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Spatial allocation of nature-based solutions in the form of public green infrastructure in relation to the socio-economic district profile–a GIS-based comparative study of Gdańsk and Rome

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ABSTRACT

With increasing environmental and climate change threats to urban areas, Nature-based Solutions (NbS), including public greenery, are becoming integral components of green infrastructure (GI) networks. These solutions provide multiple benefits in different aspects, including stormwater management, enhanced air quality and improved societal well-being, offering cost-effective and adaptable alternatives to resource-intensive and environmentally harmful grey infrastructure. However, their benefits are often unevenly distributed, resulting in patterns of environmental injustice. This article presents a GIS-based study of the spatial allocation of publicly accessible NbS (PNbS), in Gdansk, Poland, and Rome, Italy. It aims at assessing possible correlations between the socio-economic attributes of the urban districts of the two cities and the density of available PNbS in each district. Results indicate disparities in density of PNbS across different socio-economic layers, more relevant in Rome than in Gdansk, and highlight the importance of informed urban planning. The study supports concerns for fair NbS distribution, pointing to the potential exacerbation of social and economic inequalities, which puts socially vulnerable communities at higher risk of being affected by climate hazards. The results provide insights for policymakers, urging a prioritized focus on districts with crucial PNbS needs. Strategies should consider socio-economic factors to address distributive and environmental justice concerns. Overall, the study offers insights to guide urban planning toward climate-resilient and inclusive cities.

1. Introduction

Climate change is a serious issue confronting the urban world today, posing significant threats such as flooding and heat island effect to the European region (Carter, 2011; Vergara-Temprado et al., 2021; Alfieri et al., 2018; Tubridy et al., 2022). Relatively, extreme weather occurrences have caused severe economic losses in Europe of more than 436 billion euros between the years 1980 and 2016 (Sturiale and Scuderi, 2019). The traditional engineering strategies used to address the aforementioned issues, which are often referred to as "grey infrastructure", are no longer effective at eliminating the consequences of climate change because they consume significant amounts of resources such as money, human labor, materials, and energy while also having long-term environmental repercussions (Spiller et al., 2014; Kabisch et al., 2017; Nesshöver et al., 2015). As a result, there have been efforts to develop alternative solutions, and one of these approaches is called "Nature-based Solutions", most of the time shortly mentioned as "NbS". NbS have been defined as “actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits” (UNEA, 2022).

By prioritizing NbS in their plans, cities not only enhance immediate resilience but also foster long-term sustainability for residents and ecosystems (Voskamp et al., 2021; Seddon et al., 2020; Sędzicki et al., 2023). Green infrastructure (GI) complements this approach, representing a deliberate system of natural and semi-natural areas meticulously planned and maintained to offer ecosystem advantages and enhance human well-being (Chatzimentor et al., 2020). Within this mindset, NbS emerge as integral components of GI networks, providing numerous ecosystem services by replicating natural processes, such as

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biodiversity conservation, air quality improvement, and storm water management. The significance of strategically siting these solutions throughout urban areas becomes apparent, ensuring equitable access to climate hazards protection such as flooding for all citizens while avoiding exposing less affluent communities to heightened vulnerability to said hazards (Hoang et al., 2018; Woroniecki et al., 2021).

When discussing NbS it is crucial to note that this term may include a wide variety of solutions with different functions, characteristics and spatial dimensions, therefore categorizing them seems to be a challenging task. However, they can be briefly classified as gardens, parks, amenity areas, urban farms (though in this type some access restrictions may apply), linear features along routes (street trees, railway corridor greenery), constructed green infrastructure integrated with buildings (green roofs, green walls), hybrid blue-green infrastructure for water (roof gardens, attenuation ponds, rain gardens, wetlands and other non-sealed urban areas (shrub land, woodland, etc.) (Jones et al., 2022). Among various types of NbS, it is generally assumed that parks, whether regional or pocket parks operating at a neighborhood scale, are the most commonly available green spaces for public use. Garden types, on the other hand, are often privately owned and not accessible to the public. In the middle of the spectrum, there are some types of urban areas, such as urban farms and allotment gardens, where certain restrictions on citizen usability may apply.

Research on public greenery distribution and access to urban parks often exhibits specific geographical patterns. Rigolon in 2016 in a paper reviewing the existing literature concerning the history of inequality in availability of the urban parks, concluded that most of the case studies in this subject are located in the United States (67 % of the whole research) followed then by the United Kingdom and Australia. This rich representation of case studies in the global north may be due to the fact that the idea of environmental justice (EJ) was first born in the United States. It is also worth noting that few comparative studies laying in different contexts in relation to EJ or distributive justice (DJ) have been implemented (Cucca et al., 2023). There is also scarce knowledge about the current state of NbS projects in the cities to prove if these initiatives and their benefits are available and accessible to everyone (Kabisch et al., 2016). The literature has highlighted gaps in the understanding of justice and socio-spatial inequality issues connected to NbS, since NbS are mainly proposed as solutions for urban sustainability and resilience (Cousins, 2021). In particular, authors stress the need to investigate potential trade-offs between NbS implementation and social inequalities exacerbation (Anguelovski et al., 2023; Bonilla et al., 2021; Paauw and Crabbé, 2023), to understand how NbS can be designed and implemented to reduce vulnerabilities (Badiu et al., 2016; Buckland and Pojani, 2023; Da Silva et al., 2023), to consider the equitable distribution of NbS, particularly in relation to green infrastructure (Chan and Hopkins, 2017), and more generally to develop a more integrated approach to NbS, combining ecological, social and economic perspectives (Cooper et al., 2024).

The present research aims to address the study of EJ in the distribution of Public Nature-based Solutions (PNbS) by examining the correlation between its density and the socio-economic profile in the districts of the two cities of Rome and Gdansk. This selection aligns with the research goal of addressing gaps in understanding NbS in public urban landscapes, particularly in different geographical settings. As mentioned previously, there is a significant geographical research gap, with most case studies on this topic situated in the US. Additionally, it has been observed that much NbS-related research focuses on single and small-scale case studies (Langemeyer and Baró, 2021), and there is a scarcity of NbS studies in the context of urban planning (Kabisch et al., 2022). All these aspects underscore the novelty and importance of studies conducted in diverse geographical settings, at larger scales, and within the context of urban studies and society. Analyzing the NbS in relation to socio-economic factors in these case studies can shed light on the relationship between society and NbS, aiming to answer the question posed by Kabisch et al. in 2016: "Are the benefits of NbS accessible to all inhabitants?" The research gaps addressed by the present study are summarized in Fig. 1 below.

The paper is structured as follows. First, the authors offer a review of the literature concerning EJ and DJ with a focus on the allocation of PNbS in urban areas. Then, methods and tools employed are presented, and the two study areas are introduced. Gdańsk, located in northern Poland, exemplifies a post-industrial city with traces of numerous turbulences in its urban history, in rapid urbanization and redevelopment, notably along its Baltic Sea coast. Rome, famous for its ancient history and vast green spaces, presents a contrasting urban landscape with centuries-old architecture and settlement patterns. The following comparison between the cities is based on the collection of socio-economic data available per district and an analysis of the corresponding PNbS density. This results in the definition of a socio-economic priority index that provides information about the social need for PNbS enhancement in each district of both cities. The results are shared in Section 4, followed by the discussion in Section 5. The conclusions are built on the results and discussion to highlight key insights gained and indicate gaps to be addressed in future research. Results and analysis empower planners to address land use planning and policy gaps for more effective outcomes, ensuring equitable access to NbS benefits.

2. Environmental justice in the distribution of public Nature-based Solutions

2.1. Evolution of environmental and distributive justice

Before defining distributive justice (DJ), which is the main focus of the present study, it is better to briefly introduce the idea of environmental justice (EJ), as these two are deeply connected to each other (Wienhues, 2021). The concept of EJ and its importance were ignited in the early 1980s (Occelli et al., 2016) by the protests of African American activists opposing policies that disproportionately exposed people of color to environmental harm. Studies such as those by Bullard (1993) and Chavis and Lee (1987) pointed out that landfills were often located in close vicinity to African American communities, thereby increasing their risk of harm. A more recent example is the case of lead poisoning in Flint, Michigan, where between 2014 and 2015, approximately 99,000 residents were exposed to lead through their water consumption, predominantly affecting low-income communities of color (Pulido, 2016; Ranganathan, 2016). These instances of environmental injustice are

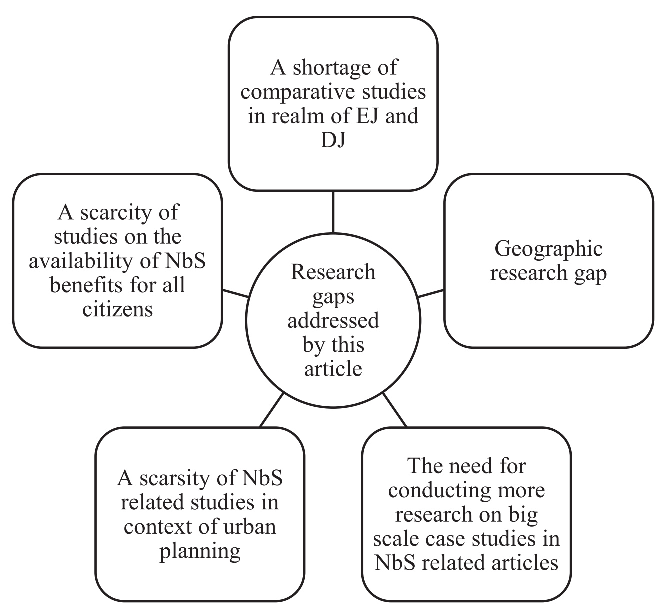

Fig. 1. Research gaps addressed by the present article.
Source: Authors.

commonly referred to as "brown cases" (Anguelovski, 2013). Over time, the focus shifted from brown cases to green cases of injustice. Green cases in environmental justice refer to instances where the focus is on the fair distribution, access, and impact of environmental benefits, particularly those related to green spaces. These often explore issues like how different communities have access to greening efforts and how environmental policies and practices may either support or hinder equitable access to these benefits (Bauer, 2023).

DJ, as an evolving concept, has seen substantial refinement through time. The modern concept, largely shaped over the last two centuries, is distinct from previous notions, where distributive principles were primarily focused on ensuring that deserving people are rewarded according to their merits, rather than a broad-based equitable distribution of resources (Frohlich, 2007). The modern concept, as mentioned by John Rawls (1971), revolves around the premise that justice entails the equal distribution of access and resources. It is defined as a type of justice principle concerning the fairness in allocating situations (Cook and Hegtvedt, 1983). Comparing the old and new concepts of DJ, it can be observed that while the older is narrower and more merit-focused, modern DJ embraces a broader, more inclusive approach that considers a range of ethical and practical factors affecting societal well-being (Frohlich, 2007).

The relationship between EJ and DJ is grounded in the equitable distribution of environmental burdens and benefits (Svarstad and Benjaminsen, 2020). DJ principles can be applied to environmental issues, considering that historically marginalized communities often face greater exposure to environmental hazards. This aligns with the broader DJ goals of fairness in the distribution of all resources and protections (Frohlich, 2007). This article focuses on DJ within green EJ cases, aiming to analyze whether citizens from diverse socio-economic backgrounds receive a fair allocation of PNbS in urban areas and benefit from them equally.

2.2. Issues of urban environmental justice related to the allocation of NbS in form of public GI

The concept of integrating nature into densely populated and rapidly growing cities is not new; it has been advocated since the 19th century (Nyka, 2017). Currently, due to the pressing challenges of climate change and the growing threat of flooding and the heat island effect, cities worldwide are hastening to design climate adaptation plans. In this context, NbS have emerged as crucial tools, integrating natural elements into urban landscapes. NbS are favored by designers and planners compared to grey infrastructure, for their adaptability and capacity to comprehensively address climate challenges. NbS not only prove to be more cost-effective but also offer numerous co-benefits, including societal well-being, reduced urban life depression, improved urban living environment quality by decreasing flood risk and enhancing air quality, and disaster prevention (Defra, 2011; Kabisch et al., 2016; Kolokotsa et al., 2020; Lečić-Toševski, 2019; Keeler et al., 2019; Ferreira et al., 2024; Beierkuhnlein, 2021; Jones et al., 2022; O'Sullivan et al., 2020).

Despite the mentioned benefits of NbS for urban societies, the issue of their fair allocation in cities, like most other urban infrastructure and facilities, has been observed in recent years (Anguelovski and Corbera, 2023; Castelo et al., 2023; Wijsman and Berbés-Blázquez, 2022; Cousins, 2021; Pineda-Pinto et al., 2021; Rigolon, 2016; Jennings et al., 2012; Wolch et al., 2014; Rigolon et al., 2018; Asl and Azadgar, 2022; Razzaghi Asl, 2023). Numerous studies have examined the availability and placement of public green spaces within urban settings worldwide. Astell-Burt et al. (2014) study in Australian cities such as Sydney, Melbourne, Brisbane, Perth, and Adelaide demonstrated a consistent trend: a lack of green space for low-income households within a 1-kilometer radius of their residences. In 2021, Cousins examined the spatial equity of open spaces in Hermosillo, Mexico, revealing that neighborhoods with the lowest socio-economic status had fewer parks, necessitating longer travel distances for residents to reach them. In Hangzhou, Wei's (2017) research showed that park allocation policies effectively increased overall green space accessibility while exacerbating spatial inequalities.

Nesbitt et al.'s (2019) analysis of 10 US urbanized areas uncovered a strong positive correlation between urban vegetation and higher education and income, with marginalized populations facing limited access to greenery in dense urban areas. In Warsaw, Pochodyła et al. (2022) and Solarek et al. (2023) found that green infrastructure was fragmented, with insufficient green spaces in densely built areas but extensive forest and park areas on urban peripheries. Sister et al. (2010) reported that less affluent individuals and ethnic minorities, particularly in the US, had limited access to parks. Boone et al. (2009) found in Baltimore that black communities were more likely to live within walking distance of a park, while white citizens had access to more park acres. Finally, Wüstemann et al. (2017) study in major German cities identified a positive influence of income, age, education, and child presence in the household on the available amount of urban greenery. Households with the highest income class (above 5000 euros per month) on average have about 11 square meters more of urban green space within a 500-meter vicinity of their residency compared to households with lower income (below 1300 per month). Similarly, households with the presence of children or elderly members have 9 square meters more of green space than others. Similar conclusions were also reached regarding education, as households with higher status in terms of education had access to more greenery.

Since studies of this kind increasingly indicate that the distribution of public greenery disproportionately advantages more affluent population groups, the uneven allocation of, and therefore the uneven availability of green space and GI are being recognized as issues of environmental and distributive justice. The pursuit of a fair distribution of PNbS is also justified by its correlation to public health issues, as proximity to urban green space has been shown to have positive impacts on physical health (Villeneuve et al., 2012) and psychological wellbeing (Ernstson, 2012). Addressing the lack of PNbS in more fragile urban areas, however, can be less intuitive than expected, as the creation itself of new quality parks or green spaces can trigger processes of "green gentrification" (Gould and Lewis, 2012; Anguelovski et al., 2022), where the increased benefits of GI result in a displacement of some population groups, thus paradoxically increasing environmental inequalities. To tackle the green paradox, Wolch et al. (2014) suggest a "just green enough" approach, where community concerns, needs and desires explicitly guide the design of green spaces. Anguelovski and Corbera's (2023) nature-based justice framework relies on a critical and re-politicized approach to NbS, explicitly addressing unsustainable economic pathways and land use patterns while avoiding greenwashing, appropriation, and speculation. Their framework guarantees the involvement of residents and users, incorporating their knowledge in the design and management process, thereby preventing undesirable effects that may occur when creating PNbS in socially and economically fragile urban areas.

3. Methodology

3.1. Tools and methods

The study aims to examine the spatial distribution of NbS in forms of publicly accessible green spaces (PNbS) in Gdansk and Rome in relation to the socio-economic context. The general methodology involves four key steps illustrated in Fig. 2.

Firstly, research objectives were established based on the main goal of examining the socio-economic profile and spatial distribution of PNbS in Gdansk and Rome to identify appropriate tools, methods, and variables for the study. The three research objectives are: (i) to verify whether PNbS are equally distributed in Gdansk and Rome based on socio-economic district features, (ii) to evaluate the correlation between the socio-economic status of districts and the spatial distribution of PNbS, and (iii) to identify districts to prioritize for PNbS

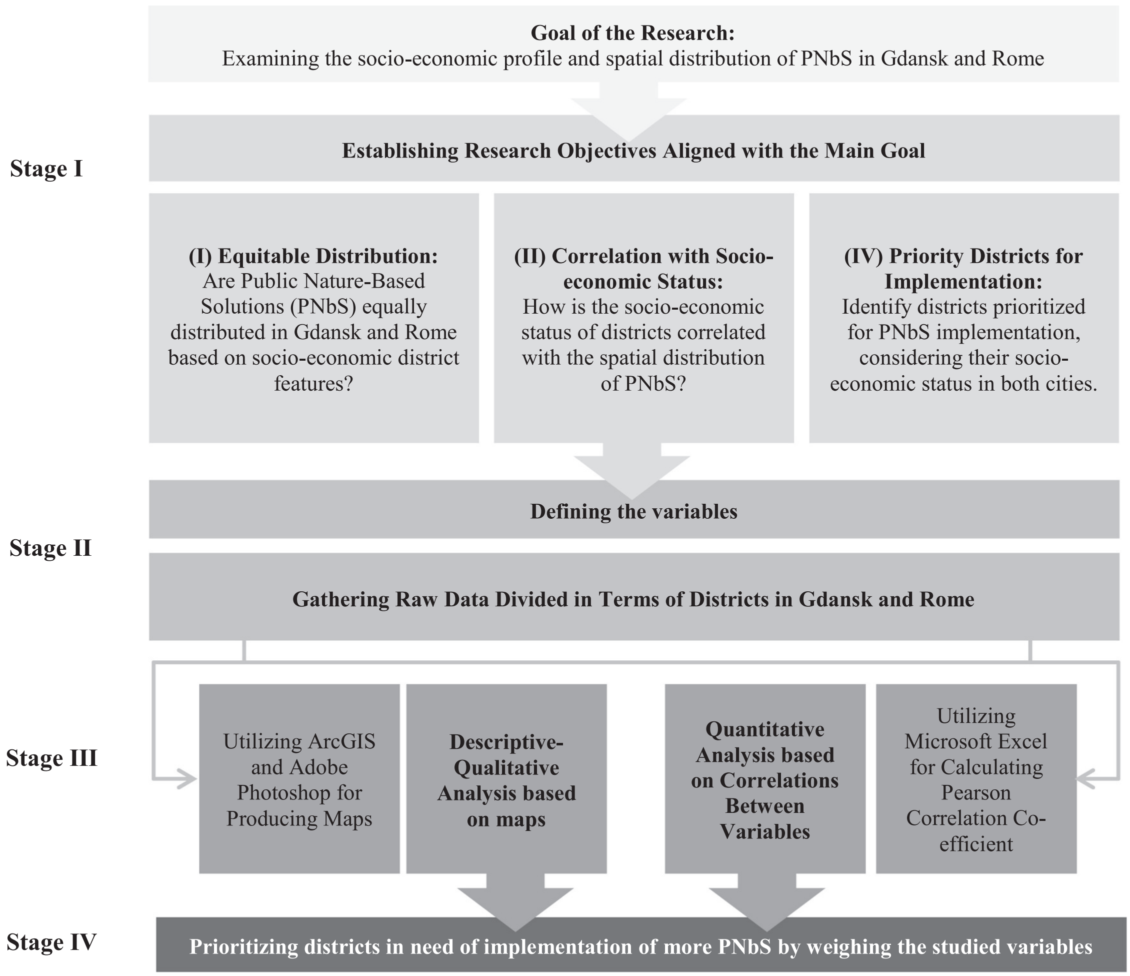

Fig. 2. Chart depicting the stages of the research.
Source: Authors.

implementation, considering their socio-economic profiles. Suitable variables were identified based on reviewing the related literature and the necessary raw data to calculate numerical values for each variable were extracted from various sources, as presented in Section 3.2. The next stage involved graphically presenting the distribution of variables by generating maps using ArcGIS 10.3.1 and Adobe Photoshop 2020 (Adobe Inc, 2020), integrating census data into the attribute tables for Rome and Gdansk. Simultaneously, the data were processed in Microsoft Excel 2010 to determine the Pearson correlation coefficient. With the graphical representation of spatial distribution and the correlation coefficients, the authors conducted a descriptive-qualitative analysis and a quantitative analysis to explore correlations between variables in each case study. The final stage involved assigning weights based on relative importance of variables to identify districts most in need of new PNbS implementation based on their socio-economic status.

3.2. Variables and data collection

Considering the main goal of the research, the authors sought to identify relevant socio-economic variables by examining those commonly used in similar studies. After establishing these variables, efforts were made to obtain the raw data necessary for their presentation and correlation calculation. The data were collected by referring to the most recent datasets available for each variable. However, due to differences in urban planning and management systems, the availability of socio-economic data varied between the cities. In Poland, data on household economic status and education levels are only available at the city level, whereas in Rome, such data is accessible at the district level. Consequently, alternative data types were obtained for Gdańsk to provide insights into the socio-economic status of its districts. Given these conditions and differences, five datasets were considered for Rome (PNbS density, population density, housing prices, education rate, and household income), and four for Gdańsk (PNbS density, population density, housing prices, and unemployment density). Detailed information about the studies that used similar variables, measurement, the data sources, and the corresponding years is provided in Table 1.

As evident from Table 1, secondary data for mapping and correlations came from various sources. Population, income, housing prices, and education rates of Rome were obtained from the city's website, Lelo et al. (2016), and ISTAT (2021). Housing prices of Gdansk were sourced from Sonarhome (SonarHome, 2024), with district data from the Gdańsk Districts portal and City Hall's Public Information Bulletin (Biuletyn Informacji Publicznej. BIP, n.d) . Unemployment data (2016) were from the municipal portal (Gdansk City Council, n.d).

The differences in municipal and planning systems between the two case studies also became evident when accessing the data needed to calculate the PNbS density at the district level. In Rome, the relevant raw data on the area of PNbS in each district was readily available in Excel table format on the municipality's website. In contrast, the data for PNbS areas in Gdańsk was provided in map format, accessible through Geoportal.gov.pl. Consequently, the authors exported the map illustrating the spatial distribution of different types of PNbS in Gdańsk, as also demonstrated in Fig. 3, and manually calculated the area of PNbS in each district. This data was then used to determine the PNbS density in

Table 1
Variables studied in this article and information related to them.

Case study	Variables	References	Measurement	Data sources	Year
Rome	Used for correlation analysis: Population density	Moos et al., 2021 state that population density can be used to identify large scale socio-economic disparities.	Population of the district divided by the area of the district (sq. km) to acquire population density.	Population was obtained from the statistics and data portal of the City (di Roma (n.d))	2022
	Used for correlation analysis: PNbS density		The PNbS density was calculated by dividing the area of PNbS within a district by the district's total area.	Area of districts was obtained from the statistics and data portal of the City (di Roma (n.d))	2022
	Used for prioritization index: Ratio of Population Density and PNbS density		Population density was divided by the PNbS density in each district.	PNbS area was obtained from the statistics and data portal of the City, based on data of the environmental protection Department (di Roma (n.d))	2021
	Median Household Income	Oka, 2022; Wüstemann et al., 2017	—	Median household income was obtained from the statistics and data portal of the City (di Roma (n.d))	2020
	Education Rate	Wüstemann et al., 2017	Percentage of population with Higher Education Degree, it was calculated by dividing the number of inhabitants with higher education degree to the total population of the district	Education rate was obtained from the National Institute of Statistics (ISTAT 2021)	2021
	Housing Prices	Li et al., 2024	Average real estate value per sq. meters in (€)	Housing prices were obtained from website mapparoma.it, based on data from the Housing Market Observatory (OMI) (Lelo et al., 2016)	2018
Gdansk	Used for correlation analysis: Population density	Moos et al., 2021	Population of the district divided by the area of the district (sq. km) to acquire population density.	Population density was obtained from District portal of the City of Gdańsk (Gdańsk Districts, n.d.)	
	Used for correlation analysis: PNbS density		The PNbS density was calculated by dividing the area of PNbS within a district by the district's total area.	Areas of the districts were obtained from District portal of the City of Gdańsk (Gdańsk Districts, n.d.)	
	Used for prioritization index: Ratio of Population Density and PNbS density		Population density was divided by the PNbS density in each district.	To obtain the spatial distribution of PNbS, the geoportal was accessed and the layers regarding playgrounds, sportfields, parks, forests, as well as greenery along shores of the lakes and rivers were exported (Geoportal.gov.pl. (n.d.)). Since data concerning the area of these layers were not divided by the districts, the area of existing PNbS in each district of Gdansk was manually calculated through pixel counting in Photoshop.	
	Housing prices	Moss et al., 2024	Average real estate value per sq. meters in (€).The original prices were in PLN and were converted to euros using the average exchange rate provided by the European Central Bank (2024) for January, the month in which the housing prices were assessed.	Home (n.d.)	2024
	Unemployed Population	Wüstemann et al., 2017	The number of unemployed people, divided by gender and age group for each district, was summed and then divided by the district's total population to calculate the percentage.	(Gdańsk.pl, n.d., Unemployed by district in 2012–2016)	2016

Gdansk. This additional step was unnecessary for Rome, as the area of PNbS for individual districts was already available in Excel format, streamlining the process for that case study.

3.3. Data integration and analysis

After entering each district's data into the attribute table of the case studies' shapefiles in ArcGIS, several maps were generated to support a descriptive-qualitative analysis. This approach focuses on interpreting complex data through qualitative methods, which is particularly useful for analyzing maps and exploring spatial relationships that quantitative methods might miss (Rabino, 2014).

To complement this, Pearson correlation analysis was conducted to quantitatively assess the relationships between PNbS density and the socio-economic factors. The Pearson Correlation Coefficient with its formula showcased in Eq. 1, ranges from + 1 to −1, measuring the strength of positive or negative linear relationships between variables (Schober and Vetter, 2020).

$$r_{x,y} = \frac{\sum_{i=1}^{n}(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\overline{y})^2}} \tag{1}$$

Eq. 1. Formula of Pearson correlation coefficient, Source: Li et al. (2022)

3.4. Assigning priority values

The final step of the study involved prioritizing districts for future PNbS implementation. To accomplish this, an attribute table was created for each case study, displaying relevant variables. For a more balanced analysis, it was decided to combine population density and PNbS density into a single variable. This adjustment allowed for constructing a more comprehensive measure that captures both population density and PNbS availability.

The authors collaboratively determined the weights for each variable, considering insights from other studies and the correlation results

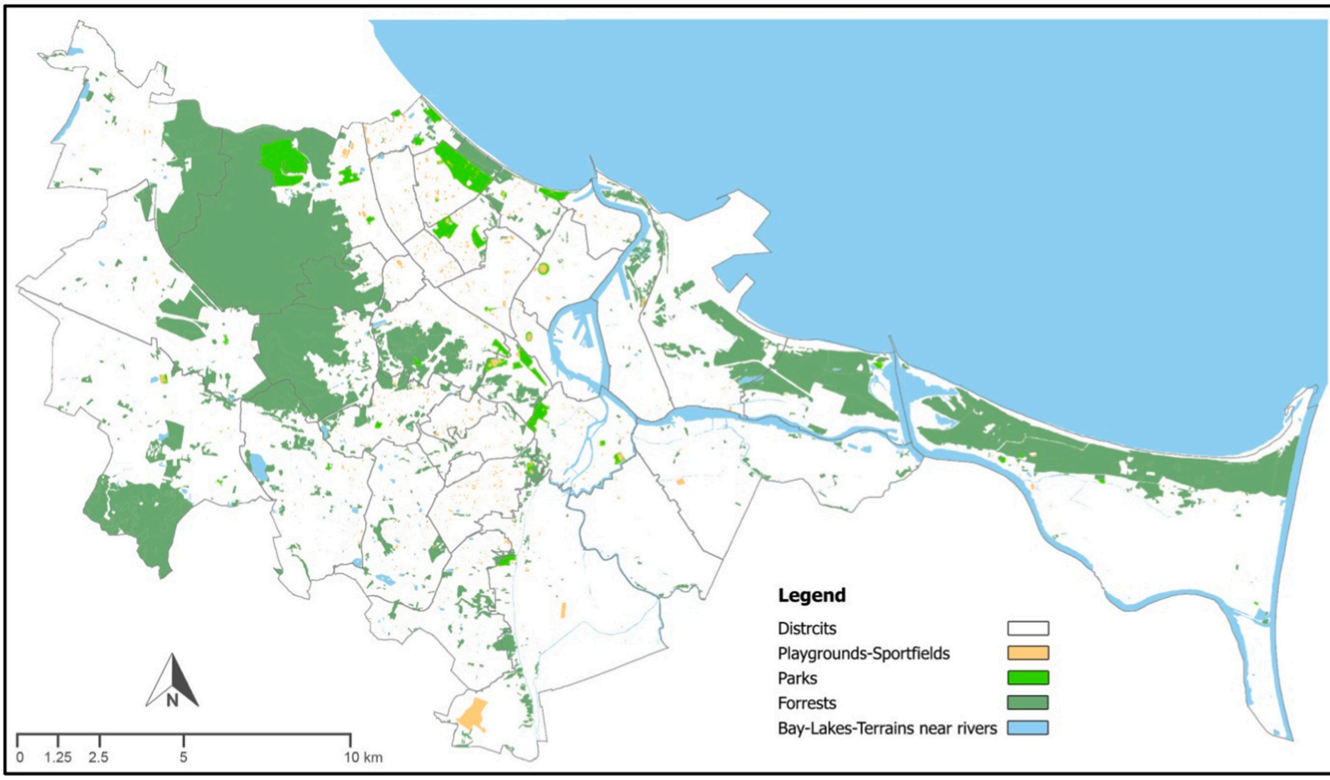

Fig. 3. Geographical location of different types of PNbS in city of Gdansk.
Source: Authors elaboration on map exported from (geoportal.gov.pl).

from this research. These weights and the rationale behind them will be thoroughly explained in the results section. The values of the indicators were normalized (scaled between 0 and 1) and then inverted, except for population density and unemployment rate. This exception was made because the authors aimed to maintain a positive correlation between these two variables and the amount of PNbS available in a district. For example, a higher unemployment rate should correspond to more PNbS in a district. In contrast, for other variables like household income, where authors applied the inversion, the goal is the opposite — districts with lower household income should have more PNbS. Finally, weights were assigned to each variable according to their importance and relevance. The prioritization was visualized using ArcGIS, creating maps that facilitate better analysis and understanding. Eq. 2 demonstrates the formula constructed for the weighting process.

$$S = \sum_{j=1}^{n} w_j \times N\left(\frac{I_j - \min(I_j)}{\max(I_j) - \min(I_j)}\right) \tag{2}$$

Eq. 2. Formula for the weighting process, Source: Authors
Where

- I_j represent the value of the j-th indicator (e.g., population density, unemployment rate, etc.).
- $N(x_j)$ represent the normalization function, which for ratio of population density and PNbS density, and unemployment rate is defined as $N(x_j) = x_j$ and $N(x_j) = 1 - x_j$ for the rest of indicators;
- $w_j \in [0, 1]$ represent the weight assigned to the j-th indicator, such that $\sum_{j=1}^{n} w_j = 1$;
- S represent the final score (or composite index) after applying all transformations and weights.

3.5. Study areas

Two case studies were selected for the present study: Gdańsk, a coastal city situated next to the Baltic Sea in Poland, and Rome, the capital city of Italy. The two cities were selected for several reasons – both metropolitan areas extend into waterfronts, they differ in geographical locations and urban development paths. Their similarities, alongside their vast differences, make them intriguing case studies that effectively highlight contrasts and distinctions when compared to one another. Rome as "eternal city" developed in a continuous manner through ages both in spatial and social terms (Hom, 2010). Gdańsk underwent a significant population exchange after 1945, was heavily damaged as a consequence of the Second World War (Bykowska, 2020; Dymnicka and Szczepański, 2016) and throughout much of the twentieth century, its economy relied heavily on the shipbuilding industry. Some insights from the comparison of the two cities are summarized in Table 2.

Geographically, Gdańsk city developed on the edge of two ecological systems, namely the moraine hills to the West, largely covered by forests, and the low-lying delta plain of river Vistula to the East. The low-lying area was transformed into a polder system, mainly devoted to agricultural activities. The Municipality of Gdańsk, of approximately 265 square kilometers, covers a large portion of coastal territory, including the three ramifications of the western branch of the Vistula river. The Vistula receives the water of its tributary the Motława on the edge of the historic center, a few kilometers before ending into the bay of Gdańsk in the Baltic Sea. The historic city is nowadays part of a linear system of urban centralities stretching between the hills and the waters of the sea and the rivers, where the main urban services and transport infrastructures are located. At the municipal level, the main urban centralities are the Main Town (the historic area), Wrzeszcz, and Oliwa, while at the metropolitan level the linear system continues along the coast with the cities of Sopot and Gdynia. In the 20th century the system of linear green spaces was established, but the outbreak of the Second World War significantly disturbed the urban development processes (Badach et al., 2022; Myślińska et al., 2021). Suburbanization observed in the last decades extended urban areas into the west and south-west

Table 2
Comparison between major urban components of Rome and Gdansk.

	Rome	Gdansk
Settlement pattern	Radial central	Linear polycentric
Ecological structure	Greenery: a green wedge structure River: reinforces green wedges system	Greenery: parallel bands River: an infrastructural corridor with scarce greenery, splits municipal area
Ideal green infrastructure (as imagined in the historical plans)	Concentric rings and large wedges Missed element: concentric rings	Parallel bands and transversal wedges Missed element: transversal wedges
Development patterns	Homogeneous growth Post-World War II: continuous; urban expansion towards east, largely unregulated Last decades: settlements growth in the peripheries, led by speculation	Almost complete (95 %) destruction in 1945 Post-World War II: disconnected; working-class neighbourhoods near the port and emptying of the center Last decades: redevelopment and densification of the urban band between center and suburbs; dispersion towards the countryside
Population	Steadily growing until 1980s; today decreasing in the center, increasing in the peripheries and hinterland	Largely replaced in 1945; today slightly but steadily growing
Function distribution	Quite homogeneous	Industry and port areas in close proximity to the city center

directions towards the rural landscape and moraine forests. Easily accessible forests and suburban meadows, along with post-industrial and post-military waterfront coastal territories that are gradually transformed into public spaces (Burda and Nyka, 2023), have become important elements in the urban greenery system. The municipal area of Gdańsk is divided into 35 territorial units. Maps showing the geographical location of Gdansk are provided in Fig. 4.

The city of Rome is located on the low hills where two volcanic systems meet, divided by the course of river Tiber. The low hills gradually wane into the coastal alluvial plain where the river forms a two-branched delta and finally reaches the Tyrrhenian Sea. The urban structure of Rome, as well as that of the entire region, is the result of a radial settlement development, following the ancient Roman road system (Caracciolo, 1991). During the last century, the urbanized areas rapidly extended over the agricultural areas which surrounded the city, leaning on the main historicized axes and thus reinforcing the "sliced" (Crisci et al., 2014) settlement pattern. As a result of radial expansion, the main green spaces have the shape of large green wedges marked by the hydrography, dotted with archaeological remains which emerge against a traditional agrarian landscape, typically intertwining history with nature (Calzolari, 1999). In the city center, the largest green spaces are the historical villas transformed into public parks. The municipal territory, extending on a surface of 1245 square kilometers (Vigna et al., 2016), includes the main urban area developed around the historic city of Rome and its surroundings, as well as a large part of the coastal plain on the left bank of the Tiber, which accommodates a secondary, partly detached urban area reaching the sea at the Tiber's mouth. The municipal area of Rome is divided into 15 territorial units. Maps depicting the geographical location of Rome are presented in Fig. 5.

4. Results

4.1. Spatial distribution of public nature-based solutions

4.1.1. Rome

As demonstrated by the left map in Fig. 6, district number 10 holds the majority of PNbS in Rome, and districts 11, 13, and 14 have the least. To have a better understanding of the PNbS area in relation to the total land area of each district, the right map in Fig. 6 was used which depicts the density of PNbS derived from the division of PNbS area by the total area of each district. Based on this map, it is evident that District 2 holds the highest density of PNbS and northern and northern west districts such as 13, 14, and 15 have the least.

4.1.2. Gdansk

Fig. 7 displays the amount of area in each district in city of Gdansk that is assigned to PNbS. The upper map shows the area of different PNbS in square kilometers while the map below presents the PNbS density. At first glance it is worth noting that two districts of Oliwa and Wyspa Sobieszewska own the largest area of PNbS while several other districts such as Nowy Port and Olszynka own the least. Observing the PNbS density, though, reveals the district of Letnica to be at the top of density pyramid whereas a district such as Wyspa Sobieszewska being among districts with relatively lower PNbS density. Following the PNbS map a pattern concerning the general placement of districts with low PNbS density is noticeable. Three districts of Rudniki, Olszynka and Orunia-Św. Wojciech-Lipce in southern skirts of the city include the lowest of PNbS density ranging from 0 to 0.101523. Four other districts of Wzgórze Mickiewicza, Młyniska, Strzyża and Nowy Port are also suffering from lower ends of PNbS density spectrum.

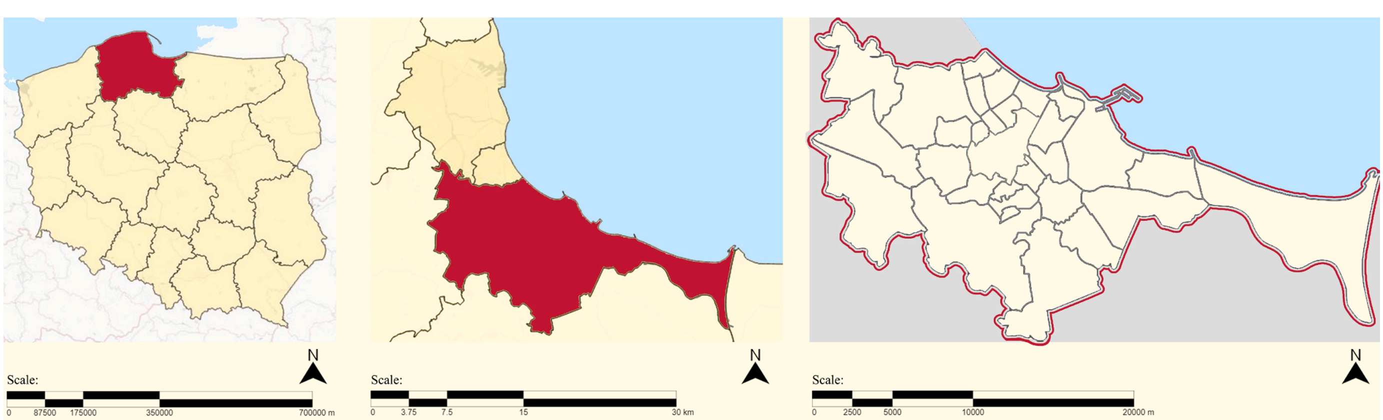

Fig. 4. Geographical location of the first case study Gdansk, from left to right: Pomeranian Voivodeship in Poland marked by red. Location of Gdansk in Tricity metropolitan area Source: adopted from Source: Authors' elaboration on shapefile obtained from (Humanitarian Data Exchange, 2022), map of Gdansk and its districts divisions, Source: Authors' elaboration on shapefile obtained from (Rad Dzielnic et al., 2023).

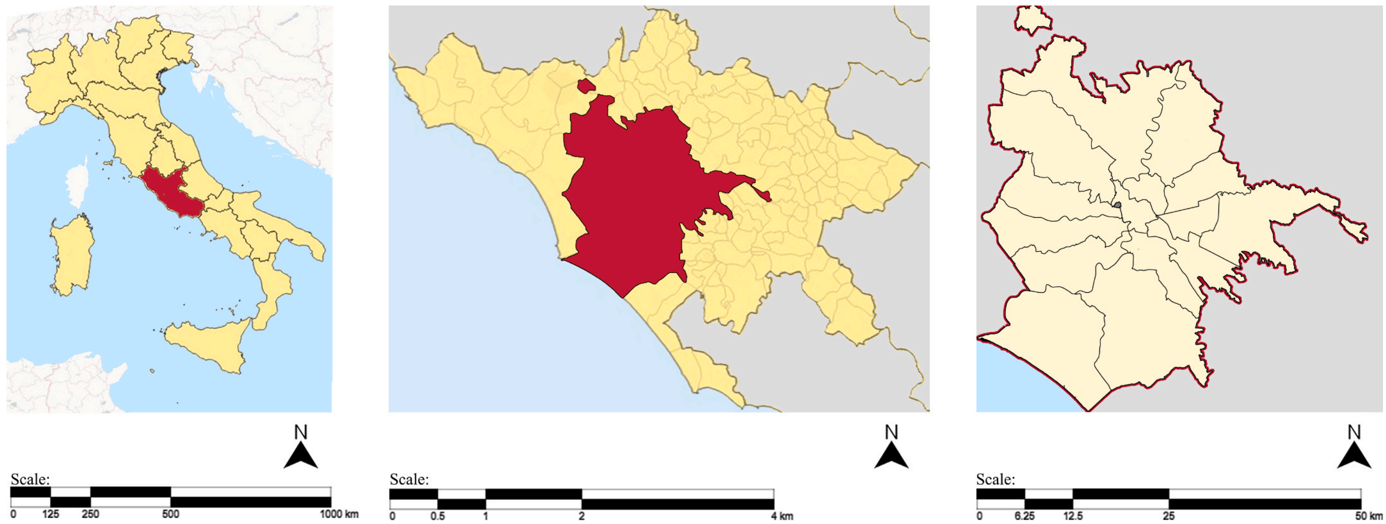

Fig. 5. Geographical location of the second case study, Rome, from left to right: Lazio region in Italy marked by red source. The location of Rome capital city in the Metropolitan City of Rome.
Source: Authors' elaboration on shapefile provided by (Hijmans, 2015), map of Rome capital city and its districts, Source: Authors' elaboration on shapefile provided by (DatiOpen, 2013).

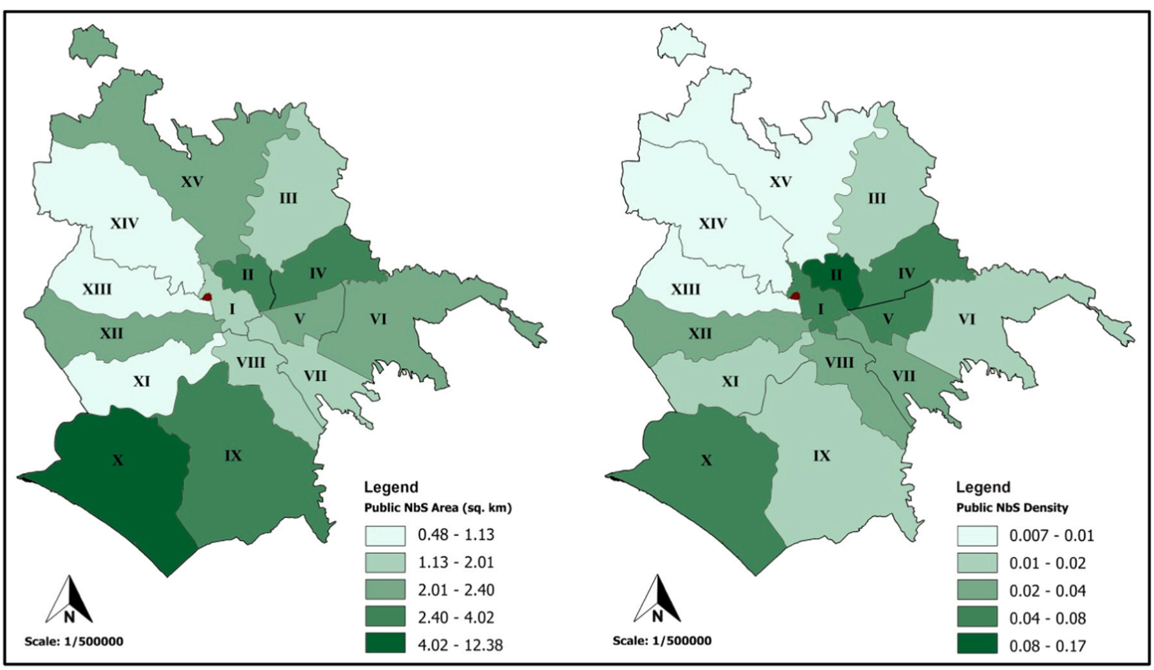

Fig. 6. Distribution of PNbS in districts of Rome, Left: Map demonstrating the PNbS area, Right: Map demonstrating the PNbS density in districts of Rome.
Source: Authors.

4.2. Public nature-based solutions in the urban socio-economic context

4.2.1. Rome

By analyzing the distribution of PNbS based on socio-economic features in each district of Rome, four maps derived from the data presented in Table 1, which are showcased in Fig. 8. Map (A) highlights that Central Districts (I and II) in Rome exhibit the highest median household income, while Districts V, VI, and XI have the lowest income levels. Correlating income data with PNbS density reveals that Districts II and I, boasting the highest household income, also exhibit the highest PNbS density. In contrast, District XI, with relatively low household income, experiences lower PNbS density. Notably, the role of District XI extends to housing prices, as it consistently reflects one of the lowest housing costs, while Districts I and II stand at the opposite end of the spectrum with the highest housing prices. Examining population density, Districts XV and XIV register low figures in both population and PNbS density. Conversely, Districts II, I, and V show higher values for both metrics. An intriguing observation is the abundance of PNbS in District X, despite its low population density. Map (D) in Fig. 8 provides a comprehensive view of the education scenario, revealing that Districts I and II lead with the highest percentages of inhabitants holding higher education degrees at 33 % and 39 %, respectively. This aligns with the higher PNbS presence in these districts. Continuing the education analysis, it is evident that District XI, with the lowest percentage of inhabitants holding higher education degrees, also ranks among the districts with the lowest PNbS density. Calculating the Pearson coefficient to assess the relationship

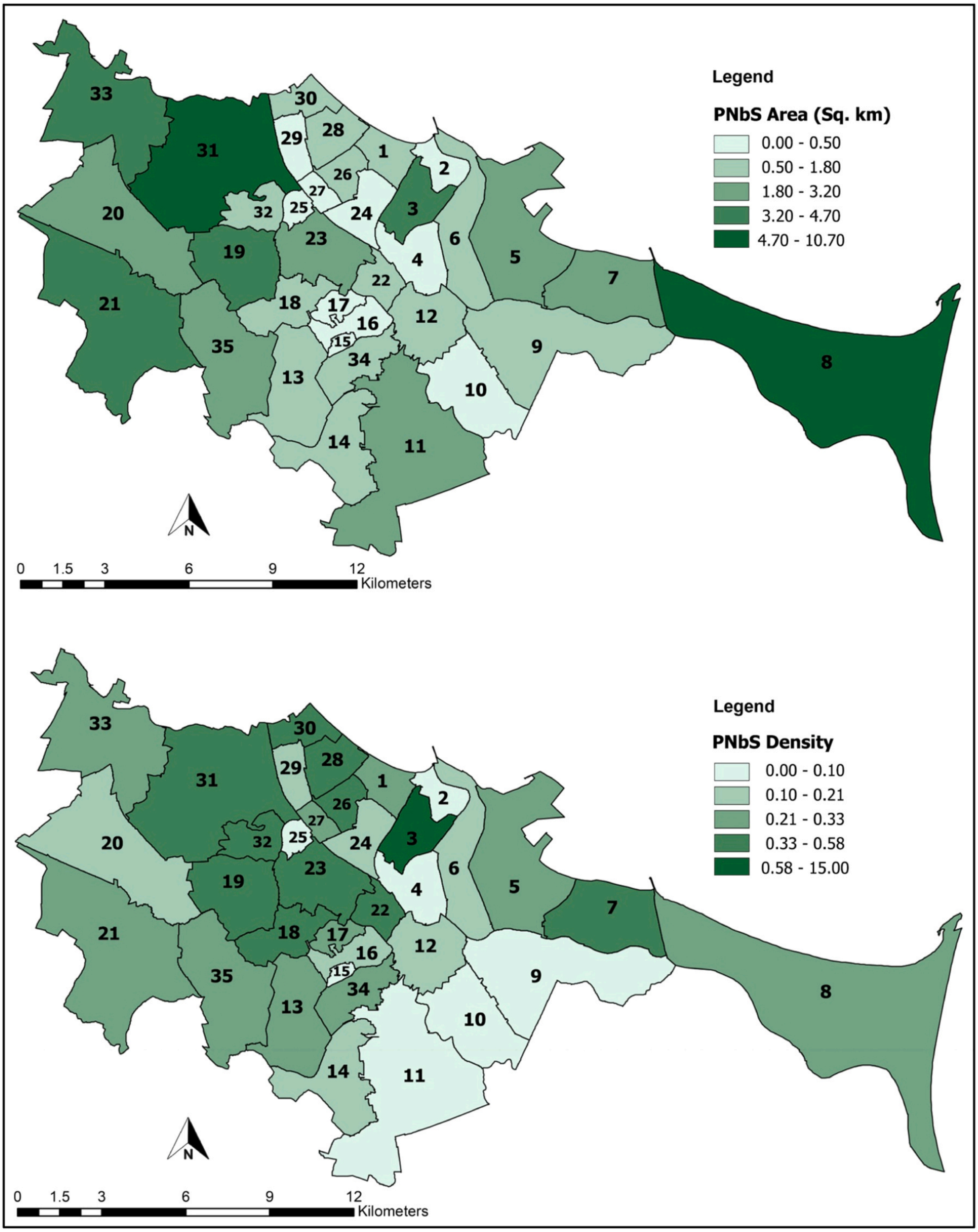

Fig. 7. Distribution of PNbS in districts of Gdansk, Above: Map demonstrating the PNbS area, Below: Map demonstrating the PNbS density in districts of Gdansk. Source: Authors.

between Rome's socio-economic criteria and PNbS density yields similar results, with Pearson co-efficient values of 0.5552, 0.7354, 0.5078, and 0.5253 for housing prices, population density, household income, and education rate, accordingly.

Overall, the maps of Rome show a clear wedge structure for the distribution of the socio-economic data, which is consistent with the spatial structure of the city. The two core districts, I and II, almost coincident with the historic center, feature the highest levels in all data collected, from population density to income, housing prices and education levels, also presenting a high PNbS density. Observing the other districts, five wedges with similar socio-economic characteristics can be identified. Among these, the eastern quadrant including districts IV, V, VI, and VII, shows a combination of high population density and lower socio-economic status, signaling a more delicate sector of the city.

4.2.2. Gdansk

In Poland, data on household income and education rates is available only for the entire city rather than specific districts. Therefore, the analysis incorporated available data on unemployment density, along with housing prices and population. Regardless of the socio-economic

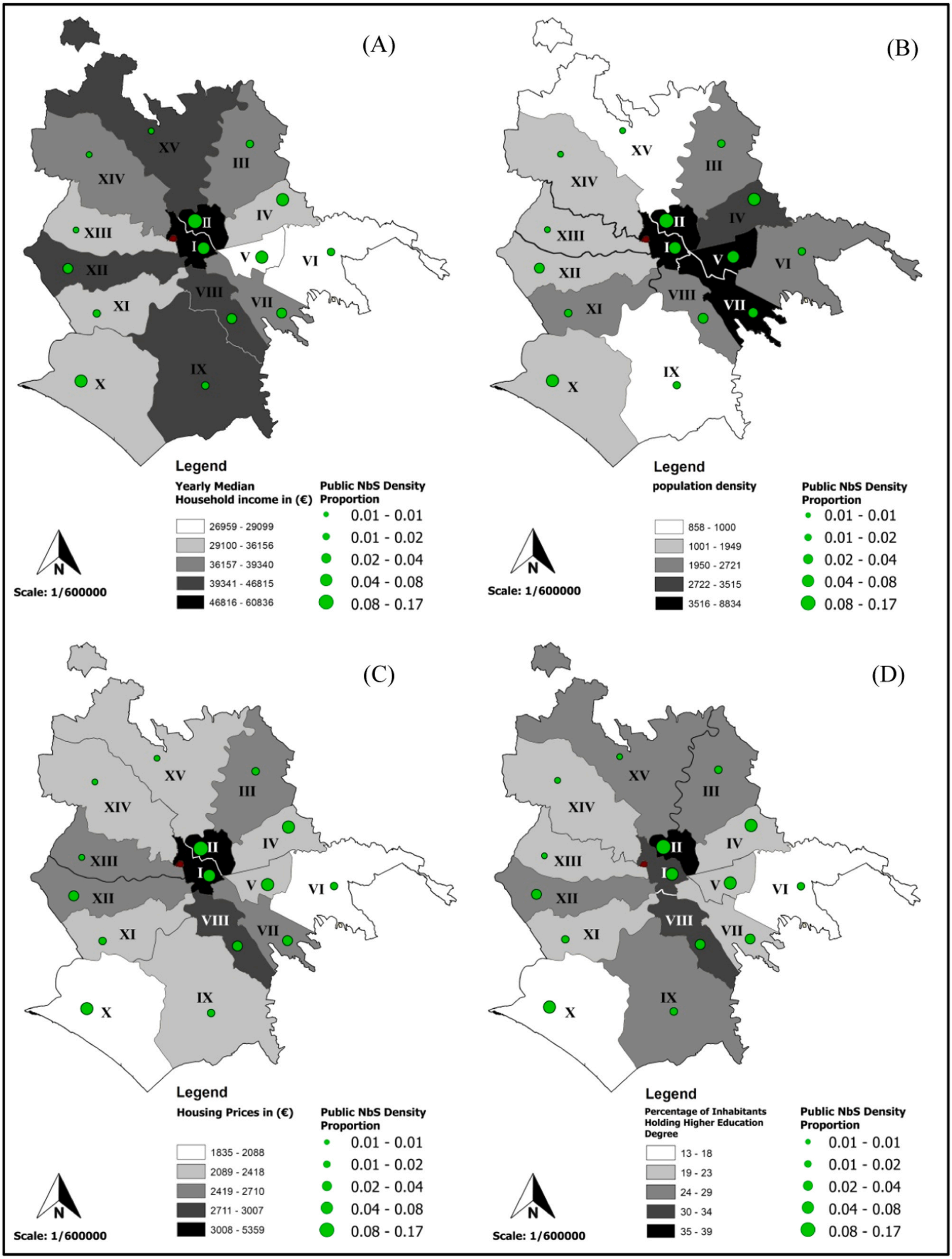

Fig. 8. Socio-economic features in districts of Rome.
Source: Authors.

position, most districts show significant PNbS density, with the density appearing largely consistent across them. On closer examination though, some southern districts exhibit a lower prevalence of PNbS. Moving from the southern outskirts, districts 15, 4, 2, and 25 scattered around the city also share this issue. Map A in Fig. 9 indicates the PNbS density and housing prices in Gdansk. Notably, districts 11, 15, 9, and 2 with the lowest housing prices include the lowest PNbS density. On the other hand, denser PNbS often correlates with higher housing costs in Gdansk, except for districts 25, 4, and 10. The calculation of the Pearson coefficient for PNbS density and housing prices in Gdansk resulted in a positive yet weak value of Pearson co-efficient of 0.3084. This implies that, overall in Gdansk; greater housing costs are associated with higher PNbS densities within districts.

Map B in Fig. 9 depicts the population density and by examining it, it is worth noting that districts on the eastern edge (10, 9, and 8) are among the least populated areas in Gdansk while a cluster of districts in north (30, 29, 28, 27 and 26) are highly populated. Although it may be difficult to determine how PNbS density and population density relate to one another, an optical inspection generally suggests that PNbS are distributed fairly uniformly throughout the city concerning population density, as the presence of districts with possible high population density and low PNbS density is scarce. Map B shows that the districts with the highest population density have a comparatively high concentration of PNbS. There are however exceptions such as districts 2, 25, 15, and 11 which although not as populated as the districts mentioned before, possess a moderately high population density and in contrast own the lowest PNbS density. Calculating the Pearson coefficient yields a weak but intriguing association with the number −0.1665, meaning that overall, lower PNbS density and higher population density in Gdansk correspond.

The unemployed population percetange in Gdansk's several districts is displayed in Fig. 9, Map C. One noteworthy observation is that Gdansk's unemployment rate generally increases from the west to the east. Qualitative descriptive analysis of overlaying the data of PNbS density and unemployment seems to be challenging since there are contrasting instances such as districts 3 and 9. District 3 displays a significantly greater PNbS amount, and district 9 shows a substantially lower PNbS density, even though both districts have the largest percentage of unemployed population. The Pearson coefficient for this section came to be 0.426, a moderately positive correlation implying that with the value of unemployed population percentage rising, there usually comes a higher PNbS density as well.

4.3. Identifying priority areas based on socio-economic considerations for implementing PNbS

4.3.1. Rome

Through an analysis of PNbS distribution in Rome and its correlation with the city's socio-economic context, it is evident that there is an uneven placement of PNbS. To address this issue with existing data, the authors designated a socio-economic priority value for each district in Rome. This value represents the district's social need in regards to the implementation of more PNbS; higher values indicate a greater demand for additional PNbS. Social priority values emerge from the analysis of the distribution of PNbS in relation to the socio-economic profile of the city's districts. These values are meant to be considered together with heterogeneous environmental information, in order to implement more equitable and just improvements in the urban GI. The results are detailed in Table 3, while Fig. 10 portrays these values on a map of Rome. Notably, District VI emerges as the top priority for building new PNbS, with Districts XI, XIII, V, XIV, and VII closely following with high priority.

The weighting process was conducted collaboratively by the authors, who discussed and agreed on the weights by referring to relevant studies and considering the Pearson co-efficient values from this study. The 40 % weight assigned to population density reflects its crucial role in green space planning, as higher density often leads to reduced green space availability (Wolff and Haase, 2019; Richards et al., 2017). Suggested weight also promotes maintaining high correlation between the population density and PNbS density (0.7354) found in this study, which is a prerequisite for equal access to the public greenery.

For the other indicators, the similar Pearson co-efficient values (0.5253 for education rate, 0.5552 for housing prices, and 0.5078 for household income) suggest the positive correlation of a similar strength, which in this case is a negative effect, promoting inequalities in the availability of PNbS. Inversion of the variables, performed after normalization was designed to tackle this issue, while the weights were assigned with minimal differences to reflect the similarity in correlations. Household income was given a 25 % weight, as it has been linked to the notion that green space availability tends to be lower in areas with a higher percentage of low-income residents (Astell-Burt et al., 2014). Education rate was weighted slightly higher than housing prices, at 20 %, due to the complexities associated with prioritizing housing prices in green space planning, particularly regarding gentrification concerns, as also mentioned earlier in this article.

4.3.2. Gdansk

Utilizing the weighted calculations as outlined elaborately in the methodology section for Gdansk, the socio-economic priority values for each district are presented in Table 4 and visually illustrated in Fig. 11. Notably, Wzgórze Mickiewicza, Nowy Port, Orunia-Św., Wojciech-Lipce, and Przymorze Małe, Strzyża emerge as top priorities for creating additional PNbS.

For weighting the socio-economic indicators in Gdansk's case, the authors closely considered the correlation results. The value of the Pearson co-efficient between the unemployment rate and PNbS density was 0.426, indicating a moderate positive correlation, meaning higher unemployment in a district corresponds with higher PNbS density. This made unemployment rate the least crucial indicator in Gdansk compared to the other two. The calculations for housing prices yielded a Pearson coefficient of 0.3084, a weak positive correlation, suggesting that higher housing prices are associated with greater PNbS density in Gdansk. Population density had a correlation of 0.1665, showing a positive but weaker correlation than the other indicators. Given these results, the lowest weight was assigned to the unemployment rate. The decision then came down to housing prices and population density. Population density was given the most weight, as its importance has been emphasized in several studies (Vervoort et al., 2023; Li et al., 2021). In contrast, prioritizing housing prices carries the risk of gentrification, so housing prices were weighted less than population density.

5. Discussion

This article has presented a GIS-based study for figuring out the spatial distribution of NbS, specifically public green spaces, taking Gdańsk and Rome as case studies. The objective was to provide a comprehensive and detailed perspective on the distribution of PNbS in relation to the socio-economic attributes of their respective geographical surroundings. This approach facilitates a comparative analysis between the two case studies, enhancing the understanding of their differences.

5.1. Spatial patterns in the distribution of PNbS

The results indicate distinctive spatial patterns in the distribution of PNbS in Rome and Gdansk. In Rome, District II has the largest density of PNbS, while Districts XI, XIII, and XIV have the least. District X stands out with the majority of PNbS area. Conversely, in Gdansk, Oliwa and Wyspa Sobieszewska own the most PNbS area, but Letnica has the highest PNbS density. The examination of PNbS within the urban socio-economic setting reveals interesting connections. Districts I and II in Rome exhibit higher PNbS densities, as well as higher household income

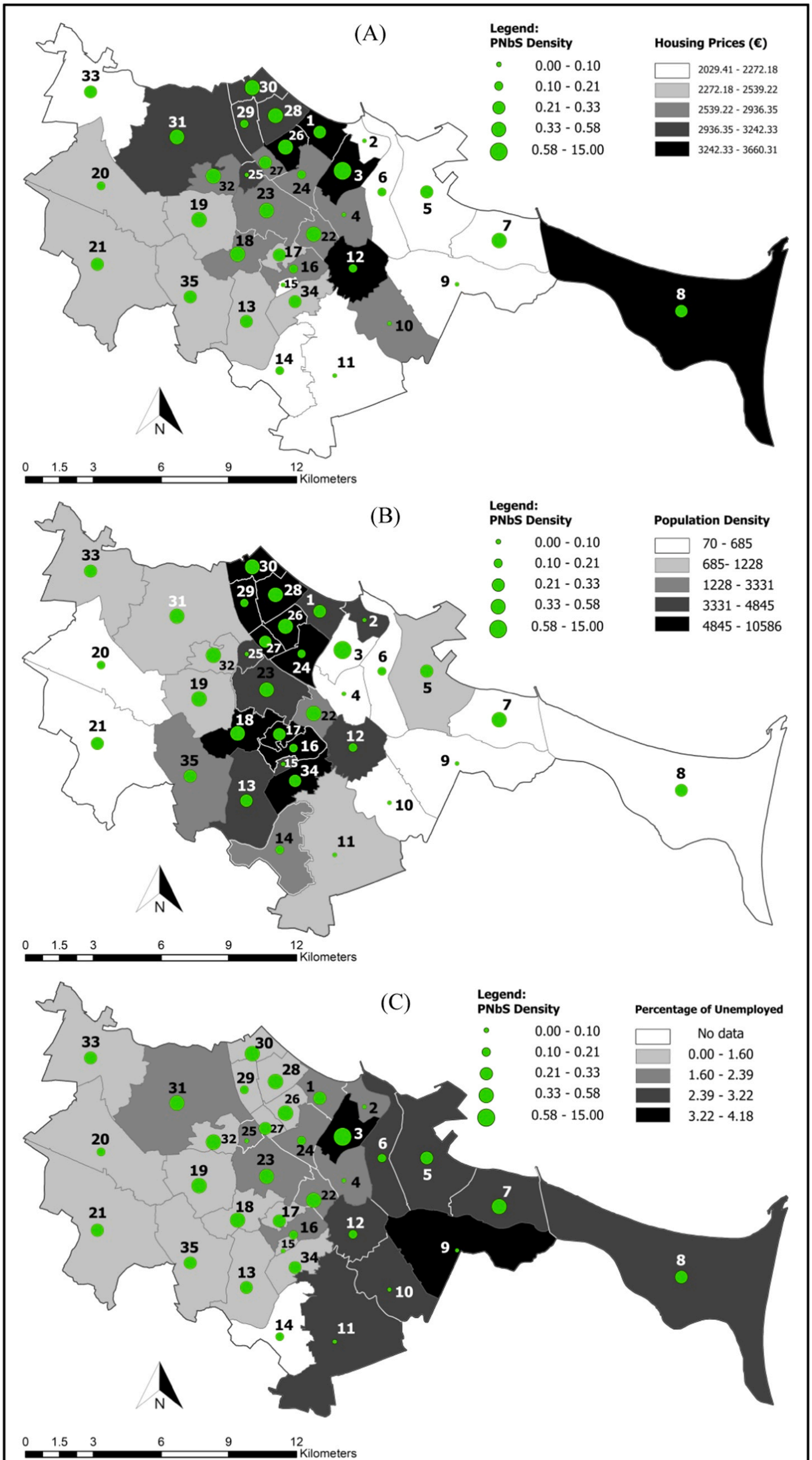

Fig. 9. Socio-economic features in districts of Gdansk.
Source: Authors.

Table 3
Data regarding PNbS and socio-economic features in Rome's districts.

Number	District	District Area (km^2)	PNbS Area (km^2)	PNbS Density	Housing Prices (€)	Population Density	Median Household Income	Percentage of population with Higher Education Degree
1	I	20.1	1.67	0.08	5359	8185	53871	33
2	II	19.7	3.26	0.17	4210	8400	60836	39
3	III	98	1.89	0.02	2689	2085	39340	26
4	IV	48.9	3.61	0.07	2292	3515	33642	20
5	V	26.9	2.15	0.08	2335	8834	29099	23
6	VI	112.3	2.33	0.02	1835	2155	26959	13
7	VII	47.6	1.96	0.04	2710	6544	37677	23
8	VIII	47.2	2.01	0.04	3007	2721	43232	29
9	IX	183.2	4.02	0.02	2395	1000	46815	27
10	X	150.7	12.38	0.08	2088	1513	35303	17
11	XI	71.5	1.12	0.02	2418	2134	32743	19
12	XII	73.1	2.33	0.03	2546	1920	41832	27
13	XIII	66.9	0.48	0.01	2678	1949	36156	23
14	XIV	133.5	1.13	0.01	2187	1425	38742	23
15	XV	187.2	2.4	0.01	2404	858	43541	25
Mean value		85.79	2.85	0.05	2743.53	3549.2	39985.87	24.47
Standard deviation		54.34	2.7	0.04	871.26	2784.61	8662.43	6.14

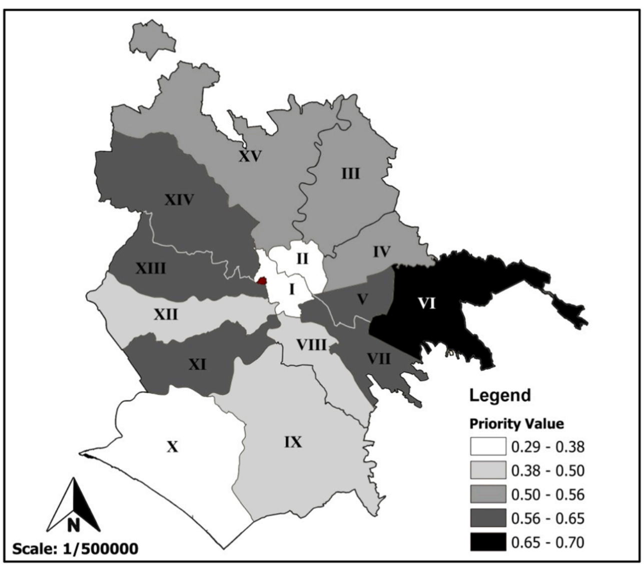

Fig. 10. Socio-economic priority values for implementing new PNbS in Rome. Source: Authors.

and education rates, while District XI, which has lower income and education rates, has lower PNbS density. The population density, household income, housing costs, and education rate all show positive associations with the density of PNbS in Rome aligning with the findings of studies reviewed in this research, including those by Astell-Burt et al. (2014), Cousins (2021), Nesbitt et al. (2019), and Solarek et al. (2023).

Regardless of the socio-economic status, the majority of Gdansk's districts have a notable PNbS density, with the exception of a few southern districts that have a lower PNbS prevalence. Weak to moderate correlations are observed between housing prices, population density, and unemployed population percentage with PNbS density. Moreover, when comparing our findings on the density of available PNbS across different districts in Gdansk with a 2013 study by Brosz et al. (2023) on environmental conditions in these areas, intriguing alignments emerged. Alignment of districts with poorer living conditions identified by Brosz et al. (2023) and those with lower PNbS density in our research provides insights into the complex relationship between urban socio-economics and PNbS distribution.

This research highlights a stronger positive link between the density of PNbS and socio-economic parameters in Rome in contrast to Gdansk, suggesting a more uneven spatial distribution of PNbS in the former city. Nevertheless, a comparison of the Pearson coefficients for PNbS density and housing prices shows that there is a larger degree of disparity in the PNbS distribution with respect to housing prices in Rome (0.5552) as compared to Gdansk (0.3084). Furthermore, a strong positive linear relationship in Rome (0.7354) but a weak negative correlation in Gdansk (-0.1549) is revealed when the correlation between PNbS density and population density in these two cities is compared. This divergence suggests that, in contrast to Rome, where higher population density corresponds with increased PNbS density, Gdansk has districts with a lower population density but high PNbS density. This difference might be explained through an evaluation of the different settlement patterns of the two cities, geo-political history, as well as their environmental structure and the public/private property proportion of the land.

5.2. Prioritizing PNbS implementation in Gdansk and Rome

As shown in Table 2, the settlement structure in Rome can be described as radial and central, while in Gdansk it is linear and polycentric. Such settlement configurations are consistent with the ecological structures of the two cities, made of large green wedges in the case of Rome, and composed by two parallel bands in Gdansk, corresponding to the hills line and the bay coastline. The rivers also play different roles in the urban and ecological structure. While river Tiber – with its tributary the Aniene - reinforces the green wedges system of Rome, river Martwa Vistula introduces an infrastructural, industrial corridor that tends to split the municipal area of Gdansk in two parts. Both priority values maps seem to correspond to the ecological structure/settlement structure relation. In Gdansk, however, the socio-economic indicators seem to draw a distinction between two parts of the city, separated by the port area along river Vistula. The existence of an infrastructural barrier in the middle of the municipal area can therefore partially explain the fact that the socio-economic status of the population doesn't clearly match the public green spaces availability. Priority areas are placed along the river, in the vicinity of shipyard and port areas, and the central urban corridor. {{{Table 5, Table 6, Table 7, Table 8}}}

The higher priority values in the denser urban fabric stripe reminds of the 1930 Greater Gdansk plan, which envisioned the development of green wedges - or tended strings, one may suggest - between the two green belts along the hills and the bay (Althoff, 1930). Today, the idea is being partially recovered in the municipal Water Policy, which suggests recovering and reinforcing the minor streams as green wedges (Biuro Rozwoju Gdańska, 2021). Almost contemporary WWII plans of Rome give an interesting insight into the ideal green infrastructure of the city, imagined as a combination of large wedges and concentric rings

Table 4
Data regarding PNbS and socio-economic features in Gdansk's districts.

Number	Distrcit Name	District Area (km^2)	PNbS Area (km^2)	PNbS Density	Housing Prices (euro)	Population Density	Unemployed Population percentage
1	Brzeźno	2.7	0.9	0.33	3419.4	4227	1.93
2	Nowy Port	2.3	0.2	0.09	2107.77	4387	2.39
3	Letnica	0.3	4.5	15	3552.74	407	4.18
4	Młyniska	4	0.1	0.03	2810.44	610	2.39
5	Stogi	11	2.7	0.25	2245.69	929	2.59
6	Przeróbka	6.9	1.2	0.17	2071.34	559	2.9
7	Krakowiec-Górki Zachodnie	8.8	3.2	0.36	2030.1	213	2.66
8	Wyspa Sobieszewska	34.3	8.1	0.24	3576.8	92	2.62
9	Rudniki	14.5	0.9	0.06	2209.04	71	4.06
10	Olszynka	7.7	0.2	0.03	2666.56	376	3.18
11	Orunia-Św. Wojciech-Lipce	19.7	2	0.1	2167.57	685	3.22
12	Śródmieście	5.5	0.9	0.16	3661.57	4343	2.63
13	Ujeścisko-Łostowice	7.9	1.8	0.23	2441.12	3590	1.49
14	Orunia Górna - Gdańsk Południe	7.2	1.5	0.21	2245.69	2887	0
15	Wzgórze Mickiewicza	0.6	0	0	2035.83	4688	1.6
16	Siedlce	2.6	0.5	0.19	2759.12	4845	2.27
17	Suchanino	1.3	0.3	0.23	2439.06	7046	1.59
18	Piecki-Migowo	3.8	1.6	0.42	2715.59	6477	1.38
19	Brętowo	7.4	4	0.54	2392.09	1044	1.44
20	Matarnia	14.9	2.3	0.15	2471.13	414	1.4
21	Kokoszki	20	4.7	0.24	2328.86	496	1.25
22	Aniołki	2.3	1	0.43	2832.66	1914	1.83
23	Wrzeszcz Górny	6.4	2.7	0.42	2777.45	3360	2.18
24	Wrzeszcz Dolny	3.5	0.5	0.14	2937.36	6386	2.02
25	Strzyża	1.2	0.1	0.08	3178.38	4774	1.79
26	Zaspa-Rozstaje	1.9	0.8	0.42	3575.19	6199	1.12
27	Zaspa-Młyniec	1.3	0.4	0.31	2802.65	10586	1.22
28	Przymorze Wielkie	3.3	1.4	0.42	3231.99	8148	1.49
29	Przymorze Małe	2.3	0.3	0.13	3243.45	6662	1.49
30	Żabianka-Wejhera-Jelitkowo-Tysiąclecia	2.1	0.8	0.38	3106.21	6720	1.59
31	Oliwa	18.5	10.7	0.58	3178.38	801	1.94
32	VII Dwór	3.2	1.5	0.47	2751.56	1176	1.01
33	Osowa	13.6	3.5	0.26	2272.96	1174	1.35
34	Chełm	3.9	1.2	0.31	2372.62	8166	1.59
35	Jasień	11.5	2.5	0.22	2540.09	1832	1.58
Mean value		51.9	5.02	6.06	2718.53	8290977	0.71
Standard deviation		7.2	2.24	2.46	487.31	2879.41	0.84

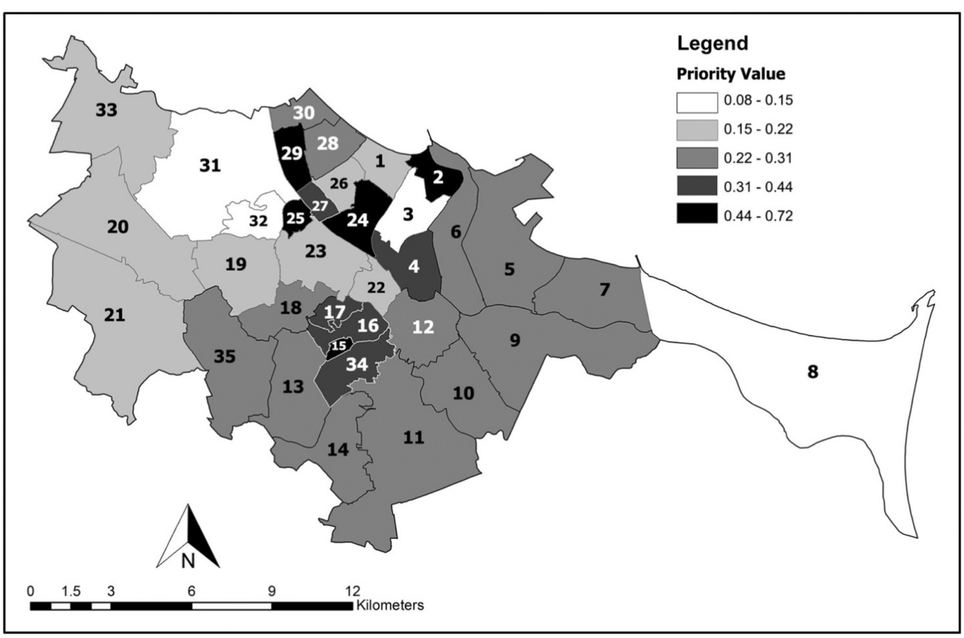

Fig. 11. Socio-economic priority values for implementing new PNbS in Gdansk.
Source: Authors.

Table 5
Weights assigned to indicators in case study of Rome.

Case study	Indicators	weights
Rome	Ratio of Population Density and PNbS density	40 %
	Median Household Income	25 %
	Education Rate	20 %
	Housing Prices	15 %

Table 6
Socio-economic priority values for implementing new PNbS in Rome.

District	Priority Value
I	0.38
II	0.29
III	0.56
IV	0.54
V	0.63
VI	0.7
VII	0.6
VIII	0.47
IX	0.44
X	0.31
XI	0.65
XII	0.5
XIII	0.63
XIV	0.62
XV	0.52

Table 7
Weights assigned to indicators in case study of Gdansk.

Case study	indicators	weights
Gdansk	Ratio of Population Density and PNbS density	50
	Housing Prices	40
	Unemployed Population percentage	10

Table 8
Socio-economic priority values for implementing new PNbS in Gdansk.

districts	Priority value
Wyspa Sobieszewska	0.08
Oliwa	0.11
Letnica	0.11
VII Dwór	0.15
Wrzeszcz Górny	0.15
Zaspa-Rozstaje	0.17
Aniołki	0.17
Orunia Górna - Gdańsk Południe	0.18
Brzeźno	0.18
Matarnia	0.19
Brętowo	0.19
Kokoszki	0.19
Osowa	0.22
Jasień	0.24
Krakowiec-Górki Zachodnie	0.25
Przymorze Wielkie	0.25
Stogi	0.25
Żabianka-Wejhera-Jelitkowo-Tysiąclecia	0.25
Rudniki	0.27
Przeróbka	0.27
Piecki-Migowo	0.27
Śródmieście	0.3
Ujeścisko-Łostowice	0.31
Olszynka	0.31
Wrzeszcz Dolny	0.33
Młyniska	0.35
Siedlce	0.37
Chełm	0.41
Zaspa-Młyniec	0.42
Suchanino	0.44
Orunia-Św. Wojciech-Lipce	0.5
Przymorze Małe	0.54
Strzyża	0.6
Nowy Port	0.66
Wzgórze Mickiewicza	0.72

(Caravaggi, 1999). The idea is recalled in some project initiatives such as the Eastern Rome Green Ring, which would involve the Centocelle Park (di Roma, 2021). While Gdansk's priority areas are placed along the central stripe, the city center in Rome, despite being densely built, benefits from the historical villas that constitute the backbone of the green structure of central Rome. The most suffering areas, on the contrary, are those urban "slices" to the South-East and North-West which happen to be further from the major green wedges. These neighbourhoods, it should be also noted, quite clearly correspond to those where the processes of illegal housing expansion were more relevant. The role of abusiveness is crucial as, it has been observed, it is the means by which the spatial separation of social classes was realized in Rome (Lelo and Risi, 2022).

Both cases of Rome and Gdansk confirm how marginality is today linked to availability of PNbS, distribution of services and environmental quality, rather than – or in addition to - traditional center-periphery dynamics. Rome's municipalities' delimitations, with their wedge shape, do not allow for an appreciation of the center-periphery gradient of socio-economic divide, which is instead significant when a finer subdivision is observed (Lelo et al., 2019).

Numerous studies considered in the literature review for this study (e.g., Astell-Burt et al., 2014; Nesbitt et al., 2019) raised emphasis on the unequal distribution of public greenery in various city regions. Therefore, the pre-assumption of this study was that Gdansk and Rome would display similar patterns; the findings of this research have revealed uneven allocation of PNbS in both cities, albeit to varying degrees. They suggest a considerably greater unevenness in Rome than in Gdansk, which could be further analyzed in future studies addressing the reasons of this difference. This observation is consistent with previous research carried out in various geographical settings, reinforcing the consistency of these patterns across different locations. Emphasizing the distribution of public greenery, the placement of PNbS in densely populated areas becomes critical, ensuring their availability to a more considerable number of citizens which seems to be undermined in Gdansk.

Investigating the idea of distributive justice, which is deeply connected to environmental justice was one of the objectives of this research. It is noteworthy how, by transitioning from a broader perspective to a more focused examination of PNbS in various socio-economic contexts, the study reconnects distributional issues with principles investigated by environmental justice. For instance, The City Forest (Polish name: Las Miejski) in Gdansk and the Centocelle park in Rome serve as examples of how the problems associated with PNbS in less affluent places go beyond quantity and extend to quality. This is consistent with the idea of environmental justice, which developed from the observation, that disadvantaged communities are frequently disproportionately affected by environmental issues that result from industrial activities (Schad, 2016). The City Forest in Gdansk, despite being high-potential natural public greenery, is surrounded by industrial operations, introducing challenges like pollution that compromise its overall quality. Historical changes and pollution studies reveal environmental impacts, posing health risks (Czarnowski et al., 1994; Raińska et al., 2007; Szczepaniak et al., 2006) and diminishing its appeal as a PNbS.

Similarly, the high potential of the Centocelle park in the South-East of Rome is undermined by the existence of illegal and improper activities – car dismantlers, garbage dumping, arsons, etc. – which, on one side, drive the environmental degradation of a large part of the green area and, on the other, block the public access to the park along the whole East border, fenced and perceived as an unsafe place to walk. These examples show that, although they cover a large area of PNbS on maps, the quality of these spaces is lacking. Therefore, it is essential not only to increase the quantity of PNbS but also to improve the quality of the existing ones. As various examples from Rome can prove (Maggioli and Tabusi, 2016; Paudice and Luciani, 2023), urban movements and citizens associations reclaim key green spaces in densely built and populated neighborhoods, advocating for a support of public authorities which is often biased in favor of private interests. By reinforcing the scientific basis of these requests, this research may contribute to a shift in public policies to better meet the inhabitants' needs.

The priority districts identified in this study for Gdansk were cross-referenced with the map of greenery-deficient areas outlined in the Gdansk Green Policy (BRG Gdańsk, 2023). Notably, the districts identified in this study as top priorities for the implementation of new (PNbS) also appear in the greenery deficiency map within the Gdansk Green Policy document. These districts, including Nowy Port, Orunia-Św., Wojciech-Lipce, and Przymorze Małe, Strzyża, emerge as focal points for introducing additional PNbS, as they are acknowledged for greenery deficiency in the same policy document.

5.3. Environmental and urban planning considerations

It is worth to note that planning and design approaches, when addressing the inequalities in PNbS distribution, should be accompanied by a careful evaluation of possible paradoxical effects such as eco-gentrification, as quality green spaces increase the attractiveness of the surrounding urban areas thus possibly leading to an increase in household prices and general cost of living. Strategies to avoid this potential drawback start from acknowledging the key importance of participatory approaches to mitigate the risks and assure the benefits provided meet the actual needs of those they are meant for.

Moreover, although the presented research identifies city districts with a scarcity PNbS, it is important to recognize that in some cases, urban or environmental regulations, legal protections, or natural constraints limit the development of new PNbS. For instance, these limitations may apply to protected natural areas or regions with rare ecosystems, where construction or significant alterations are prohibited or strictly regulated to preserve biodiversity (Witkowski, 2020; Fu, 2013). Similarly, creating new PNbS in areas prone to natural disasters, such as landslides, flooding, or erosion, could exacerbate existing risks (Lin et al., 2024). This also applies to locations with environmental contamination, such as brownfields, where cleanup efforts are required before any new development can take place (Chowdhury et al., 2020). Furthermore, restrictions may arise in the context of water resource management, as interventions near water bodies could disrupt natural flows, water quality, or aquatic habitats (Liu et al., 2023; Piacente et al., 2020). In some cases, particularly in historic urban centers, land planning restrictions may apply, specifying only certain types of green infrastructure solutions that can be used (Moreno et al., 2023).

It should be also emphasized that while prioritization based on socio-economic data is important, it should never diminish the role of environmental considerations in planning NbS. NbS can address several environmental challenges, including severe threats such as flooding. While recognizing the importance of environmental priorities, this study suggests that at stages beyond initial environmental assessments, socio-economic factors should also be considered. In this context, the prioritization proposed in this study is intended to complement existing climate adaptation plans or similar initiatives. Integrating socio-economic considerations with environmental planning could result in more comprehensive strategies for mitigating the adverse effects of climate change.

Specifically, in many cases, districts with limited availability of PNbS are also identified as crucial for the successful implementation of green stormwater infrastructure in climate adaptation plans. A good example is Nowy Port district in Gdańsk, where not only PNbS, but also the introduction of flood preventive measures is needed. Refurbishment of existing fenced allotment gardens in Nowy Port, and transforming them into high-quality green public parks with water reservoirs would not only serve local inhabitants but greatly reduce the risk of flooding. The area is adjacent to the Dead Vistula River and intersected by canals Warzywód I and Warzywód II – watercourses originating from the former Lake Zaspa, traversing wetlands towards the Vistula River. This area is susceptible to riverine floods and flash floods resulting from water runoff from higher-located urban territories in Gdansk. The introduction of new PNbS for this specific area would not only address the observed deficiency in socio-economic context but also serve as a mitigation strategy against potential flooding, acting as a climate change adaptation initiative.

5.4. Recommendations for future research

The last case discussed also indicates that future research might focus on other types of PNbS, such as agricultural land which are not public but contribute to the environmental quality of the peri-urban areas, potentially providing significant ES. Forms of public access can be envisaged for these spaces, as experimented in the agricultural park formulas.

While this study aimed to provide a comprehensive overview of PNbS' distribution across districts with diverse socio-economic characteristics, evaluating real accessibility demands further research due to variations in park size, quality, amenities, and availability of organized recreation (Wolch et al., 2014). Furthermore, despite the generally acknowledged positive impacts of NbS, it is crucial to acknowledge potential challenges and drawbacks. Researchers have highlighted issues ranging from their potential role in causing gentrification to concerns about their cost-effectiveness. On the other hand, there are still unabridged gaps in research on the economic practicality of NbS, potentially leading to the underestimation of their economic benefits, especially in the long run (Seddon et al., 2020; Bočkarjova et al., 2020).

Going back to the methodology, in further research it is would be recommended to test more precise tools for assessing the correlation between the variables of the study, for especially in the case of Rome that features only 15 districts, the Pearson coefficient may not be as precise as desired. Future research can maybe attempt to implement other types of correlation assessment tools for instance Kendall's Tau that gives a more accurate estimate of mutual dependency between random variables with fewer data points (Derumigny and Fermanian, 2018; Kendall, 1955). It is also important to note that the comparison between Rome and Gdansk should be treated cautiously since the number of data points in these two cities was different; with Gdansk having more than double the number of data points in Rome. The use of smaller territorial units in Rome was considered, since the 15 districts ("Municipi") are composed by 157 units ("Zone urbanistiche"). However, most of the data are provided based on the main districts, and the disparity of data points would not be solved but rather accentuated. Future studies aiming to deepen the case of Rome, however, may use such smaller units to analyze internal disparities, given the considerable extension of the districts.

6. Conclusions

NbS, as integral components of green infrastructure networks, offer numerous benefits in mitigating climate hazards such as flooding. Without overshadowing environmental considerations, this study emphasizes that socio-economic factors should also be taken into account in their planning and implementation. It is crucial to distribute them equitably throughout urban areas to ensure all citizens, regardless of socio-economic background, can benefit from their advantages. This paper has highlighted the relevance of fair allocation of PNbS within urban contexts. The spatial distribution of PNbS can exacerbate or mitigate the existing social and economic inequalities. Therefore, public policies regarding their allocation can prove a powerful instrument in the quest for spatial and environmental justice. Through a collection, elaboration and correlation analysis of relevant indicators, the study presented in this paper has highlighted in both cities, but particularly in

Rome, a tendency to concentrate PNbS in the districts with better socio-economic conditions, thus accentuating the disparities between wealthier and more fragile districts.

The socio-economic prioritization proposed in this study is intended to enhance existing climate adaptation plans or related initiatives. By integrating socio-economic factors into environmental planning, more holistic strategies can be developed to effectively mitigate the negative impacts of climate change and contribute to creating resilient urban environments. The results of this study provide an indication for public authorities to prioritize districts needing more urgent action in the provision and organization of their green spaces and NbS strategies. Such strategies should consider the relation between socio-economic status and PNbS availability to adopt an explicit approach to distributive and environmental justice concerns. As research reveals, planners should seize the opportunities of intervening in priority areas by focusing on the connective potential of public green spaces, implementing NbS to improve the environmental quality of these areas, reclaiming and redeveloping decommissioned or underused spaces of these districts to increase their green space dotation. Finally, the discussion of the results has highlighted several key points for future research to address existing gaps. Future studies may address the issues of spatial and environmental quality of existing green spaces and their accessibility. Furthermore, both researchers and urban planners could study the distribution of new PNbS projects, investigate their complementarity with existing ones, identify top-down and bottom-up initiatives and evaluate the level of community engagement in the different districts.

CRediT authorship contribution statement

Giulia Luciani: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lucyna Nyka:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Data curation. **ANAHITA AZADGAR:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Data availability

Data will be made available on request.

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