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City-Scale Revegetation Strategies Impact on the Temperature-Related Long-Term Mortality: A Quantitative Assessment in Three Cities in Southern Europe

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Abstract

Nature-based solutions (NBS) have attracted increasing attention in local air quality and climate change adaptation plans as suitable measures to reduce health risks. Although several studies have reported health benefits from short-term urban cooling effects of NBS, medium- to long-term health benefits are still poorly understood. In this study, we assess the changes in long-term mortality related to temperature fluctuations induced by city-scale vegetation actuations in three Southern European cities. We performed two annual high-resolution simulations with the Weather Research and Forecasting model to anticipate the impact of future revegetation strategies on temperature in these urban areas. Further, we assessed the impact of temperature changes on health using a country-specific minimum mortality temperature (MMT) reported in scientific literature. It was found that NBS could provide non-negligible reductions of long-term mortality related to temperature regulation (central estimate of 4.1, 1.2, and 3.4 cases avoided per year in Madrid, Milano, and Bologna, respectively). The effect of vegetation is site-dependent, and the cooling effect explains most of the benefits, especially in densely built-up areas of the cities analyzed. Future research should combine short/long-term temperature effects with other indirect implications (air quality, mental health) in the context of climate change.

Keywords: mesoscale meteorological modelling; urban vegetation; temperature; nature-based solutions; health impact; mortality

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1. Introduction

Considering that around 68% of the world's population will live in urban areas by 2050 [1], global threats such as climate change and biodiversity loss cannot be tackled independently of urban growth [2]. In this context, nature-based solutions (NBS) may contribute to less vulnerable and more resilient cities to climate change, enhance human well-being, and protect biodiversity [3–5] and are increasingly included in local strategies [6–9]. The concept of NBS refers to "interventions based on nature that are envisaged to address sustainability challenges such as resource shortages, flood and heat risks and ecosystem degradation caused by processes of urbanization and climate change" [10] and include permeable pavements, urban forests and green corridors, vertical farming and green roofs, among others [11–16].

There are several studies addressing the usefulness of NBS in enhancing biodiversity, increasing carbon storage, improving urban rainwater/stormwater management, or mitigating air pollution and urban noise [17–23]. Proximity to green spaces not only fosters human-nature relationships but also interactions among city dwellers [24] and has been reported to improve physical [25–27], mental [28–30], and social health [31,32]. NBS and, specifically, the introduction of vegetation, is often considered as one of the main tools for urban climate regulation [3]. Several studies highlight the short-term urban cooling impact of vegetation [33], and the corresponding benefits in terms of heatwave and urban heat island mitigation [34,35], which are usually accompanied by marked decreases in short-term mortality [36]. Nonetheless, the findings of these studies highlight the need to perform high-resolution, city-specific analyses since the effect of vegetation on temperature and humidity in urban environments is driven by multiple factors [37,38] and largely depends on local features. For instance, de la Paz et al. [39] found that the net effect of afforestation within the same city might differ depending on the species selection or prior land use.

On the other hand, medium- to long-term health impacts of NBS are less understood [40], and given that climate change influences not only temperature extremes but also thermal variability over extended timeframes, it is important to understand how these prolonged exposures may impact public health [41–45]. According to Zanobetti and O'Neill [46], who made a thorough review of published papers on long-term effects of temperature on health, regional and local temperatures (and changing conditions in weather due to climate change) are clearly associated with multiple health outcomes. They also highlighted that the diversity of study designs and outcomes makes it difficult to draw general conclusions, so continued study of this phenomenon would be useful to inform climate change adaptation policies. More recently, Palmeiro-Silva et al. [47] confirmed that further region-specific analyses are needed to better understand long-term, temperature-related health impacts.

Considering these knowledge gaps and the growing need for developing tools for the correct design, installation, operation and maintenance of NBS in the context of sustainable urban development [21], the work here presented aims at providing a first estimate (to our best knowledge) of the impact that city-scale NBS strategies may have on long-term, temperature-related mortality. For this purpose, temperature changes induced by future vegetation scenarios in three cities in Southern Europe (Madrid, Milano, and Bologna) are modelled and translated into attributable long-term mortality changes. This study has been developed within the VEG-GAP Life project (https://www.lifeveggap.eu) that selected these cities to draw light on the potential effect of NBS in urban areas prone to O_3 and PM air quality issues. The impact of future city-scale revegetation strategies was investigated through the application of two state-of-the-art atmospheric modelling systems (AMS), WRF-CMAQ [48] for Madrid and AMS-MINNI [49–51] for the cities of Milano and Bologna. Mircea et al. [52] found that vegetation impacts on air quality were largely driven by the meteorological changes induced.

The present study intends to add complementary information on the health implications of NBS, focusing on temperature changes exclusively for these three cities, contributing to a more comprehensive view of the potential of urban greening strategies to improve public health.

2. Methodology

2.1. Modelling System, Setup and Performance Evaluation

The weather research and forecasting (WRF) limited-area, non-hydrostatic meteorological mesoscale model [53] was used to assess temperature in the target cities with 1 km^2 spatial resolution and 1 h temporal resolution. Changes in vegetation are reflected in the modeling system by the land use in each grid cell and their corresponding physical properties according to the Noah Land-Surface model (LSM) scheme [54]. Relevant physical properties (albedo, canopy height, roughness length, etc.) are computed as weighted averages using these percentages in the properties table used by the LSM (VEGPARM.tbl) for each grid cell. The WRF model included the building energy parametrization (BEP) [55] with minor modifications to allow a more flexible description of vegetation and urban fraction changes induced by NBS strategies through an extended (7 additional classes to the 24-category USGS land use cover) land use classification [39]. A complete view of the physical options and parametrizations used is shown in the Appendix A (Table A1). More information about the setup and the model performance evaluations is provided in [56].

This model has been extensively applied and assessed for the three urban areas of interest [39,57–59]. Nonetheless, a specific model evaluation for the complete year 2015, baseline scenario for the VEG-GAP project, was performed [56]. Regarding temperature (T2), the key variable in this study, model performance was satisfactory considering both low mean biases and root mean squared errors (see [56]). The model consistently yielded a very high Pearson's correlation coefficient between observed and modelled temperature (around 0.97), demonstrating the ability of the model to accurately capture temperature trends [60]. Further details regarding modelling domains, observational datasets, and statistical evaluation can be found in [56].

2.2. Vegetation Scenarios

The future vegetation scenarios elaborated in the VEG-GAP project derive from the municipal urban green development plans (including location and tree species selection), where NBS are seen as measures to improve urban wellness and quality of life. City-specific vegetation scenarios were defined, and the influence of urban vegetation was derived from the comparison of two model simulations corresponding to the following scenarios (all annual runs) for each city:

- Baseline (SVR): intended to represent the current situation (year 2015) (see [56] for further details);
- Future (SVSR): includes the vegetation associated with city-scale revegetation strategies and NBS interventions involving vegetation in each of the three cities (see [56] and [61] for further details).

2.2.1. Madrid

Madrid is the capital and largest city of Spain (3.3 million inhabitants) and the core of a larger metropolitan area. Madrid municipality has a surface of 604.5 km^2, of which 182.3 km^2 are currently (SVR scenario) covered by green areas. The resulting average population density is 5500 inhabitants/km^2. The city's climate is classified as Csa under the Köppen-Geiger system, indicative of a hot-summer Mediterranean climate [62]. The future scenario used in this study represents the updated urban plans and strategies for Madrid. The methodology used for the construction of the new scenario is fully described in [39]. The future scenario contains new important NBS interventions, especially those within the so-called "Metropolitan forest". This project aims to create a 75 km peri-urban green ring, covering more than 5000 hectares, to expand, connect, and balance current peri-urban green areas in Madrid [39]. It involves 30 actuation areas and more than 1.51 million new trees of the most suited species, depending on soil type, topography, and ecological features. More than 50 tree species will be planted, but Mediterranean oaks (*Quercus ilex*) and Aleppo pine (*Pinus halepensis*) make up more than 50% of the total. Within the city, two interventions also stand out: "Urban orchards", which are areas designated for the municipal network of urban vegetable gardens (53 distributed all over the city with an average size around 30,000 m^2) and "Madrid New North" which is a major urban development approved by the local and regional governments. The green areas within intend to contribute to a carbon-neutral mix of uses. Lacking more specific information, the average characteristics (in terms of trees and shrub species and density) of existing parks in Madrid were assumed. Finally, and mainly outside the municipality of Madrid, the "Green Arch" intervention consists of linear plantations along 135 km of drovers' roads, trails, and other rural paths to connect already existing peri-urban forests or green areas across 17 municipalities around Madrid, connecting different biodiversity areas (Figure 1). This intervention involves 92,000 tree native species (*Quercus*, *Pinus*, *Ulmus*, *Olea*, etc.) individuals and 184,000 shrubs (*Rosa*, *Crataegus*, *Juniperus*, etc.).

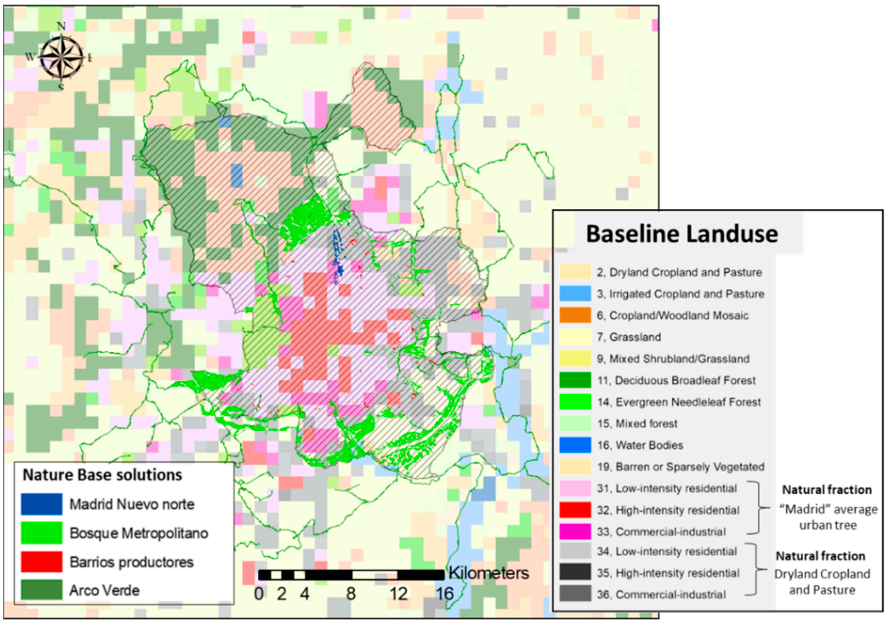

Figure 1. NBS interventions in the future scenario (SVSR) and land use grid cells from the baseline scenario (SVR) for the city of Madrid.

2.2.2. Milano

Milano is the business center and the second largest city of Italy (1.3 million inhabitants), being one of the most densely populated urban areas of the northern part of the country (7554 inhabitants/km^2). According to the Köppen–Geiger classification, the urban area of Milan falls within the Cfa climate zone (humid subtropical), characterized by fully humid conditions and hot summers [63]. Currently, green areas occupy 42.3 km^2 of the total 181.7 km^2 surface of the city. The Municipality of Milan provided, during the project, preliminary information about the green areas planned to be developed. The future vegetation areas are included in four main actions: "Public areas", areas located inside the city where trees are planned to be planted; "20 new parks", areas originally dedicated to different activities (e.g., industrial or railway) to be partially converted into parks; "Ecological Enhancement areas", areas where new green infrastructures are planned to be located; "Blue and Green Infrastructure", roads along which trees are planned to be planted. All these interventions are part of an ongoing strategy to address the fragmentation of formerly contiguous green corridors and the loss of green spaces in the urban expansion process over the last decades, and cover around 750 hectares, mainly in the outskirts of the city (Figure 2). The revegetation plan entails planting around 200,000 individuals. Tree species were selected considering the need for adaptation to climate change and to create multifunctional green spaces, and avoiding infesting and/or aggressive species as well as those outside the phytoclimatic range. Species such as *Quercus robur*, *Quercus pubescens*, *Acer campestre*, *Fraxinus ornus*, or *Carpinus betulus* are the preferred species for this city.

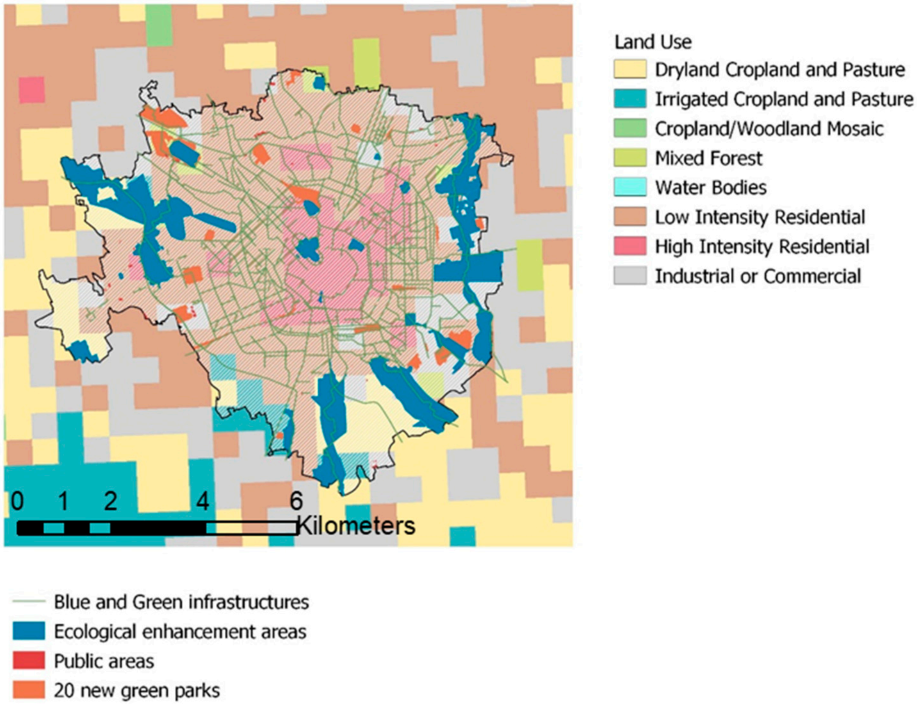

Figure 2. NBS interventions in the future scenario (SVSR) and land use of the baseline scenario (SVR) for the city of Milano.

2.2.3. Bologna

Bologna is the capital and largest city (140.9 km^2) of the Emilia–Romagna region in Northern Italy. It is an important agricultural, industrial, financial, and transport hub that gathers 0.38 million people (2745 inhabitants/km^2). Like Milano, Bologna falls within the Cfa climate zone (humid subtropical) of the Köppen–Geiger classification, characterized by warm-temperate conditions, year-round precipitation, and hot summers [64]. Green areas cover 55.5 km^2 in the SVR scenario. As for the future, the urban green planning for the city of Bologna was still under development during the VEG-GAP project, so a hypothetical vegetation scenario was elaborated using information made available from a previous project. Four types of actions are anticipated: "Historical and green areas" and "greening strategical areas" planned to increase urban vegetation in areas of particular historical and environmental/landscape significance, respectively; "Highway requalification areas" plantations along highway and main roads; "Extraction and manufacturing areas", areas originally dedicated to extraction and manufacturing activities to be potentially converted into parks. All interventions concentrate in the northern part of the city (Figure 3) and are intended to foster ecosystem services to support the new General Urban Plan (PUG). Since this document is not officially enacted, the composition and species selection, focused on maximizing CO_2 capture potential and minimize the emission of reactive VOCs, was based on the outcomes of two previous LIFE projects (GAIA—Green Area Inner City Agreement and BLUEAP—Bologna Local Urban Environment Adaptation Plan for a Resilient City). The combined extension of the four interventions affects an area of 1510 hectares and considers the planting of a variety of trees (*Carpinus*, *Quercus*, *Acer*, and *Populus* among others) and shrub individuals (*Sambucus*, *Cornus*, *Rosa*, etc.).

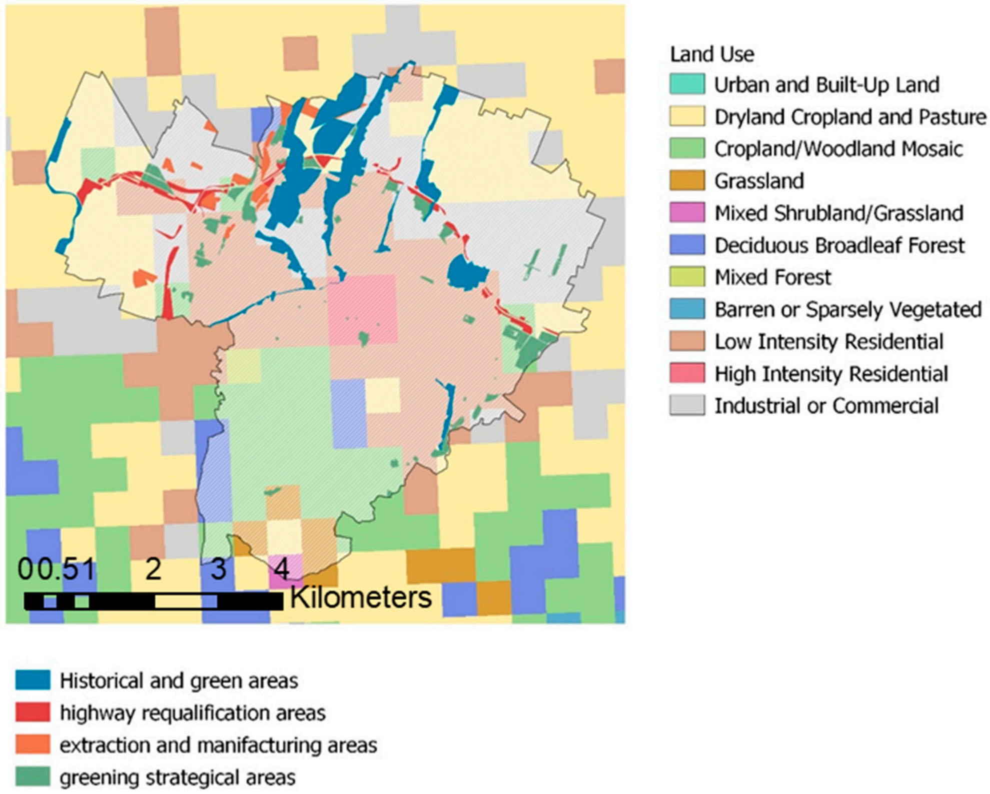

Figure 3. NBS interventions in the Future Scenario (SVSR) and land use of the baseline scenario (SVR) for the city of Bologna.

2.3. Health Impact Assessment

The weather research and forecasting (WRF) limited-area, non-hydrostatic meteorological mesoscale model [53] was used to assess temperature in the target cities with 1 km^2 spatial resolution and 1 h temporal resolution. It was coupled with the building energy parametrization (BEP) [55] with minor modifications to allow a more flexible description of urban vegetation [39]. Physical options and parametrizations used are shown in Table A1 of the Appendix A. More information about the setup and the model performance evaluations is provided in [56].

This study estimates the potential health benefits from NBS interventions at the city scale using the spatial variability of temperature changes at 1 km^2 resolution. It is particularly interesting to investigate long-term associations between temperature and mortality when considering time frames of several decades, as in the case of vegetation scenarios. A variety of methods have been proposed to assess longer-term temperature and health effects that involve multiple temperature metrics and epidemiological approaches [46]. There is a consensus that the impacts of both cold and heat on mortality should be considered [65,66]. Consequently, several authors propose assessment methods based on thermal oscillations, such as the diurnal temperature range (DTR) [67] or deviations from optimum ambient temperature [68] to estimate temperature-related mortality. This approach implicitly takes into account the adaptation of a population to local climatic conditions, highlighting the importance of considering city-specific optimal temperature ranges [69]. The spatial heterogeneity of mortality has also been reported in the few studies that addressed long-term effects [40], so it is important to consider location-specific relative risks. As for temperature data sources, we rely on model outputs. They have high accuracy for predicting this meteorological variable [56] and have been successfully used in epidemiological analyses of temperature-related risks [70], including areas far from weather stations [71].

Considering these factors, the long-term impact on mortality due to temperature changes induced by vegetation was assessed in this study following the methodology proposed by [72]. They analyzed the attribution of heat and cold to mortality in 11 countries, including Spain and Italy. Based on multi-annual datasets over a 40-year period, they identified a country-specific minimum mortality temperature (MMT) that accounts for thermal adaptation of the population in each country and derived percent excess relative risks (ERR) that represent the increments in annual mortality relative risk (%) per 1 °C increase in annual mean degrees above or below the defined MMT (Table 1). They are referred to as heat and cold degrees, respectively, and represent the average departure of daily mean temperatures from MMT [72].

Table 1. Minimum mortality temperature and percent excess relative risks (ERR) per 1 °C change in temperature (from Armstrong et al. [72]).

City	MMT (°C)	Heat ERR% (95% Confidence Interval)	Cold ERR% (95% Confidence Interval)
Madrid	21.4	3.2 (0.6, 5.8)	2.7 (1.5, 3.9)
Milano and Bologna	21.8	8.3 (2.5, 14.4)	−1.1 (−5.2, 3.3)

This methodological approach is consistent with air pollution health impact assessment studies [73,74] and thus, the difference between the number of deaths (ΔM) attributable to changes on heat or cold degrees (ΔT) under any two scenarios of interest can readily be computed in each grid cell of our modelling domains by means of Equation (1).

$$\Delta M = M_0 \cdot \left[1 - e^{\beta \cdot \Delta T}\right] \cdot P \tag{1}$$

where M_0 and P, represent the baseline mortality rate and population for the reference year or baseline scenario, respectively, and β is the fractional increase in RR per °C (ERR%/100).

Of note, the number of locations used by [72] to obtain ERR varied considerably depending on the country (2 locations for Italy and 50 for Spain). This contributes to the larger confidence interval reported in Table 1 for the ERR of Italian cities. In both cases, heat-related mortality risks are larger than those related to cold temperatures. This is consistent with other studies that suggest the vulnerability of the Mediterranean to the effect of high temperatures [75] and contrasts with the findings of other studies for northern European countries, where cold drives most temperature-related deaths [76].

Consistent with the methodology used to derive long-term relative risks [77], the baseline mortality rate represents all-age, all-cause mortality excluding accidents (International Classification of Diseases [ICD]-9 0-799). Baseline natural mortality data were retrieved from the national statistical institutes (INE (www.ine.es) and ISTAT (www.istat.it) for Spain and Italy, respectively) for the year 2015 at the municipality level. The official population census for that year was spatially allocated using the JRC 2018 population density cover (Figure 4) [78]. Spatially disaggregated number of deaths (M_0·P) for the baseline scenario, the data are shown in the Appendix B (Figure A1). The population (P) considered (considering all the grid cells intersected by each municipality) was 3,339,709, 1,442,995, and 416,033 inhabitants for Madrid, Milano, and Bologna municipalities. The corresponding number of deaths (all-age, [ICD]-9 0-799) are 27,557, 18,853, and 5486, respectively, which represent, with an average baseline mortality of 8.3, 12.7, and 13.0 (per 1000 people) in the cities of Madrid, Milano, and Bologna.

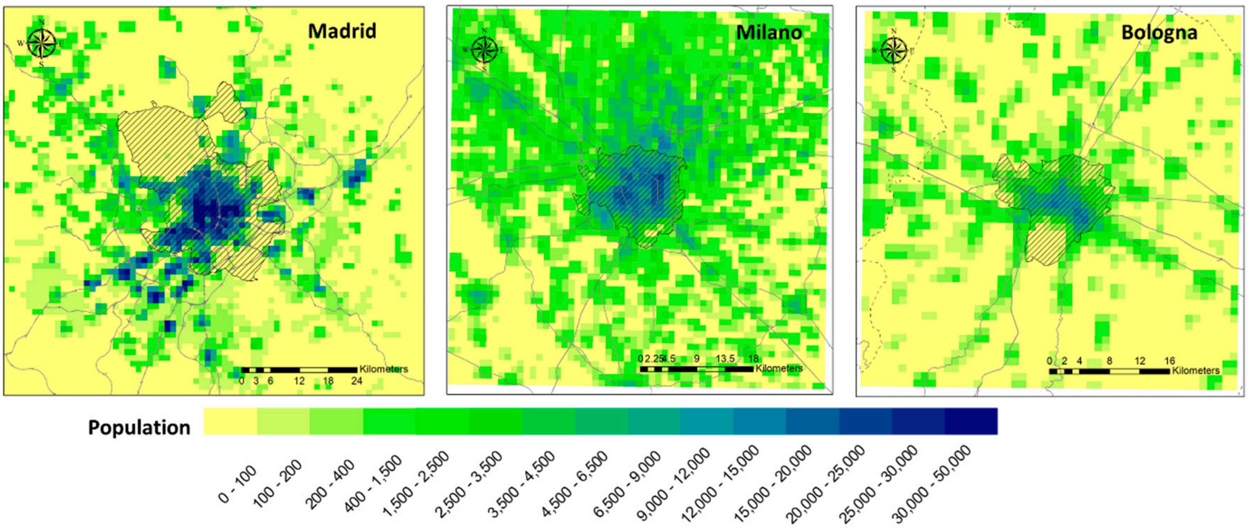

Figure 4. Spatial distribution of the total population in the three selected cities.

3. Results

3.1. Impact of Vegetation on Temperature

Figure 5 shows the near-ground level temperature (T2) annual mean for the three cities for the baseline (SVR) scenario. Madrid (Figure 5a) is the warmest city (15.2 °C annual average) and the area with the highest spatial variability, ranging from 9.1 to 17.1 °C, due to a larger dimension of the modelling domain but also a more complex topography and a greater distance from the sea. Average (minimum, maximum) T2 annual means for the Italian cities are 15.0 (14.4, 16.1) °C for Milano (Figure 5b) and 15.1 (12.0, 16.5) °C for Bologna (Figure 5c). The urban heat island (UHI) effect [79] can be clearly observed in all cases, with maximum annual mean temperatures corresponding to the more densely urbanized areas.

As discussed in D'Isidoro et al. [56], the foreseeable impact of NBS differs depending on local characteristics. As illustrated in Figure 5, the re-vegetation scenario (SVSR) is expected to decrease annual mean temperature downtown in all three cities, with changes up to −2.6 °C in the case of Madrid. The cooling mechanism of vegetation when introduced in densely built areas. According to our results, the cooling effect found in consolidated urban areas is due to increases in latent heat fluxes (up to 17% relative to the SVR scenario) and higher evapotranspiration [80]. On the other hand, vegetation may slightly increase average temperature when new trees are planted outside the urban areas, around +0.1 °C in most of the outskirts of the city. The drivers of these increments are the changes in sensible heat fluxes induced by a decrease in albedo and enhanced energy absorption [39]. To a lesser extent (note the difference on the color scale), this effect is also observed in Milano (Figure 5e) with T2 annual mean changes in the range of −0.1, +0.0 °C, while a net cooling effect dominates in Bologna (Figure 5f), with changes around −0.2 °C in the city center.

The limited impact of the implemented NBS on temperature in Milan may be related to the size and distribution of planned revegetation actions (Figure 2) but may also be attributed to the city's specific urban morphology, characterized by flat topography and high building density. These features pose significant challenges to achieving substantial cooling effects through vegetation alone [38].

Spatially averaged changes over the whole modelling domain are quite subtle, with net changes of less than 0.01 °C in absolute values in all cases.

Changes in annual heat degrees and cold degrees from SVSR (future scenario) relative to SVR (baseline scenario) were computed following the methodology described in Armstrong et al. [72]. The results are presented in Figure 6. Values above 0 in both cases imply an increase in the distance to MMT.

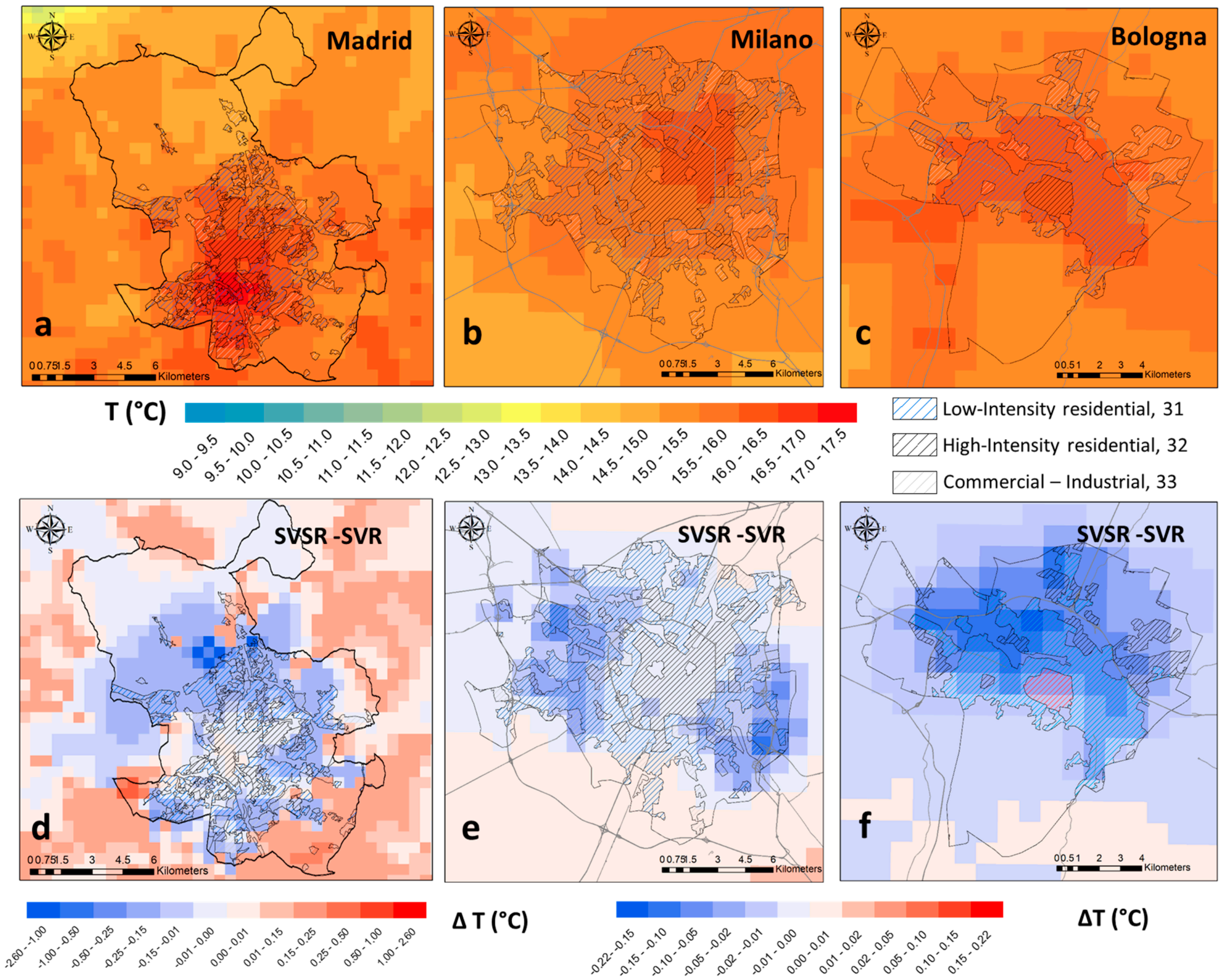

Figure 5. Annual mean temperature (T2) for the baseline scenario (SVR) in (**a**) Madrid, (**b**) Milano and (**c**) Bologna and expected change under the future scenario (SVSR) in (**d**) Madrid, (**e**) Milano and (**f**) Bologna (zoom over the urban areas with indication of the distribution of low and high intensity residential areas as well as commercial-industrial zones, consistently with the WRF-BEP inputs for the SVR scenario).

The results for Madrid indicate a reduction (blue) of heat degrees in most of the city (up to 1.0 °C) and slight increases (red) in the surroundings, most evidently in the areas where future interventions take place. Nonetheless, the increases predicted are below 0.1 °C in all cases, and the aggregated change (sum of changes over the whole city) corresponds to −7.7 °C (Table 2). By contrast, cold degrees are increased in most grid cells, up to 1.6 °C, since the cooling effect of vegetation in consolidated urban areas tends to increase temperature differences below MMT. Only in some areas around the city (negative values, represented by red colors), the average deviation from optimal temperature (MMT) is slightly reduced. Therefore, the implementation of the simulated NBS future scenarios would increase cold degrees in Madrid, with an aggregated change over the city of 6.5 °C (Table 2). Nonetheless, variations at the grid cell level fall in the ±0.2 °C range in all cases.

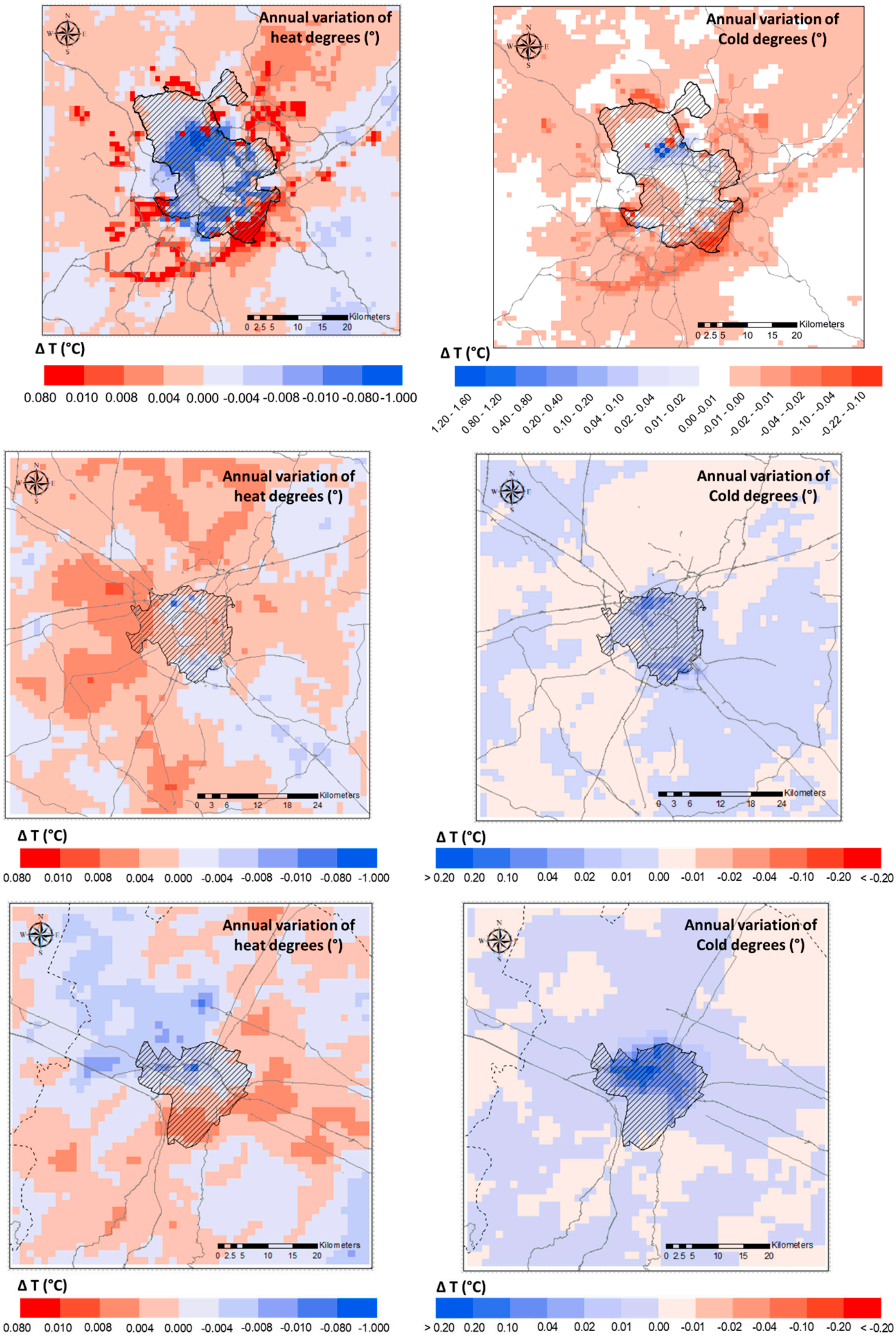

Figure 6. Changes in heat (**left column**) and cold (**right column**) degrees for the city of Madrid (**top**), Milan (**center**), and Bologna (**bottom**). In all cases, they refer to SVSR—SVR.

Table 2. Accumulated mortality (total annual deaths) changes induced by future NBS interventions in the three cities.

City	Δ T (°C)		Δ*M* (95% Confidence Interval in Brackets)		
	Heat	Cold	Heat Deaths	Cold Deaths	Net Change in Temperature-Related Mortality
Madrid	−7.7	6.5	−7.4 (−1.4, −13.4)	3.2 (1.8, 4.7)	−4.1 (−11.6, 3.3)
Milano	0.1	2.4	0.9 (0.3, 1.6)	−2.1 (−10.0, 6.3)	−1.2 (−9.7, 8.0)
Bologna	−0.7	2.0	−0.4 (−0.1, −0.6)	−3.0 (−14.1, 8.9)	−3.4 (−14.3, 8.8)

Similar results are obtained for Milano and Bologna, although the changes in heat and cold degrees induced by new vegetation are predicted to be smaller. In Milano, both heat and cold degrees would be increased under SVSR (future scenario), although the changes suggest a dominant effect of cooling with an accumulated figure (aggregated change) of 2.4 cold degrees for the whole city (Table 2), in comparison with the nearly negligible increase of heat degrees (Figure 6). Similarly to the Madrid case, Bologna would see a net increase of cold degrees (2.0 accumulation for the whole city) due to the predominantly cooling effect of future vegetation, with changes up to 0.2 °C in the northern part of the city.

That would result in a reduction of annual mean departures above the optimal temperature (MMT) as well, with an aggregated value over the city of −0.7 heat degrees.

Of note, red and blue tones have been used for temperature increases and decreases, respectively, in Figure 6. However, they have different interpretations health-wise for the panels in the left column (variation of heat degrees) and in the right one (variation of cold degrees). Values above 0 in both cases imply an increase in the deviation from MMT and vice versa.

3.2. Impacts on Temperature-Related Mortality

Aggregated changes in annual deaths (ΔM) attributable to changes in heat degrees and cold degrees are summarized in Table 2.

In the city of Madrid, the scenario with new vegetation (SVSR) will result in a net reduction in temperature-related mortality. The expected decrease in heat degrees, along with the higher relative risk (EER 3.2%) associated with heat-related mortality, outweighs the potential increase in cold-related mortality (EER 2.7%). For the Italian cities, heat-related mortality relative risk is considerably higher (EER 8.3%) than that of Spain, so that the impact would be larger even for smaller variations in heat degrees. It should be noted as well that according to Armstrong et al. [72], cold relative risks are negative (EER −1.1%), so an increase of cold degrees would imply reductions in long-term mortality. Consequently, our results suggest a net beneficial long-term effect on the mortality of future vegetation scenarios (SVSR).

Notably, the values reported in Table 2 refer exclusively to the municipal area of the three cities analyzed. However, similar patterns are observed for the whole modeling domains, which include the corresponding metropolitan areas; therefore, the beneficial effects of NBS could be higher than those reported here.

4. Discussion

4.1. Health Impacts

The effects of extreme temperatures on the human body are well documented, and recent literature reports the increasing risk of heat-related mortality associated with climate warming [81,82]. Human adaptation to future meteorological conditions may alleviate, to some extent, the burden on mortality [83], but significant efforts are being devoted to understanding how urban regeneration plans may alleviate the city's overall temperature and the UHI effect [84,85]. The use of NBS in urban areas has been largely proposed as a means to locally reduce temperature [86] and to improve population health [87,88]. Our model simulations quantify the potential long-term temperature-related health benefits associated with plausible NBS in three densely populated southern European cities. We show here that the effects of NBS on urban temperature are site-specific. City-scale aggregated effects on mortality are relatively small in comparison with short-term health impacts related to green urban infrastructure reported elsewhere (e.g., Iungman et al. [89]). Nonetheless, our results point out that a net health benefit (net reduction of the total cases of non-accidental temperature-related mortality) could result from the implementation of NBS in all three cities: −4.1 (−11.6, 3.3) in Madrid, −1.2 (−9.7, 8.0) in Milano and −3.4 (−14.3, 8.8) in Bologna, on an annual basis. Of note, these figures may be explained through different processes. New NBS in Madrid may promote a reduction of temperature above the MMT, but also an increase below the MMT. This will translate into a reduction in heat-related deaths attributable to higher temperatures, but a smaller increase in cold-related deaths associated with cooler temperatures. This is consistent with recent studies that conclude that urban green infrastructure may be particularly beneficial to alleviate the UHI effect in densely urbanized areas [90].

A very limited impact on heat degrees is reported for the city of Milano, although a slight reduction of mortality may be derived from increasing cold degrees according to the ERR defined in [72]. In the domain centered around the city of Bologna, the NBS may determine a reduction in high temperatures above the minimum mortality temperature (MMT) but an increase in the cold ones below the MMT, both results adding to mortality avoidance. As a result, Bologna presents the highest impact of all three cities relative to its population size.

4.2. Policy Implications

While most of the publications available on the effects of NBS are based on surveys collected in the population under investigation or statistical modelling, here we report data obtained from a mesoscale atmospheric modelling system combined with meteorological data. This approach enabled exploration of the potential health benefits of NBS in three EU cities based on plausible scenarios of the positioning of new vegetation. In highly urbanized areas, the selection and regeneration of areas with green infrastructure is a complex task that takes into account the requirements of new service areas and housing, which may reduce the availability of areas suitable for introducing vegetation.

The results we report suggest that the location of new NBS is a key parameter for properly assessing the beneficial effects in terms of local temperature modulation and improvement of public health. Policies to promote NBS should take into account not only space availability but also the distribution of population and green infrastructures, as well as the specific combination of land uses and topography for each city. Our study suggests that reforestation of peri-urban barren areas may slightly increase average temperature, and the results from the three cities point out that the cooling effect of vegetation is stronger in consolidated urban areas that correspond to densely populated areas. That may be of interest in the scope of climate change, especially in Southern Europe, where heat-related mortality is expected to grow in the future [91]. As a result, policy translation of our results would be subject to a detailed analysis of these features in other urban areas, along with the limitations discussed in the following section.

5. Limitations

While this study presents one of the first quantitative analyses of long-term temperature mortality changes induced by urban-scale revegetation strategies, there is a series of limitations that should be considered for the interpretation of the results and to identify further investigations. Our approach relies on relative risks derived at the national level, and ideally, city-specific minimum mortality temperature (MMT) should be derived to more accurately assess health benefits. On the other hand, the uncertainty of our estimates, given by the amplitude of the 95% confidence intervals, is relatively large. In fact, the upper confidence interval regarding net mortality change (Table 2) for the three cities is positive, suggesting that the expected net outcomes may vary considerably. To the greatest extent possible, future research may delve into a comprehensive assessment of public health benefits associated with NBS by scrutinizing multiple health indicators, including mental health [69] or other indirect effects [92].

Regardless of the epidemiological approach followed and health endpoints considered, enhanced methodologies to better reflect exposure may help capture socio-economic variability and the specific impact on vulnerable groups [93]. Dynamic population exposure methods [94] may be explored for a more comprehensive understanding of NBS that not only modulate temperature but may modify population lifestyles and thus, exposure patterns. Projections on demography and population aging may also contribute to a more realistic assessment of long-term health effects [95] and may be included in future research that integrates longitudinal datasets to account for NBS health impacts within a holistic assessment that considers the whole life cycle of the project [96]. Besides health and psychological effects, ecological benefits (e.g., on biodiversity) and potential unintended consequences (e.g., wildfire risk) may be addressed in future studies as well. In addition, our study does not consider indoor effects or the potential interactions with other heat mitigation options such as air conditioning systems. Evolutions of the BEP parameterizations, such as the BEP-BEM (Building Energy Model) scheme [97] or WRF-Comfort [98], may be useful to support future studies in that direction. Of note, future studies may assess the combined effectiveness of a wider range of strategies, such as reflective surfaces, urban form adjustments, or hydrological interventions.

Incorporating advanced mesoscale modelling tools, however, allows further studies to assess the combined effects of temperature and air quality, or to integrate climate change mitigation and adaptation measures in future development projects (climate proofing). Such studies may combine high-resolution dynamic downscaling of climate models [99] with a more detailed description of NBS implementation and vegetation growth modelling. Unlike other methodologies that relay on spatial regression and other statistical models [100] to derive associations between health endpoints and land uses, including urban green space (UGS) [101] the explicit consideration of the physical processes involved in the thermal regulation induced by vegetation may allow more detailed future research where the impact of very specific features such as the type of vegetation or the interactions with previous and surrounding land uses may be explicitly incorporated in the planning process. Nonetheless, models also bring uncertainty, and the representation of the mechanisms through which vegetation modifies momentum, heat, and humidity fluxes (see Section 2.1) is still limited even in advanced mesoscale meteorological models [39].

To assess the combined effects of new vegetation on temperature and air quality at the city scale, it is important to consider that biogenic VOC emissions are likely to enhance ground-level ozone and secondary particulate matter concentrations in urban areas [102,103] that can have a detrimental effect on health [104]. Moreover, urban vegetation may limit the dispersion of fine particulate matter [105], resulting in higher local population exposure and potentially higher health impacts if emission sources such as road traffic are not effectively controlled. Again, that analysis should be city-specific and be based on detailed emission reduction scenarios that reflect local plans and measures intended to meet the new air quality limit values set up in Europe by the Directive (EU) 2024/2881.

6. Conclusions

We present one of the few assessments of long-term health effects associated with temperature changes induced by planned urban revegetation strategies in three cities of southern Europe. This contribution illustrates how mesoscale modelling tools may be integrated into the impact assessment of nature-based solutions (NBS) on public health at the city scale. Our study demonstrates that all-cause mortality excess relative risks (ERR) associated with departures from a minimum mortality temperature (MMT) may be suitable for this kind of health impact assessment. While these EERs are county-specific, our results suggest that city- or even municipality-specific relative risks may be needed to reduce the uncertainty of the estimates. Our results also suggest that the NBS envisaged in Madrid, Milano, and Bologna may have a non-negligible effect on temperature-related long-term mortality and thus, may add to the benefits related to short-term effects from the alleviation of heat and cold temperature extremes. According to our results, the introduction of vegetation in densely populated zones may be particularly beneficial due to the net cooling effect of the vegetation in consolidated urban areas. While this recommendation may hold for other southern Mediterranean cities or others around the world with similar geophysical features, revegetation policies should be specifically designed for each city to take into account the particularities of the urban landscape, population distribution, etc. Despite addressing the technical and scientific limitations highlighted in this study, it is advisable to include social issues for a broader view on how NBS may help improve the sustainability of human agglomerations in the future.

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Data Availability Statement: The dataset is available on request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Modelling System Setup

The main features of the WRF modelling systems applied in the project are summarized in Table A1.

Table A1. WRF model setup summary.

Model Feature	Madrid	Bologna and Milano
Version	WRFv4.1.2	WRFv3.9.1.1
Nested domains (spatial resolution in km)	4 (27, 9, 3, 1)	3 (12, 4, 1)
Vertical layers (layers within the first km)	38 (17)	39 (12)
Initialization	ERA5 (Copernicus Climate Change Service)	ERA5 (Copernicus Climate Change Service)
Microphysics	WSM6 [106]	WSM6 [106]
Cumulus Parametrization	Off	Off
PBL Scheme	Bougeault-Lacarrère PBL [107]	Mellor Yamada Jancic (MYJ) [108]
Urban Physics	BEP [55]	BEP [55]
Land Surface	Noah LSM [109]	Noah LSM [109]
Longwave Radiation	GFDL [110]	RRTMG [111]
Shortwave Radiation	MM5 [112]	RRTMG [111]

Appendix B. Baseline Mortality

Figure A1 presents the spatially disaggregated number of deaths (M_0·P) for the baseline scenario.

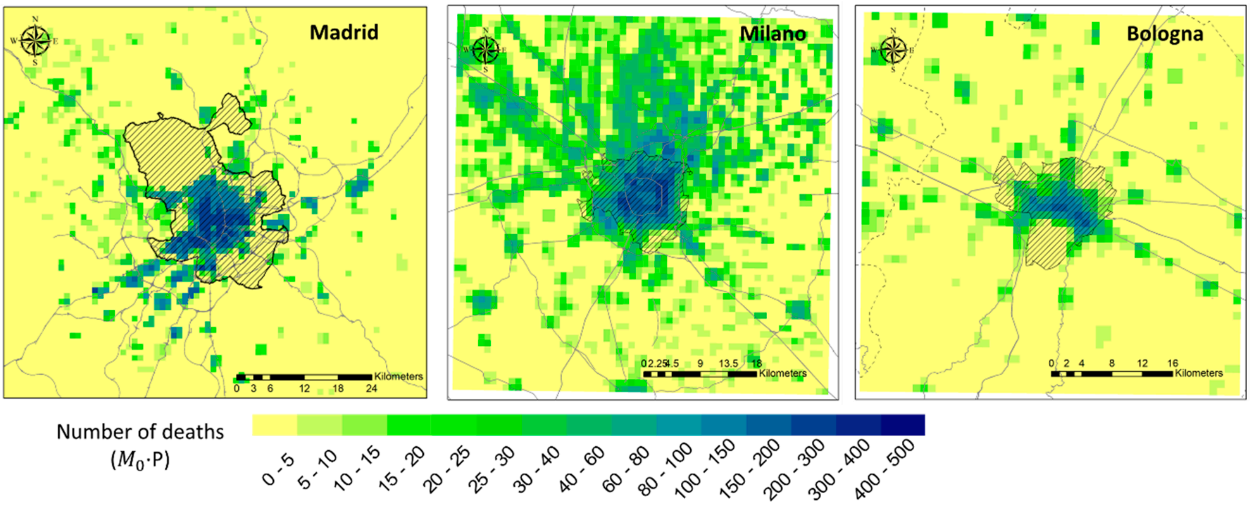

Figure A1. Spatially disaggregated baseline mortality ([ICD]-9 0-799, all ages) is considered in the three selected cities.

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