradient: tenants (Fig. 4c), the population younger than 14 years (Fig. 4d), and the population aged 25–44 years (Fig. 4e).

Table 2
Kruskal-Wallis Test shows that the distribution of PET significantly differs across every two types of urbanity.

Independent-Samples Kruskal-Wallis Test Summary					
Null Hypothesis	Total N	Test Statistic	Degree Of Freedom	Asymptotic Sig.(2-sided test)	Decision
The distribution of PET is the same across categories of Urbanity.	2480	591.448[a]	3	0.000	Reject the null hypothesis.
Pairwise Comparisons of PET across different urbanity types					
Sample 1-Sample 2 *	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adj. Sig.****
No urbanization-Low urbanization	274.865	41.879	6.563	0.000	0.000
No urbanization-Moderate urbanization	550.170	45.746	12.027	0.000	0.000
No urbanization-High urbanization	828.287	35.013	23.656	0.000	0.000
Low urbanization-Moderate urbanization	−275.305	53.816	−5.116	0.000	0.000
Low urbanization-High urbanization	553.423	45.049	12.285	0.000	0.000
Moderate urbanization-High urbanization	278.118	48.664	5.715	0.000	0.000

* Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is 0.050.
** Significance values have been adjusted by the Bonferroni correction for multiple tests.

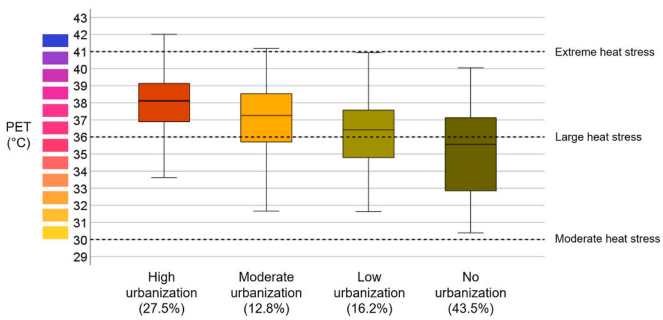

Fig. 2. Distribution of PET across the residential zones with different types of urbanization.

4.3.3. *Urban-rural comparison of the most overexposed socioeconomic groups to heatwave*

After identification of the locations with significant over- or under-exposure to heatwave PET in the previous section, the socioeconomic group with the highest overexposure, i.e. the highest significant positive standardised coefficient (*p-value* < 0.05), in each zone is identified. The result shows that in more than 95 % of the residential zones, the population aged 25–44 years, immigrants, tenants, or women experience the highest heatwave PET. They also indicate that the population aged 25–44 is the most heatwave-exposed socioeconomic group in all urbanization types. The chance of the age group being the most heat-prone socioeconomic group increases with urbanization, from 45 % of non-urbanized areas to 62 % of highly-urbanized areas. The second most heat-prone socioeconomic group includes immigrants. However, the group is likelier to be the most heat-prone in less-urbanized areas: 29 % of non-urbanized areas compared to 15 % of highly-urbanized areas. The third and fourth most heat-prone groups are tenants and women minus men, without a significant trend across the urbanity types (Fig. 5).

5. Discussion

5.1. *Urban-rural similarities of heatwave socioeconomic exposure*

Areas across the urban-rural gradient are similar regarding the demographic composition of the most heatwave-exposed socioeconomic groups. The top rankings of the most heatwave-exposed inhabitants are the same in all areas: population aged 25–44, immigrants, tenants, and females. This is presumably due to societal factors which attract these groups to the most central locations of a settlement, whether urban or rural. The following paragraphs introduce and discuss a series of possible societal factors.

In 2021, 56 % of the Dutch aged between 25 and 34 had tertiary education (OECD, 2022). The attraction of the population aged 25–44 years to tertiary education centres, presumably located in the central locations of urban and rural areas, can explain their heatwave overexposure across the settlements. This presumption is in line with the study of Moos et al., which found a significant association between the location of post-secondary (university, college, etc.) campuses and the so-called youthification and studentification of an area in Canada (Moos et al., 2019a, Revington, et al., 2019). Revington et al., too, spotted youthification and studentification of the population in the vicinity of tertiary campuses in the U.S. (Revington et al., 2021). Another possible reason is the more central location of service activities compared to manufacturing and agriculture sectors in urban and rural areas. In 2021, the share of the population aged 25–44 employed in the manufacturing and agriculture sectors was 4.55 and 0.57 % compared to 6.46 % and 0.63 % for the aged group 45 years or older (authors' computation based on CBS, 2023). The presumption resembles Moos et al. observation that the presence of the young population had a negative association with the presence of manufacturing jobs in North American metropolitan areas (Moos et al., 2019b, Filion, et al., 2019).

Immigrants and tenants are among the most heatwave-exposed inhabitants in urban and rural areas. This is presumably related to the fact that both groups tend to dwell in relatively low-value properties and, subsequently, in zones with relatively lower amounts of green and blue spaces. CBS data suggests robust negative correlations between the presence of immigrants and property value in the residential zones, −0.48 (own computation based on CBS, 2015). Lower property values are presumably associated with a lower presence of green spaces and higher exposure to heat stress. Previous studies on the real estate market in the Netherlands have suggested that dwellings closer than 250 m to parks are about 9 % more expensive than their immediate neighbours in Amsterdam (Daams et al., 2019), and those within 500m to 7 km to parks are between 1.6 % and 16 % more expensive than dwellings further than 7 km (Daams et al., 2016). Street trees were also associated with higher property prices (Siriwardena et al., 2016; Pandit et al., 2013).

Females' overexposure to heat in urban and rural areas is presumably related to their overrepresentation in the service sector, which drives them to the most central locations of urban and rural areas. In 2020, 92 % of employed Dutch women worked in the service sector, compared to 73 % of employed men. Women's participation in agriculture was only 1.2 % - compared to 3 % of men - and their employment in the industry sectors was as few as 6 % - compared to 25 % of men (The World Bank Group, 2020). Women's overexposure to heatwave will continue and grow in the coming decades due to the so-called

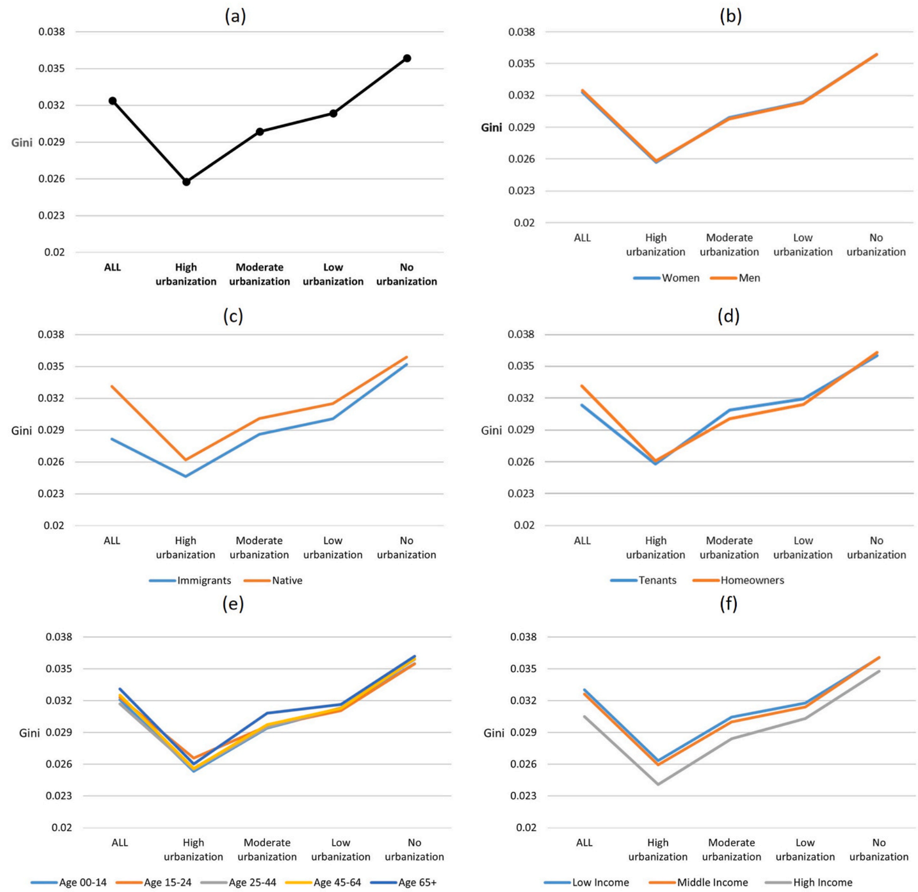

Fig. 3. Inequality in heat stress exposure within the socioeconomic groups and urbanization types measured by population-weighted Gini coefficient.

Table 3
Diagnoses of the OLS and GWR models.

Variable	OLS results		GWR results			
	β	VIF	β mean	β SD	β min.	β max.
Intercept	0.000		0.032	0.833	−1.689	1.501
Women minus men (%)	0.162	1.8	0.112	0.102	−0.152	0.464
immigrants (%)	0.288	2.1	0.086	0.190	−1.390	0.929
Tenants (%)	0.030	3.6	0.009	0.173	−0.641	0.770
Population aged 14 or younger (%)	−0.122	1.6	−0.045	0.111	−0.347	0.275
Population aged 25–44 (%)	0.265	3.5	0.230	0.148	−0.282	0.719
Population aged 45–66 (%)	0.105	3.1	0.040	0.134	−0.308	0.609
Low-income (%)	−0.154	1.7	−0.010	0.123	−0.429	0.323
Middle-income (%)	−0.111	1.1	0.007	0.111	−0.353	0.486
R-square	0.257		0.926			
Adjusted R-square	0.254		0.895			
AICc	6319.69		2079.980			
Residual Moran's I	0.60		0.05			
Bandwidth	NA		85			
GWR ANOVA Table	**SS**	**DF**	**MS**	**F**		
Global Residuals	1841.4	2471				
GWR Improvement	1657.7	720.5	2.3			
GWR Residuals	183.8	1750.5	0.11	21.9		

β: standardized regression coefficient.
OLS coefficients significant at the *p-value* <0.05 level are marked underlined.
The percentage of the GWR positive and negative significant coefficients (%) calculated at p-value <0.05

feminisation of labour (Christiansen et al., 2016; Guisan & Aguayo, 2013) and the expected dominant females' role in the service sector of the 21st century (Rosin, 2012).

5.2. Urban-rural differences in heatwave socioeconomic exposure

There are three major differences between urban and rural areas. The first difference is the severity of heat stress in urban and rural areas. The results show that most highly-urbanized or sub-urban zones experience a "large heat stress" during a heatwave. In contrast, "moderate heat stress" is frequently observed in the low- and non-urbanized zones. This is presumably related to urban-rural variations in land cover and surface temperature. Previous studies show that an increase in surface temperature is significantly associated with higher air temperature (Mohan et al., 2020; Wang et al., 2019) and intensifies in compact urban settlements (Ren et al., 2022).

The second difference is the larger inequality of heatwave exposure in less urbanized areas, presumably due to paling differences in extremely heated urbanized areas. This is in line with the study by Tian et al., which found that the surface temperature was higher during heatwaves but less varied in compact urban canopies of Nanjing megacity, China (Tian et al., 2023). Similarly, Zeng et al. found that inequality among most socioeconomic groups was larger in less-urbanized areas than in the core city of Shanghai, China (Zeng et al., 2022a, Sun, Shi, et al., 2022).

The third difference is the intensified heatwave exposure of the population aged 25–44 years in more urbanized areas and the intensified heatwave exposure of immigrants in less urbanized areas. The urban heatwave exposure of the population aged 25–44 is presumably related to their tendency to cluster in high-density areas of cities due to the presence of cultural services, active nightlife, availability of small and

Fig. 4. Spatial distribution and frequency of socioeconomic groups' over- and underexposure to heatwave PET.

affordable housing units, and walkability (Moos, 2016). Such a tendency presumably intensifies the heatwave overexposure of the age group in more urbanized areas. The increase of immigrants as the most heatwave-exposed group in the less urban areas is likely related to the type of non-urbanized areas they tend to settle in. In 2021, 1 % of the native inhabitants were employed in agriculture compared to 0.5 % of non-EU inhabitants (authors' computation based on CBS, 2023). This suggests that immigrants tend to dwell in low-urbanized areas with artificial land cover (such as the vicinity of industrial ports) more than native citizens and, therefore, are more heatwave-exposed compared to other groups.

6. Conclusion and policy implications

This article aims to provide a comprehensive assessment of heatwave disparities based on socioeconomic characteristics and by using psychological equivalent temperature –a detailed indicator of human thermal comfort-that has not been investigated across urban-rural gradients at a large scale. The results of the study have met the research objectives in three ways. First, our results show that due to the severity of heatwaves, inhabitants in all urbanization gradients experience heat stress and inequality. Second, our findings on similarities between urban and rural areas suggest that certain socioeconomic groups need specific attention at the national scale. Certain life circumstances expose millennials, women, immigrants and tenants to higher heat levels than other socioeconomic groups. Third, our results also urge introducing a location-specific approach to mitigate heatwave vulnerability, as the most heatwave-exposed socioeconomic group can differ from one area to another.

These results suggest certain actions for future studies and policies in the Netherlands. The results urge the preparation of spatial plans to face the heatwaves across the country, given that even the residents of the

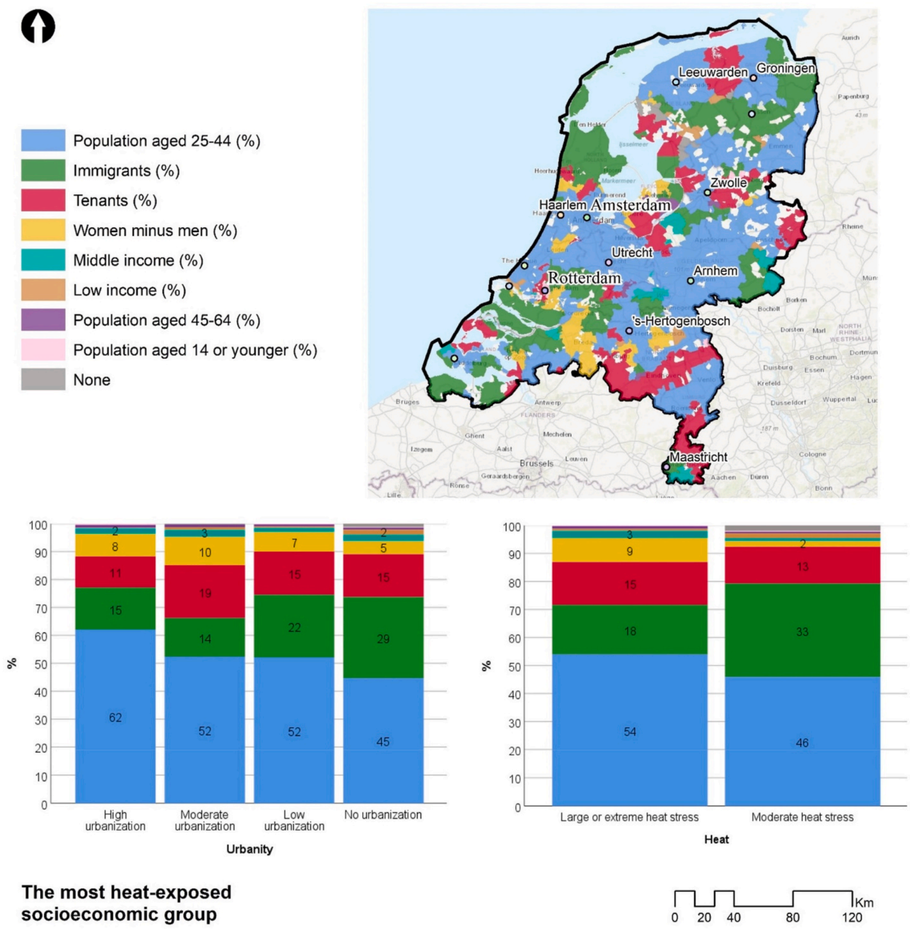

Fig. 5. The socioeconomic groups experiencing the highest heatwave PET cially vulnerable communities in the US. One Earth, 4(12), pp.1764-1775.

least urbanized areas are no longer safe from excessive heat. Such plans need to include a variety of measures, among them climate adaptation actions such as an increase in green spaces and an increase in hospitalisation capacity. National policies must provide safety nets for groups overexposed to heatwave in urban and rural areas. For instance, after the breakout of the Ukraine crisis and the rapid gas price increase in 2022, many European governments introduced a price cap for space heating. Similar price caps or subsidies could be introduced for energy consumption for space cooling of millennials, women, immigrants or tenants during heatwaves. Given the spatial variations of the most heatwave-exposed socioeconomic groups, municipal and local policies must identify the local circumstances that create such inequalities. The results show that a particular socioeconomic group can be overexposed in one area and underexposed in another. The lesson to be learned is that one-size-fits-all policies are insufficient for mitigating heatwave inequality and must be combined with local ones. Ultimately, to introduce policies aiming to mitigate heatwave vulnerability and inequality, *trans-* and interdisciplinary research and collaborations are essential. Scientists from environmental law, spatial planning, geography, meteorology, sociology and health (to name a few) need to join forces to define citizens' ecological needs and rights. Policymakers must grow awareness that climate change does not affect all inhabitants equally and include combating environmental inequality in their social and spatial approaches. Climate change is more than a meteorological matter. It can soon cause divisions in our society if not adequately addressed.

Limitations and further studies

Further studies can consider the simulation and corporation of a more extensive PET dataset. The current database on PET only includes the simulation of 12:00 to 18:00 on July 1st, the peak point of the heatwave in the respective year. A heatwave, however, extends over at least three days (by definition) and affects the residents' health outside the hours with peak heat, for instance, causing mortal dangers to senior citizens during the nights. Given that the simulation of PET is a time-intensive and costly process requiring vast computation capacities, future studies could approach the matter in two ways. The first is expanding the simulated time span for selected areas with the highest heat exposure and inequality. The second is to use the existing PET database to train a machine-learning model to predict PET for other periods. The second point of improvement for further studies is including the daily routine of different socioeconomic groups and studying the heatwave inequality beyond citizens living in neighbourhoods. The current study uses census data on the neighbourhood residents and cannot cover the heat exposure in the places where citizens work, study, shop, etc. To do so, future heatwave studies can benefit from the travel survey data or use social media data to allocate citizens' activities during the day.

CRediT authorship contribution statement

Bardia Mashhoodi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Data curation, Conceptualization. **Dena Kasraian:**

Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Data curation, Conceptualization.

Appendix 1

Table 4

Significant statistics of Kolmogorov-Smirnova and Shapiro-Wilk tests show that distributions of average PET are not normal in the areas with different levels of urbanity. Therefore, nonparametric tests must be employed to compare the distributions.

Tests of Normality of PET distribution							
	Urbanity type	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Average PET	**High urbanization**	0.072	683	0.000	0.970	683	0.000
	Moderate urbanization	0.089	317	0.000	0.966	317	0.000
	Low urbanization	0.072	401	0.000	0.974	401	0.000
	No urbanization	0.115	1079	0.000	0.936	1079	0.000
	a. Lilliefors Significance Correction						

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