Environment International xxx (xxxx) xxxx

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Changing the urban design of cities for health: The superblock model

Natalie Mueller[a,b,c], David Rojas-Rueda[a,b,c,d], Haneen Khreis[a,b,c,e,f], Marta Cirach[a,b,c], David Andrés[g], Joan Ballester[a,b,c], Xavier Bartoll[h,i], Carolyn Daher[a,b,c], Anna Deluca[a,b,c], Cynthia Echave[g], Carles Milà[a,b,c], Sandra Márquez[a,b,c], Joan Palou[g], Katherine Pérez[h,i], Cathryn Tonne[a,b,c], Mark Stevenson[j], Salvador Rueda[g], Mark Nieuwenhuijsen[a,b,c,*]

[a] *ISGlobal, Barcelona, Spain*
[b] *Universitat Pompeu Fabra (UPF), Barcelona, Spain*
[c] *CIBER Epidemiología y Salud Pública (CIBERESP), Madrid, Spain*
[d] *Department of Environmental and Radiological Health Sciences, Colorado State University, Fort Collins, CO, USA*
[e] *Texas A&M Transportation Institute (TTI), College Station, TX, USA*
[f] *Center for Advancing Research in Transportation Emissions, Energy, and Health (CARTEEH), College Station, TX, USA*
[g] *Agència d'Ecologia Urbana de Barcelona (BCNEcologia), Barcelona, Spain*
[h] *Agència de Salut Pública de Barcelona (ASPB), Barcelona, Spain*
[i] *Institut d'Investigació Biomédica (IIB Sant Pau), Barcelona, Spain*
[j] *Melbourne School of Design/Melbourne School of Population and Global Health, University of Melbourne, Australia*

A R T I C L E I N F O

Handling Editor: Zorana Jovanovic Andersen

Keywords:
Active transport
Health impact assessment
Public space
Sustainability
Transport planning
Urban planning

A B S T R A C T

Background: Car-dependent city planning has resulted in high levels of environmental pollution, sedentary lifestyles and increased vulnerability to the effects of climate change. The Barcelona Superblock model is an innovative urban and transport planning strategy that aims to reclaim public space for people, reduce motorized transport, promote sustainable mobility and active lifestyles, provide urban greening and mitigate effects of climate change. We estimated the health impacts of implementing this urban model across Barcelona.
Methods: We carried out a quantitative health impact assessment (HIA) study for Barcelona residents ≥20 years (N = 1,301,827) on the projected Superblock area level (N = 503), following the comparative risk assessment methodology. We 1) estimated expected changes in (a) transport-related physical activity (PA), (b) air pollution (NO_2), (c) road traffic noise, (d) green space, and (e) reduction of the urban heat island (UHI) effect through heat reductions; 2) scaled available risk estimates; and 3) calculated attributable health impact fractions. Estimated endpoints were preventable premature mortality, changes in life expectancy and economic impacts.
Results: We estimated that 667 premature deaths (95% CI: 235–1,098) could be prevented annually through implementing the 503 Superblocks. The greatest number of preventable deaths could be attributed to reductions in NO_2 (291, 95% PI: 0–838), followed by noise (163, 95% CI: 83–246), heat (117, 95% CI: 101–137), and green space development (60, 95% CI: 0–119). Increased PA for an estimated 65,000 persons shifting car/motorcycle trips to public and active transport resulted in 36 preventable deaths (95% CI: 26–50). The Superblocks were estimated to result in an average increase in life expectancy for the Barcelona adult population of almost 200 days (95% CI: 99–297), and result in an annual economic impact of 1.7 billion EUR (95% CI: 0.6–2.8).
Discussion: The Barcelona Superblocks were estimated to help reduce harmful environmental exposures (i.e. air pollution, noise, and heat) while simultaneously increase PA levels and access to green space, and thereby provide substantial health benefits. For an equitable distribution of health benefits, the Superblocks should be

Abbreviations: BCNEcologia, Barcelona Urban Ecology Agency; CadnA, Computer Aided Noise Abatement Software; CI, Confidence interval; ERF, Exposure response function; HIA, Health impact assessment; IPAQ, International Physical Activity Questionnaire; L_{den}, EU day-evening-night noise indicator with 5 dB and 10 dB weights for the evening and night time, respectively; LE, Life expectancy; METs, Metabolic equivalents of task; NO_2, Nitrogen dioxide; NDVI, Normalized Difference Vegetation Index; PA, Physical activity; PAF, Population attributable fraction; PI, Prediction interval; $PM_{2.5}$, Particular matter with diameter ≤ 2.5 μm; RR, Relative risk; SDGs, Sustainable Development Goals; TRAP, Traffic-related air pollutants; UHI, Urban heat island; VSL, Value of a statistical life; WHO, World Health Organization; %GS, Percentage green space

* Corresponding author at: ISGlobal, Dr. Aiguader 88, 08003 Barcelona, Spain.
E-mail address: mark.nieuwenhuijsen@isglobal.org (M. Nieuwenhuijsen).

https://doi.org/10.1016/j.envint.2019.105132
Received 6 May 2019; Received in revised form 20 August 2019; Accepted 26 August 2019

implemented consistently across the entire city. Similar health benefits are expected for other cities that face similar challenges of environmental pollution, climate change vulnerability and low PA levels, by adopting the Barcelona Superblock model.

1. Introduction

Worldwide, car-dependent city planning has resulted in low levels of physical activity (PA) and high levels of environmental pollution (i.e. air pollution, noise, and anthropogenic heat) (Nieuwenhuijsen and Khreis, 2016). Contemporary cities devote up to 70% of public space to accommodate motor vehicles (Crawford, 2002; Manville and Shoup, 2005), whereas no more than 25% is suggested for a sustainable design (Barcelona Urban Ecology Agency, 2018; Dávalos et al., 2016). Comparatively little space in cities is assigned to public open and green space. Reclaiming these spaces, however, for recreational (e.g. PA performance) and community activities, would add aesthetical appeal, and could provide urban resilience and climate change adaptation through the provision of eco-system services (i.e. passive air and noise pollution control, cooling through shading and evapo-transpiration of water) (Nieuwenhuijsen et al., 2017; Wolf and Robbins, 2015).

The original plan for the 'extension' of the city of Barcelona (i.e. Eixample), by 19th century progressive Catalan urban planner Ildelfons Cerdà, considered the human needs for natural lighting, ventilation, open space and greenery, and a transport network fairly accommodating pedestrians, horse-drawn carriages and public tram lines. Nevertheless, Barcelona's streets became filled with concrete structures, cars and traffic (Barcelona City Council, 2018). Consequently, air and noise pollution levels are high, persistently exceeding WHO limits, and are estimated to cause a large health burden (Mueller et al., 2017a, 2017b). The city's densely-constructed urban design, accommodating > 1.6 million people on 100 km^2, leaves little available space for green and public open space, and amplifies the generation of anthropogenic heat. Temperature in the city center can be up to 8 °C higher in comparison with less urbanized surrounding areas because of the urban heat island (UHI) effect (Moreno-Garcia, 1994).

To recuperate Cerdà's progressive design and remedy the negative effects of the current situation, the Barcelona Superblock model has been proposed: an innovative land use intervention that aims to reclaim space for people, reduce motorized transport, promote sustainable mobility and active lifestyles, provide urban greening and mitigate the effects of climate change (Rueda, 2018). A total of 503 Superblocks, stretching over the city of Barcelona, have been developed by the Urban Ecology Agency (BCNEcologia), a public consortium integrated into the Barcelona City Council. Superblocks are constructed cells transforming

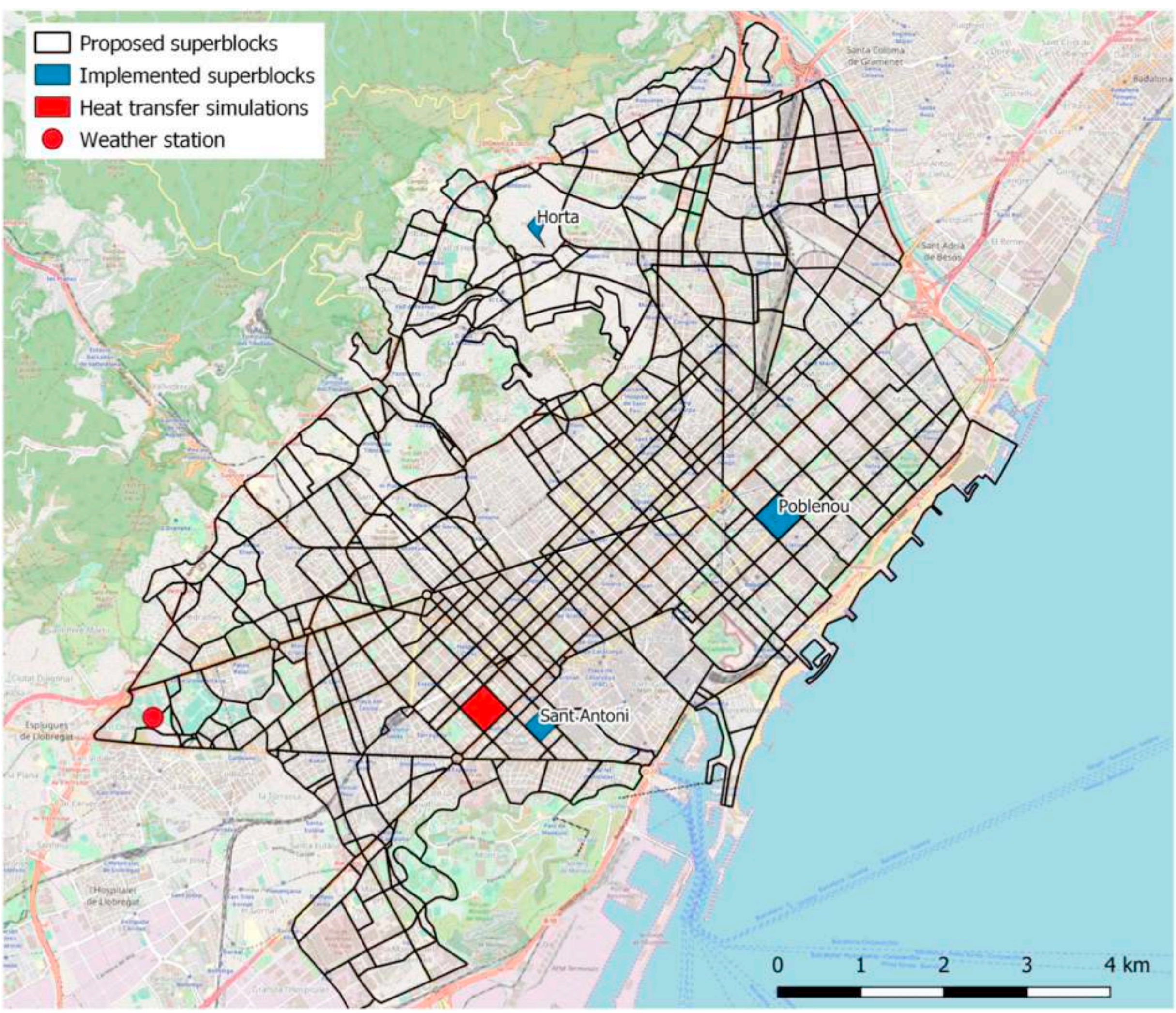


Fig. 1. Barcelona's 503 proposed Superblocks.

the city into sustainable (and healthy), compact and connected neighborhoods with a mixed land use, and high potential for social capital. The Superblock model also works towards achieving the ambitious targets set by the Sustainable Development Goals (SDGs) that define sustainable city and community development in SDG 11 as a pressing issue and leverage point to overcome global challenges related to poverty, inequality, climate, environmental degradation, prosperity, peace, and justice (United Nations, 2015).

While by mid 2019 the Barcelona City Council has implemented three Superblocks (Poblenou, Sant Antoni, Horta neighborhoods) (Fig. 1), and is committed to six more (http://ajuntament.barcelona.cat/superilles/es/), the present study aimed at estimating the health impacts related to the potential implementation of all 503 proposed Superblocks. We estimated the impact on preventable premature mortality, changes in life expectancy (LE) and economic impacts based on expected changes in urban and transport planning related exposures of (a) transport-related PA, (b) air pollution, (c) road traffic noise, (d) urban green space, and (e) mitigation of the urban heat island (UHI) effect through heat reductions.

2. Materials and methods

2.1. The Barcelona Superblock model

In the Eixample neighborhood, which covers most of the city center and is laid out in an orthogonal grid pattern, a Superblock will cover approximately 400 m × 400 m. In other parts of the city, the Superblock design can deviate (Fig. 1). Within the Superblocks, pacified interior roads will provide a local road network that is accessible primarily to active transport (i.e. walking and cycling) and secondarily to residential traffic with a maximum speed of 20 km/h (Fig. 2) (Rueda, 2018). The Superblocks will be framed by the basic road network that connects the city and accommodates through traffic at a maximum speed of 50 km/h (Rueda, 2018). Besides accommodating cars/motorcycles, the basic road network will contain segregated cycling and pedestrian infrastructures and segregated bus lanes for rapid transit. For optimal access, bus stops will be placed every 400 m at the main intersections of the Superblocks (in the non-grid-like neighborhoods this distance can vary) and buses will circulate at a high frequency, making public transport an attractive alternative. With the implementation of the 503 Superblocks, private motorized traffic is expected to decrease considerably, and traffic flow on the basic road network is expected be less congested, because of avoided turns into the Superblocks (Barcelona City Council, 2014; Rueda, 2018). In addition to reconfiguration of transport, liberation and re-allocation of public space are planned: the Superblock model foresees the development of public open and green space throughout the city, consisting of plazas, parks, green corridors, green patches and general greening in and outside the Superblocks (Fig. 3 and Fig. 4).

2.2. Health impact assessment

A quantitative health impact assessment (HIA) was carried out for the Barcelona population ≥20 years (*N* = 1,301,827; 2017) (Table 1) (Barcelona City Council, 2017a), at the projected Superblock area level (*N* = 503) (Fig. 1). Anticipated changes in the urban form and transport system are expected to result in changes of (a) transport-related PA, (b) air pollution, (c) road traffic noise, (d) green space, and (e) mitigation of the UHI effect through heat reductions.

Preventable premature mortality, changes in LE and economic impacts related to the Superblock model were estimated. We used a comparative risk assessment framework (Murray et al., 2004), and followed standard HIA methodologies (Mueller et al., 2017a, 2017b), comparing the baseline situation with the counterfactual scenario (i.e. Superblocks). We obtained exposure-response functions (ERFs) from the literature to quantify the strength of association between the exposures and mortality (Table 2). We obtained the annual natural-cause mortality rate for Barcelona (1,144 deaths/100,000 persons; 2015) (Table 1) (Barcelona Public Health Agency, 2017). We combined the exposure data with the ERFs, population data and mortality statistic to calculate population attributable fractions (PAFs) to quantify the Superblock scenario attributable preventable mortality burden:

$$PAF = \frac{\sum_{i=1}^{n} p_i RR_i - 1}{\sum_{i=1}^{n} p_i RR_i}$$

where p_i is the proportion of population at exposure level i, RR_i is the relative risk that quantifies the strength of association between the level of exposure i and mortality, i is the level of exposure (i.e. the difference in exposure between baseline situation and Superblock scenario), and n the number of exposure categories (i.e. 503 Superblocks) (Zapata-Diomedi et al., 2018).

We assumed immediate build-up of health benefits and the population size, age structure and mortality rate to stay constant. Children

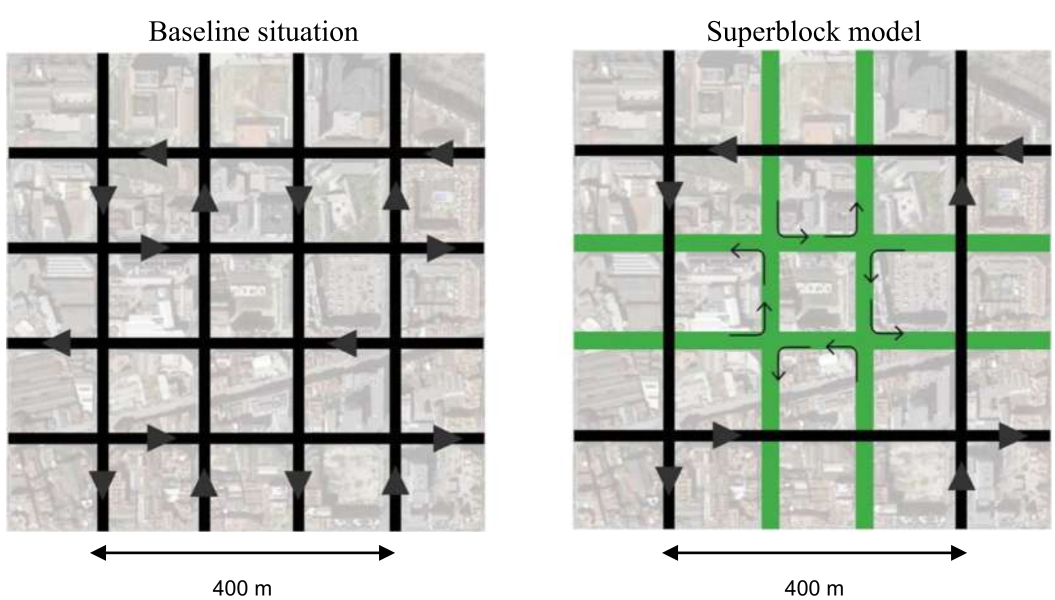


Fig. 2. Road hierarchy and traffic circulation aimed at with the Superblock model.

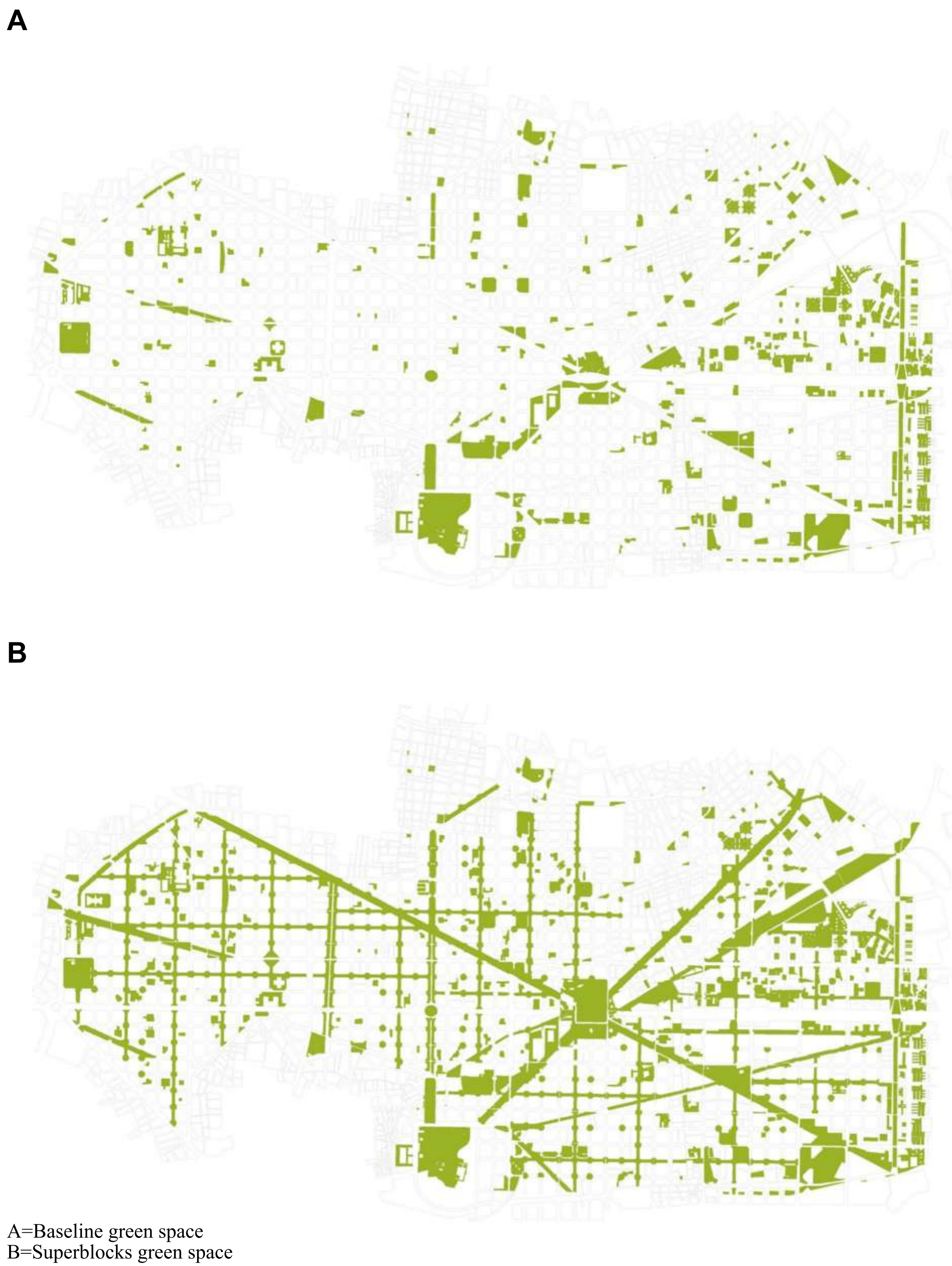


Fig. 3. Green space development for the Eixample neighborhood.

and adolescents were excluded from the analyses as their exposure-health relationships; their transport behaviors and the natural-cause mortality rate are different from the adult population. Analyses were conducted in R (v 3.5.2), Microsoft Excel (v 12.0) and QGIS (v 3.4.2).

2.3. Exposure data

2.3.1. Transport-related physical activity

With the implementation of the 503 Superblocks, the private motorized transport share is estimated to be reduced by 19.2% (Table 3). This scenario is based on transport projections made for the Barcelona

Fig. 4. Sant Antoni Superblock (2019).

Table 1
Barcelona population characteristics.

Population ≥20 years (2017)	Natural-cause mortality rate (2015)	Expected natural-cause mortality
1,301,827	1,144/100,000 persons	14,893

Urban Mobility Plan 2013–2018, that included infrastructure, quality and safety measures to promote public and active transport and reduce private motor vehicle use (Barcelona City Council, 2014). Hence, of the current almost 1,190,000 car/motorcycle trips/weekday (Barcelona City Council, 2017b), almost 228,000 trips would be shifted to public and active transport. We estimated health impacts associated with expected changes in transport-related PA levels resulting of shifting car/motorcycle trips to public transport, cycling or walking for 5 days/week. Supported by transport data, we assumed that Barcelona residents carry out on average 3.5 trips/weekday (Metropolitan Area of Barcelona, 2013) (Table 3). Metabolic equivalents of task (METs) were used as a measure of energy expenditure during PA. We calculated the gain in marginal METs for persons substituting car/motorcycle trips (i.e. 65,092 persons/weekday) with public transport, cycling or walking, considering baseline PA levels. Baseline PA levels were derived from the Barcelona Health Survey 2016/2017. The Barcelona Health Survey draws on a population-based random sample of 4,000 residents studying their health status, life-styles and use of health services (Bartoll et al., 2018). PA levels were assessed in the Health Survey with the International Physical Activity Questionnaire (IPAQ) short form (IPAQ, 2005). We included Health Survey participants ≥20 years with complete PA data (i.e. 3,217 adults) to determine baseline PA levels as a combination of walking, moderate and vigorous-intensity PA (Table A.1). Accounting for shorter trips and peoples' willingness to cycle or walk for transport, we assumed that a new bicycle trip would have the distance of an average baseline bicycle trip (i.e. 3.84 km), and a new walking trip would have the distance of an average baseline walking trip (i.e. 1.2 km) (Table 3). Accounting for longer trips, we assumed a new public transport trip would replace an average baseline car/motorcycle trip (i.e. 8.45 km) and would include a total 10 min walk to/from public transport to final destinations (Rojas-Rueda et al., 2012). We assigned the new bicycle trip 6.8 METs (Ainsworth et al., 2011), and the new walking trip and 10 min walk to/from public transport 3.5 METs (Ainsworth et al., 2011). The association between PA and mortality was quantified using a curvilinear ERF, applying a 0.25 power transformation (Table 2) (Woodcock et al., 2011). We calculated the relative risk (RR) and the population attributable fraction (PAF) for both baseline PA and gained PA. The estimated number of preventable deaths for baseline PA was subtracted from the estimated number of preventable deaths for the gained PA.

2.3.2. Air pollution

Baseline nitrogen dioxide (NO_2) concentrations (2012) were calculated and averaged at the Superblock area level using the Street 5.2 air quality model (KTT Umweltberatung und Software Dr. Kunz GmbH, 2005). Changes in NO_2 concentrations were modeled and reflect the expected 19.2% car/motorcycle share reduction, including changes in vehicle fleet and increased average speeds due to avoidance of congestion (Barcelona City Council, 2014) (Fig. 5). The association between NO_2 and mortality was quantified using a linear ERF (Table 2) (Atkinson et al., 2018). The RR and PAF corresponding to the exposure level difference between baseline and the Superblock scenario were calculated at the Superblock area level. The expected changes of other traffic-related air pollutants (TRAPs), such as particulate matter (e.g. $PM_{2.5}$), were not modeled for the Superblock scenario, and therefore, health impacts could not be estimated.

Table 2
Risk estimates for mortality by exposure domain.

Exposure	Risk estimate	Exposure	Health effect	Study design	Reference
Physical activity	RR = 0.81 (95% CI 0.76–0.85)	11 versus 0 MET-h/week	All-cause mortality	Meta-analysis	Woodcock et al., 2011
NO_2	RR = 1.02 (PI 0.99–1.06)	per 10 μg/m^3	All-cause mortality	Meta-analysis	Atkinson et al., 2018
Noise	HR = 1.04 (95% CI 1.02–1.06)	per 10 dB L_{den} (Road)	CVD mortality	Cohort study	Héritier et al., 2017
Green space	RR = 0.99 (95% CI 0.98–1.01)	per 10% increase in greenness	All-cause mortality	Meta-analysis	Gascon et al. 2015
Heat	RR = 1.19 (95% CI 1.16–1.23)	99th versus 74th temperature percentile	All-cause mortality	Time-series study	Guo et al., 2014

CVD = cardiovascular disease; HR = hazard rate; L_{den} = EU day-evening-night noise indicator with 5 dB and 10 dB weights for the evening and night time, respectively; MET = metabolic equivalent of task (1 MET = 1 kcal/kg/h); PI = prediction interval; RR = relative risk; 95% CI = 95% confidence interval.

Table 3
Barcelona transport data.

Mode	Baseline			Superblocks			Difference		Transport data		
	Mode share (%)[a]	Trips/weekday	Persons/ weekday[b]	Mode share (%)[c]	Trips/weekday	Persons/ weekday[b]	Persons/weekday		Mean distance (km)	Mean duration (h)	Mean speed (km/h)
Car/motorcycle	26.10	1,189,219	339,777	21.10	961,399	274,685	–	65,092	8.45[d]	0.41[f]	20.60[g]
Public transport	39.50	1,799,776	514,222	41.30	1,881,791	537,655	+	23,433	6.22[d]	0.51[f]	12.20[g]
Bicycle	2.10	95,684	27,338	2.50	113,910	32,546	+	5,208	3.84[e]	0.28[f]	13.71[h]
Walking	32.30	1,471,716	420,490	35.10	1,599,295	456,941	+	36,451	1.20[e]	0.25[f]	4.80[h]
Total	100.00	4556395[b]	1,301,827	100.00	4556395[b]	1,301,827					

[a] Barcelona City Council, 2017b.
[b] Calculated based on 3.5 trips/person/day (2003 – 2012) (Metropolitan Area of Barcelona, 2013).
[c] Barcelona City Council, 2014.
[d] Calculated as duration (h) * speed (km/h).
[e] Raser et al., 2018.
[f] Encuesta de Movilidad en Día Laborable (EMEF) 2015 (Metropolitan Transport Authority, 2015).
[g] Barcelona City Council, 2016.
[h] Calculated as distance (km)/duration (h).

2.3.3. *Road traffic noise*

Baseline annual mean 24-h noise indicator L_{den} (in dB) for road traffic (2016) was calculated in 5 dB intervals by using the Computer Aided Noise Abatement (CadnaA) software (v 3.7) (DataKustik GmbH, 2007) and was averaged at the Superblock area level. Changes in L_{den} levels were modeled reflecting the 19.2% car/motorcycle share reduction (Fig. 5). Missing noise values were imputed by using the mean. Currently, only evidence for L_{den} and cardiovascular mortality exists (van Kempen et al., 2018). It is believed though that the greatest contribution of noise to mortality is through cardiovascular effects (van Kempen et al., 2018), which was recently reinforced by a mega cohort study (Héritier et al., 2017). The association between L_{den} and cardiovascular mortality was quantified using a linear ERF (Table 2) (Héritier et al., 2017). The hazard ratio and PAF corresponding to the exposure level difference between baseline and the Superblock scenario were calculated at the Superblock area level.

2.3.4. *Green space*

Baseline and Superblock green space was estimated and developed by BCNecologia exclusively for the Eixample neighborhood (Fig. 5), using cartographic data (2010) (resolution 1:1,000) from the Barcelona City Council (Barcelona City Council, 2019). Using PostgreSQL/PostGIS (v 2.3), the current percentage green space (%GS) and projected increase in %GS under the Superblock scenario was calculated for the 202 Superblock areas compromising the Eixample neighborhood (population ≥20 years N = 464,216) (Fig. 3). The exposure difference between the current %GS and the Superblock %GS was calculated. A linear ERF was used to quantify the association between green space and mortality (Gascon et al., 2016b). The RR and the corresponding PAF were calculated for each of the 202 Eixample Superblocks. The remaining 301 Superblock areas framing the Eixample neighborhood (i.e. population ≥20 years N = 837,611) and either representing the historic city center (i.e. Ciutat Vella) or neighborhoods located at Barcelona's periphery in the north, west and south, were excluded from the analyses as no quantifiable green space vision exists yet for these neighborhoods.

2.3.5. *Heat*

Daily mean temperatures (2012–2017) were available through a weather station located in the south-west of the city (Fig. 1) (Klein Tank et al., 2002), and were averaged to obtain typical temperatures for one calendar year. Following an empirical model (Guo et al., 2014), the 74th daily mean temperature percentile, which defines the minimum mortality temperature (MMT) for Spain, was determined to be 21.5 °C for Barcelona (2012–2017). Between the 74th and 99th temperature percentiles, a linear mortality ERF was assumed (Guo et al., 2014) (Table 2). Daily mean ambient air temperatures (2016) were simulated with the UrbClim Model (v 1.1) (resolution 1:100) provided by the Flemish Institute for Technological Research (VITO) within the European climate-fit.city project (Ridder et al., 2015), and were averaged at the Superblock area level (Fig. 5). On 132 days during 2016, at least one Superblock exceeded the MMT of 21.5 °C (Table 4). The exposure level difference between the MMT and the simulated daily mean temperature was calculated at the Superblock area level. To account for seasonal variability in mortality, we based the daily mortality rate on averaged daily mortality count data for Barcelona for the meteorological summer season (June through August) provided by the Spanish Institute for National Statistics (i.e. 3 deaths/100,000 persons/day). The corresponding RR and PAF were calculated.

Thermal simulations of heat transfer from finite elements (i.e. surface) to ambient air temperatures for one centric Superblock in the densely-constructed city center (Fig. 1 and Fig. B.1), were conducted using RadTherm Heat Transfer Software (v 9.0.1) (Thermo Analytics Inc., 2016). Considering statistical summer day weather conditions, the use of semi-permeable materials and additional green space, heat transfer simulations simulated in a daily average 2 °C heat transfer reduction (Fig. B.2 and Fig. B.3). To be more conservative and to allow for varying land uses, densities, traffic volumes, surface elements and the presence of green and blue spaces across the city, we assumed a 1 °C ambient air temperature reduction as a more realistic scenario for the implementation of all 503 Superblocks. Supporting this assumption, compared to rural background, the city-wide UHI effect for summer 2016 was estimated to be around 2 °C (Fig. 5). Given that rural background conditions are unlikely to be achieved in the city, reducing the UHI effect by half (i.e. 1 °C) seemed a more plausible scenario for the Superblocks. Nevertheless, we also present results of the 2 °C Superblock heat reduction scenario as a sensitivity analysis in the appendix (Table B.1).

Under the Superblock scenario, we reduced 2016 daily mean air temperatures by 1 °C at the Superblock area level. The exposure difference was calculated for each Superblock for each day still exceeding 21.5 °C (i.e. 116 days) (Table 4). The corresponding RR and PAF were calculated. The number of deaths attributable to ambient air temperatures theoretically reduced by 1 °C was subtracted from the number of deaths attributable to the simulated ambient air temperatures for 2016.

2.4. *Life table analysis and economic impact*

We estimated average changes in LE anticipated with the Superblock model, using life tables for Barcelona (2016) (Table C.1) (IDESCAT, 2018), applying life table methods, as first described by

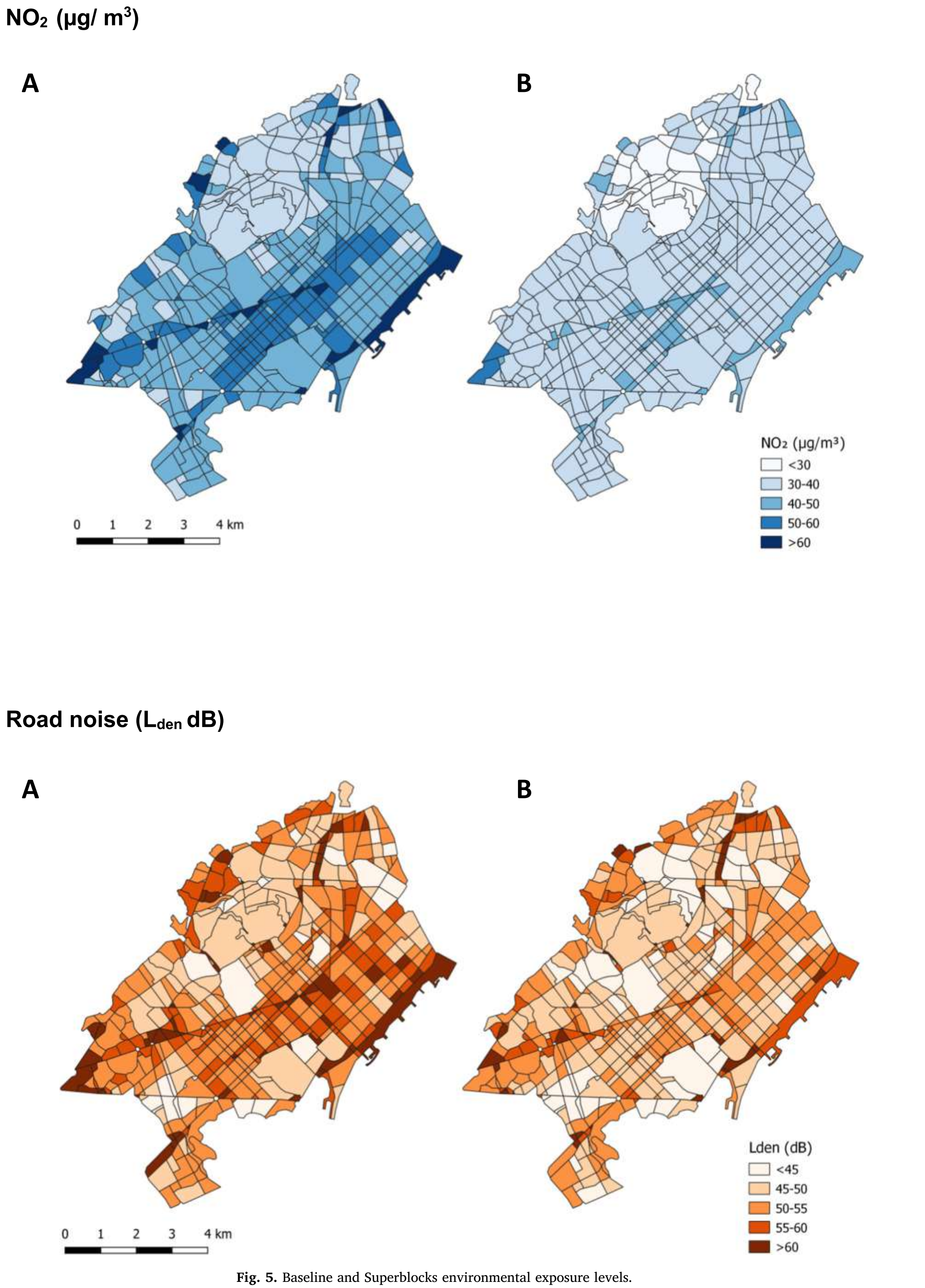
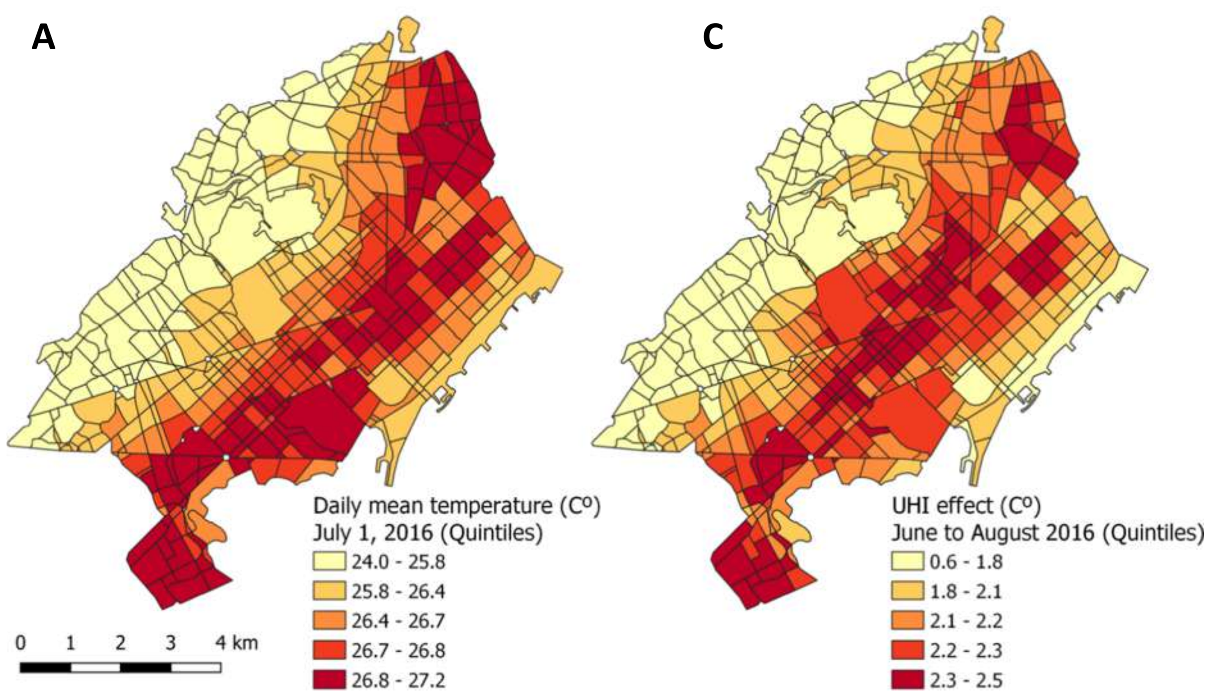


Fig. 5. Baseline and Superblocks environmental exposure levels.

Green space (%)

Temperature (ºC)



A=Baseline exposure level
B=Superblock exposure level
C=UHI effect summer 2016

Fig. 5. (*continued*)

Table 4
Baseline and Superblocks exposure levels and annual preventable premature deaths.

Exposure (year)	Baseline	Superblocks	Preventable deaths (95% CI)
Transport physical activity (2017)	Mean 29.39 MET-h/week (SD 35.93 MET-h/week)	Public transport +16.78 MET-h/week Bicycle +23.99 MET-h/week Walking +5.99 MET-h/week	36 (26–50)
NO_2 (2012)	47.18 μg/m^3 (Range 31.64–90.47 μg/m^3)	35.72 μg/m^3 (Range 27.31–56.83 μg/m^3)	291 (0–838)
Noise (2016)	54.18 dB L_{den} (Range 39.15–74.60 dB L_{den})	51.26 dB L_{den} (Range 37.52–71.01 dB L_{den})	163 (83–246)
Green space (Eixample) (2010)	6.54%GS (Range 0.00–66.78%GS)	19.57%GS (Range 0.20–97.95%GS)	60 (0–119)
Heat (2016)	132 days at least one Superblock > 21.50 °C Mean exceedance 3.55 °C (SD 2.11 °C)	116 days at least one Superblock > 21.50 °C Mean exceedance 3.15 °C (SD 1.77 °C)	117 (101–137)
Total			667 (235–1,098)

dB = decibel; L_{den} = EU day-evening-night noise indicator with 5 dB and 10 dB weights for the evening and night time, respectively.
MET = metabolic equivalent of task (1 MET = 1 kcal/kg/h); SD = standard deviation; %GS = percentage green space; 95% CI = 95% confidence interval.

Brunekreef (1997) for air pollution. We estimated average gains in LE for the Barcelona population ≥20 years by changing the probabilities of dying because of estimated city-wide mean improvements in environmental exposure levels (i.e. NO_2, noise, heat and green space) and increases in transport-related PA for persons expected to habitually replace car/motorcycle trips with public and active transport. We also estimated economic impacts of the changed premature mortality risk based on the value of a statistical life (VSL) (2,510,000 EUR for Spain, 2015) (WHO, 2017).

3. Results

With the implementation of the 503 Superblocks, the car mode share was projected to be reduced by 19.2% (Barcelona City Council, 2014), that translated into almost 230,000 car/motorcycle trips/weekday being shifted to public transport, cycling or walking (Table 3). Accordingly, baseline city-wide annual mean NO_2 levels of 47.2 μg/m^3 were estimated to be reduced to 35.7 μg/m^3 (−24.3%), and baseline city-wide annual mean road traffic noise levels of 54.2 dB L_{den} were estimated to be reduced to 51.3 dB L_{den} (−5.4%) (Table 4). In the Eixample neighborhood, baseline mean percentage green space of 6.5% was estimated to be increased to 19.6%. In 2016, on 132 days at least one Superblock exceeded the MMT of 21.5 °C daily mean temperature, whereas with an assumed reduction of ambient air temperatures by 1 °C, on 116 days at least one Superblock would have exceeded 21.5 °C.

With the implementation of the 503 Barcelona Superblocks, we estimated that 667 premature deaths (95% CI: 235–1,098) could be prevented annually (Fig. 6). The greatest proportion of preventable premature deaths could be attributed to reductions in NO_2 levels (291, 95% PI: 0–838), followed by road traffic noise (163, 95% CI: 83–246), heat (117, 95% CI: 101–137), and green space development in the Eixample neighborhood (60, 95% CI: 0–119). The estimated increased PA from the habitual shift from cars/motorcycles to public and active transport for approximately 65,000 persons (Table 3) resulted in 36

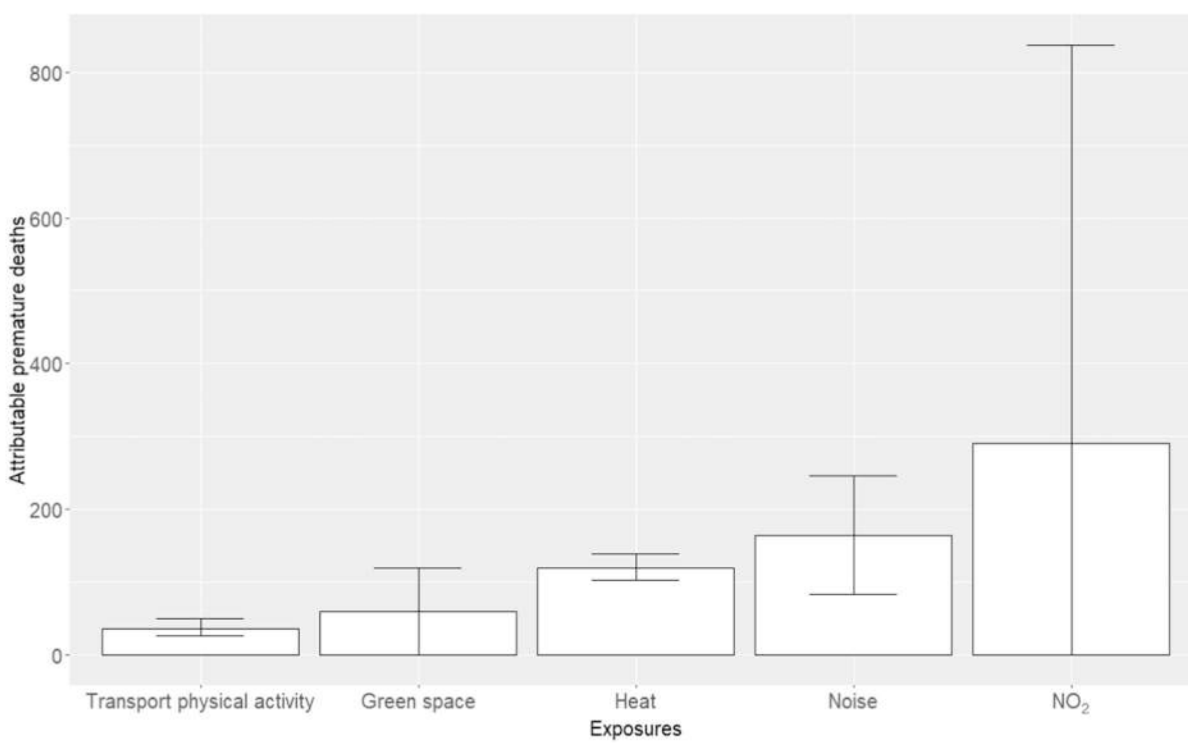


Fig. 6. Annual preventable premature deaths estimated for the Barcelona Superblock model.

preventable premature deaths annually (95% CI: 26–50) among this population.

In terms of changes in LE, we estimated that Barcelona residents ≥20 years would gain on average 198 days (95% CI: 99–297) because of reductions in NO_2, noise and heat. Additionally, Eixample neighborhood residents ≥20 years were estimated to gain on average 37 days (95% CI: 0–76) because of green space development. Adults habitually replacing car/motorcycle trips with public transport, cycling or walking were estimated to gain on average 97 days (95% CI: 79–159), 125 days (95% CI: 102–192), and 44 days (95% CI: 36–95), respectively, because of increases in PA (Table C.1).

The reduction in 667 premature deaths resulted in economic impacts of 1.7 billion EUR annually (95% CI: 0.6–2.8).

4. Discussion

The Superblocks are a new innovative model in urban and transport planning that reframe the current mobility paradigm and places people and well-being at the center. We estimated that with the implementation of the 503 planned Superblocks, 667 premature deaths could be prevented annually in Barcelona (Fig. 6), translating into a substantial economic impact of 1.7 billion EUR and considerable average gains in LE of almost 200 days due to reductions in harmful environmental exposures. Further gains in LE are expected with green space development and uptake of public and active transport.

The present study is the first study to comprehensively estimate the health impacts of this proposed real-life innovative intervention, holistically considering the expected changes in the multiple urban and transport planning related exposures. Previous HIA studies for the city of Barcelona estimated that 20% of premature mortality and 13% of the total burden of disease could be prevented under the assumption that international exposure guidelines for PA, exposure to air pollution, noise, heat and access to green space were complied with (Mueller et al., 2017a, 2017b). However, these scenarios were not associated with an actual urban and transport planning intervention.

In contrast to other HIA studies of transport scenarios, that considered the impacts of PA, besides other risk factors, and commonly estimated PA to be the most important health determinant (de Hartog et al., 2010; Mueller et al., 2015; Rojas-Rueda et al., 2011; Woodcock et al., 2009), our estimated transport-related PA benefits were smaller compared to those attributable to air pollution, noise and heat reductions. This result can be explained by the different baseline populations for which health impacts were estimated for. While motorized transport emission reductions (i.e. NO_2 and noise) and mitigation of the UHI effect would benefit the general Barcelona adult population ($N = 1{,}301{,}827$), green space benefits were estimated for Eixample neighborhood residents only ($N = 464{,}216$) and benefits linked to increases in transport-related PA relate exclusively to the population that is expected to habitually switch from cars/motorcycles to public and active transport ($N = 65{,}029$).

By far the strongest mortality impacts for the Superblocks resulted from air pollution reductions (291 deaths) - under the assumption that the association between NO_2 and mortality is causal. This finding is linked to the assumption of reduction of traffic volume and decline in congestion, that reduces NO_2 concentrations substantially (Zhang and Batterman, 2014) (Table 4). Estimated road traffic noise and heat mitigation effects were of considerable magnitude (163 and 117 deaths, respectively), emphasizing the importance of these understudied environmental exposures in urban environments. Further, green space development in the Eixample neighborhood alone resulted in a considerable number of preventable deaths (60 deaths), underlining the epidemiological significance of vegetation in cities in times of increasing population densities, general space scarcity and climate change.

In addition to the health benefits presented in this study, other potential co-benefits that we were not able to quantify should be highlighted: quality spaces with less disturbing factors (e.g. cars and motorcycles) help create place attachment and provide security that positively affects the formation of identity, sense of community and emotional and social well-being (Rollero, 2013). Public space helps facilitate social interaction and therefore contribute to social cohesion (Holland et al., 2007). In addition, Superblocks can help facilitate safe and independent child play. Research on Play Streets (i.e. street closure from traffic to foster child play) showed that children's PA levels significantly increased, enhanced their sociability and reduced parental safety concerns (Cortinez-O'Ryan et al., 2017; D'Haese et al., 2015). Also, leisure time PA levels, although not considered in the present analysis, are expected to increase with compact neighborhoods, mixed land-use and quality spaces, and result in even greater health benefits.

4.1. Limitations and strengths

As with all HIA studies, causal inferences may be an issue and results have to be understood as estimations based on best available epidemiological evidence. All changes in environmental exposures were modeled and depend on assumptions made in the models and data availability. Further work is needed to validate these models with actual post-intervention measurements. Despite the longstanding epidemiological study of air pollution, the evidence base for a causal relationship between long-term NO_2 exposure and mortality remains uncertain partly due to concerns relating to potential confounding effects by co-pollutants, especially fine particulate matter (i.e. $PM_{2.5}$), and the heterogeneity of individual study results (Atkinson et al., 2018). The evidence base for $PM_{2.5}$ for inference of a causal effect on mortality is stronger (U.S. Environmental Protection Agency, 2009), but exposure level changes of $PM_{2.5}$ under the Superblock scenario were not modeled, and $PM_{2.5}$ can have many other sources than road traffic (i.e. industry, the port and ships, construction, domestic, natural, etc.). Particularly in the city of Barcelona, which has the highest-traffic density in Europe (Barcelona City Council, 2018) and a large share of diesel-powered vehicles, NO_2 is believed to be a good marker for road traffic related air pollution. A 2014 meta-analysis found a statistically significant pooled effect of 1.04 (95% CI: 1.02–1.06) for NO_2 on mortality (Faustini et al., 2014). If the true effect of NO_2 on mortality was indeed that reported by Faustini and colleagues, then Superblock-related NO_2 reductions would result in more certain and stronger health benefits of 570 preventable premature deaths (95% CI: 291–838).

While the largest contribution of noise to mortality is believed to be through cardiovascular effects (van Kempen et al., 2018), underestimation of the effect of noise on multiple causes of mortality cannot be ruled out: a recent and growing body of evidence has associated noise exposure with a wide range of physiological and psychological health reactions (e.g. metabolic effects, respiratory symptoms, effects on cognition, annoyance and sleep disturbance) (WHO, 2018). Despite the Swiss population, from which the noise risk estimate was obtained (Héritier et al., 2017), probably not being representative of the Barcelona population, confounding by socio-economic position is unlikely, because the Swiss analyses were adjusted for socio-economic covariates.

Although our heat analyses were supported by thermal simulations, Superblock heat mitigation analyses were limited by the fact that the conversion from surface to ambient air temperature is largely uncertain and hardly generalizable because many different factors related to urban structures and macro- and microclimate play a role. Additional uncertainties might have been introduced with modeling the association between heat and mortality linearly and omission of the UHI effect possibly being protective during the winter months preventing cold-related deaths, which we did not account for.

Using cartographic data of green spaces and the corresponding exposure unit %GS does not differentiate between intensity and quality of green areas. The Normalized Difference Vegetation Index (NDVI), which detects live green vegetation canopy using multispectral remote sensing data, has been suggested to be a better indicator (Gascon et al., 2016a), and has been linked to stronger health benefits (Crouse et al., 2017; James et al., 2016), but is more difficult to project in the future as it is vegetation type-specific. Moreover, until now, a quantifiable green space vision exists only for the Eixample neighborhood. However, the other 301 Superblocks are also expected to receive green space interventions, which would translate into larger health benefits than estimated here.

For the transport-related PA analysis, although supported by records, we assumed that Barcelona residents conduct 3.5 trips/day on average (Metropolitan Area of Barcelona, 2013). This assumption strongly determines the traveling population of Barcelona and thus the population shifting from private to public and active modes of transport and consequently the magnitude of health benefits.

Furthermore, there might have been exposure and outcome misclassification. Exposure, transport, health and demographic data were only available for different years. Additionally, it is uncertain whether people spend most of their time in their Superblock of residence and therefore if exposures were assigned correctly.

Besides the benefit of allowing the comparison of severities between the exposures, when considering multiple exposures, there may be the risk of ‘double-counting’ of premature deaths, especially if the exposures are correlated. Independence of health effects has so far only been demonstrated for noise and air pollution (Tétreault et al., 2013). Health effects of air pollution could possibly be modified by temperature (Li et al., 2017), and health benefits of green spaces may in fact result from increases in PA or mitigation of air pollution, noise and heat (Gascon et al., 2016b). In fact, exposure to multiple risk factors associated with the same health outcome (e.g. mortality) leads to the health outcome being preventable in more than one way, from which could potentially follow that preventable cases are being counted more than once (Rowe et al., 2004). Therefore, the presented sum of preventable deaths should be interpreted with caution.

Finally, this HIA study assumed immediate and simultaneous implementation of all 503 Superblocks; this is rather unlikely and also time-lags in the change of transport behaviors and exposure levels would delay health benefits. Unaccounted political, social, and cultural factors will influence the Superblock implementation process and therefore health impacts, something important to consider in times of increasing urban populations, demographic as well as climate change and transformations in transportation and vehicle fleets.

Despite these limitations, there are many strengths of this study: This HIA should be understood as a robust overall estimation, based on best epidemiological evidence according to the current research, of what health impacts of the real-life Superblock intervention may look like. The multiple urban and transport planning related exposures were considered holistically and where uncertainty on causal inferences existed, assumptions were defined with caution and impacts were estimated conservatively. Further, the presented premature mortality impact has to be understood as the ‘tip of the iceberg’ because mortality is an extreme event. Non-fatal impacts such as the expected reduction in chronic disease, improvements in quality of life, social cohesion and mental health have not been quantified in the present analysis. Consequently, the total health and well-being impact of the Superblocks can be expected to be considerably larger than the numbers presented here, which would make an even stronger case for the rapid implementation of this urban and transport planning – as well as public health – intervention.

4.2. Other implications

Certain concerns and possible negative consequences of the Superblock model need to be acknowledged, especially in the context of health equity and environmental justice. Since almost half of the two million daily suburban commuter trips from the Metropolitan Region are made in car/motorcycle (Barcelona City Council, 2016), the Superblock model calls for a simultaneous improvement of the suburban commuter network that provides people with true alternatives. Improvement of the less-well developed public transport system for the wider Metropolitan Region is therefore a prerequisite for the Superblocks to function well. Furthermore, gentrification is a potential risk, which can occur when depressed areas are occasionally improved (with green and other popular infrastructure) and become attractive for upper classes, resulting in rent rises and subsequently forced migration (Cole et al., 2017). Also, the possibility of undesired relocation of car/motorcycle traffic (to potentially already deprived areas) outside the Superblocks needs to be considered and avoided and therefore supplementary interventions that further discourage the use of private motorized transport in the city are necessary (e.g. reduction of on-road parking, congestion charging, low emission zones, etc.). In order to mitigate the identified risks, consistent and equitable implementation of the model across the entire city is recommended.

5. Conclusions

The Barcelona Superblock model is a promising urban model as well as public health strategy to reclaim public space for people and help the city become cleaner, greener, more physically active and climate change resilient through the reconfiguration of urban and transport structures. We showed that the Superblocks have the potential to reduce the premature mortality burden and increase LE considerably through reductions in air pollution, noise and heat and increased access to green space and transport-related PA performance. The magnitude of estimated health impacts should make a case for the rapid implementation in Barcelona and the scale-up to other cities, where similar health benefits can be expected. For full and equitable distribution of health benefits, the Superblock model should consistently be implemented across the entire city.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

We declare no competing interests.

Acknowledgements

We would like to thank Maria Foraster for helpful advice on the noise analyses and Glòria Carrasco for taking the pictures of the Sant Antoni Superblock. JB gratefully acknowledges funding from the European Union's Horizon 2020 research and innovation programme under grant agreements No 727852 (project Blue-Action), 730004 (project PUCS) and 737480 (Marie Sklodowska-Curie fellowship ACCLIM). The climate-fit. city is developed as part of the PUCS project, which has received funding from the European Union's H2020 Research and Innovation Programme under Grant Agreement No. 73004.

Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105132.

References

Ainsworth, B.E., Haskell, W.L., Herrmann, S.D., Meckes, N., Bassett, D.R., Tudor-Locke, C., Greer, J.L., Vezina, J., Whitt-Glover, M.C., Leon, A.S., 2011. 2011 compendium of physical activities: a second update of codes and MET values. Med. Sci. Sports Exerc. 43, 1575–1581. https://doi.org/10.1249/MSS.0b013e31821ece12.

Atkinson, R.W., Butland, B.K., Anderson, H.R., Maynard, R.L., 2018. Long-term concentrations of nitrogen dioxide and mortality. Epidemiology 29, 460–472. https://

doi.org/10.1097/EDE.0000000000000847.
Barcelona City Council, 2014. Urban mobility plan of Barcelona PMU 2013-2018. [WWW Document]. URL. http://www.bcnecologia.net/sites/default/files/proyectos/pmu_angles.pdf, Accessed date: 11 April 2019.
Barcelona City Council, 2016. Dades bàsiques de mobilitat 2015. [WWW Document]. URL. http://mobilitat.ajuntament.barcelona.cat/sites/default/files/DB_2015.pdf, Accessed date: 25 May 2018.
Barcelona City Council, 2017a. Population Characteristics. Official Figures of Population. 2017. [WWW Document]. URL. http://www.bcn.cat/estadistica/angles/dades/tpob/pad/ine/a2017/edat/edatq11.htm, Accessed date: 17 July 2018.
Barcelona City Council, 2017b. Dades bàsiques de mobilitat 2016. [WWW Document]. URL. http://mobilitat.ajuntament.barcelona.cat/sites/default/files/DADES-BASIQUES-MOBILITAT16_13_1.pdf, Accessed date: 25 May 2018.
Barcelona City Council, 2018. Qualitat de l'Aire. Sabies que…? [WWW Document]. URL. https://ajuntament.barcelona.cat/qualitataire/ca/sabies-que, Accessed date: 17 April 2018.
Barcelona City Council, 2019. CartoBCN. [WWW Document]. URL. http://w20.bcn.cat/cartobcn/, Accessed date: 15 December 2018.
Barcelona Public Health Agency, 2017. Llibre mortalitat anual 2015 [WWW Document]. Barcelona 2015, ambdós sexes. Mortalitat segons Grup d'edat i causes defunció. URL. http://www.aspb.cat/docs/sisalut/SISalutLlibresIndicadors/LlibreMortalitat_2015.html, Accessed date: 23 May 2018.
Barcelona Urban Ecology Agency, 2018. Charter for Designing New Urban Developments and Regenerating Existing Ones. (Barcelona).
Bartoll, X., Pérez, C., Pasarín, M., Rodríguez, M., Borrell, C., 2018. Enquesta de salut de Barcelona 2016/17. (Barcelona).
Brunekreef, B., 1997. Air pollution and life expectancy: is there a relation? Occup. Environ. Med. 54, 781–784.
Cole, H.V.S., Lamarca, M.G., Connolly, J.J.T., Anguelovski, I., 2017. Are green cities healthy and equitable? Unpacking the relationship between health, green space and gentrification. J. Epidemiol. Community Health 71, 1118–1121. https://doi.org/10.1136/jech-2017-209201.
Cortinez-O'Ryan, A., Albagli, A., Sadarangani, K.P., Aguilar-Farias, N., 2017. Reclaiming streets for outdoor play: a process and impact evaluation of "Juega en tu barrio"(play in your neighborhood), an intervention to increase physical activity and opportunities for play. PLoS One 12, e0180172. https://doi.org/10.6084/m9.figshare.3437033.
Crawford, J., 2002. Reclaiming cities for citizens. [WWW Document]. URL. https://www.opendemocracy.net/ecology-climate_change_debate/article_480.jsp, Accessed date: 16 August 2018.
Crouse, D.L., Pinault, L., Balram, A., Hystad, P., Peters, P., Chen, H., van Donkelaar, A., Martin, R.V., Ménard, R., Robichaud, A., Villeneuve, P.J., 2017. Urban greenness and mortality in Canada's largest cities: a national cohort study. Lancet Planet. Heal. 1, e289–e297. https://doi.org/10.1016/S2542-5196(17)30118-3.
DataKustik GmbH, 2007. Computer Aided Noise Abatement (CadnaA) Software.
Dávalos, D., Maldonado, D., Polit, D.J., 2016. The hidden potential behind the city planned for cars. Procedia Eng 145, 924–931. https://doi.org/10.1016/j.proeng.2016.04.120.
De Hartog, J., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Environ. Health Perspect. 118, 1109–1116. https://doi.org/10.1289/ehp.0901747.
D'Haese, S., Van Dyck, D., De Bourdeaudhuij, I., Deforche, B., Cardon, G., 2015. Organizing "play streets" during school vacations can increase physical activity and decrease sedentary time in children. Int. J. Behav. Nutr. Phys. Act. 12, 1–9. https://doi.org/10.1186/s12966-015-0171-y.
Faustini, A., Rapp, R., Forastiere, F., 2014. Nitrogen dioxide and mortality: review and meta-analysis of long-term studies. Eur. Respir. J. 44, 744–753. https://doi.org/10.1183/09031936.00114713.
Gascon, M., Cirach, M., Martínez, D., Dadvand, P., Valentín, A., Plasència, A., Nieuwenhuijsen, M.J., 2016a. Normalized difference vegetation index (NDVI) as a marker of surrounding greenness in epidemiological studies: the case of Barcelona city. Urban For. Urban Green. 19, 88–94. https://doi.org/10.1016/j.ufug.2016.07.001.
Gascon, M., Triguero-Mas, M., Martínez, D., Dadvand, P., Rojas-Rueda, D., Plasència, A., Nieuwenhuijsen, M., 2016b. Residential green spaces and mortality: a systematic review. Environ. Int. 86, 60–67.
Guo, Y., Gasparrini, A., Armstrong, B., Li, S., Tawatsupa, B., Tobias, A., Lavigne, E., de Sousa Zanotti Stagliorio Coelho, M., Leone, M., Pan, X., Tong, S., Tian, L., Kim, H., Hashizume, M., Honda, Y., Guo, Y.-L.L., Wu, C.-F., Punnasiri, K., Yi, S.-M., Michelozzi, P., Saldiva, P.H.N., Williams, G., 2014. Global variation in the effects of ambient temperature on mortality: a systematic evaluation. Epidemiology 25, 781–9. doi:https://doi.org/10.1097/EDE.0000000000000165.
Héritier, H., Vienneau, D., Foraster, M., Eze, I.C., Schaffner, E., Thiesse, L., Rudzik, F., Habermacher, M., Köpfli, M., Pieren, R., Brink, M., Cajochen, C., Wunderli, J.M., Probst-Hensch, N., Röösli, M., 2017. Transportation noise exposure and cardiovascular mortality: a nationwide cohort study from Switzerland. Eur. J. Epidemiol. 32, 307–315. https://doi.org/10.1007/s10654-017-0234-2.
Holland, C., Clark, A., Katz, J., Peace, S., 2007. Social Interactions in Urban Public Places. The Policy Press, Bristol. https://doi.org/10.1186/1745-6215-12-264.
IDESCAT, 2018. Taula de vida abreujada. Tots dos sexes Barcelona. 2012-2016. [WWW Document]. Life Expect. Heal. Popul. Indic. URL. http://www.idescat.cat/pub/?id=iev&n=8641&geo=prov%3A08&lang=en&t=201400, Accessed date: 20 July 2018.
IPAQ, 2005. Guidelines for Data Processing and Analysis of the International Physical Activity Questionnaire (IPAQ) – Short and Long Forms. [WWW Document]. URL. http://www.institutferran.org/documentos/scoring_short_ipaq_april04.pdf, Accessed date: 10 October 2016.
James, P., Hart, J.E., Banay, R.F., Laden, F., 2016. Exposure to greenness and mortality in a nationwide prospective cohort study of women. Environ. Health Perspect. 124, 1344–1352. https://doi.org/10.1289/ehp.1510363.
Klein Tank, A., A.M.G., et al., 2002. Daily dataset of 20th-century surfaceair temperature and precipitation series for the European climate assessment. Int. J. Climatol. 22, 1441–1453 EUROPEAN CLIMATE ASSESSMENT & DATASET (ECA&D).
KTT Umweltberatung und Software Dr. Kunz GmbH, 2005. Street 5.2.
Li, J., Woodward, A., Hou, X.-Y., Zhu, T., Zhang, J., Brown, H., Yang, J., Qin, R., Gao, J., Gu, S., Li, J., Xu, L., Liu, X., Liu, Q., 2017. Modification of the effects of air pollutants on mortality by temperature: a systematic review and meta-analysis. Sci. Total Environ. 575, 1556–1570. https://doi.org/10.1016/j.scitotenv.2016.10.070.
Manville, M., Shoup, D., 2005. Parking, people, and cities. J. Urban Plan. Dev 131, 233–245. https://doi.org/10.1061/(ASCE)0733-9488(2005)131:4(233).
Metropolitan Area of Barcelona, 2013. Mitjana desplaçaments per persona i dia dels residents a l'EMT i a l'AMB, 2003-2013 [WWW Document]. URL. http://www.amb.cat/web/area-metropolitana/dades-estadistiques/mobilitat-i-transport/mobilitat-quotidiana, Accessed date: 25 May 2018.
Metropolitan Transport Authority, 2015. Encuesta de Movilidad en Día Laborable (EMEF). [WWW Document]. URL. https://www.atm.cat/web/es/observatori/encuestas-de-movilidad.php, Accessed date: 21 January 2019.
Moreno-Garcia, M.C., 1994. Intensity and form of the urban heat island in Barcelona. Int. J. Climatol. 14, 705–710.
Mueller, N., Rojas-Rueda, D., Cole-Hunter, T., de Nazelle, A., Dons, E., Gerike, R., Götschi, T., Int Panis, L., Kahlmeier, S., Nieuwenhuijsen, M., 2015. Health impact assessment of active transportation: a systematic review. Prev. Med. (Baltim). 76, 103–114. https://doi.org/10.1016/j.ypmed.2015.04.010.
Mueller, N., Rojas-Rueda, D., Basagaña, X., Cirach, M., Cole-Hunter, T., Dadvand, P., Donaire-Gonzalez, D., Foraster, M., Gascon, M., Martinez, D., Tonne, C., Triguero-Mas, M., Valentín, A., Nieuwenhuijsen, M., 2017a. Urban and transport planning related exposures and mortality: a health impact assessment for cities. Environ. Health Perspect. 125, 89–96. https://doi.org/10.1289/EHP220.
Mueller, N., Rojas-Rueda, D., Basagaña, X., Cirach, M., Cole-Hunter, T., Dadvand, P., Donaire-Gonzalez, D., Foraster, M., Gascon, M., Martinez, D., Tonne, C., Triguero-Mas, M., Valentín, A., Nieuwenhuijsen, M., 2017b. Health impacts related to urban and transport planning: a burden of disease assessment. Environ. Int. 107, 243–257. https://doi.org/10.1016/j.envint.2017.07.020.
Murray, C., Ezzati, M., Lopez, A., Rodgers, A., Vander Hoorn, S., 2004. Comparative Quantification of Health Risks: Conceptual Framework and Methodological Issues, Comparative Quantification of Health Risks. Global and Regional Burden of Disease Attributable to Selected Major Risk Factors. World Health Organziation, Geneva. https://doi.org/10.1007/s12263-011-0248-4.
Nieuwenhuijsen, M.J., Khreis, H., 2016. Car free cities: pathway to healthy urban living. Environ. Int. 94, 251–262. https://doi.org/10.1016/j.envint.2016.05.032.
Nieuwenhuijsen, M.J., Khreis, H., Triguero-Mas, M., Gascon, M., Dadvand, P., 2017. Fifty shades of green: pathway to healthy urban living. Epidemiology 28, 63–71. https://doi.org/10.1097/EDE.0000000000000549.
Raser, E., Gaupp-Berghausen, M., Dons, E., Anaya-Boig, E., Avila-Palencia, I., Brand, C., Castro, A., Clark, A., Eriksson, U., Götschi, T., Int Panis, L., Kahlmeier, S., Laeremans, M., Mueller, N., Nieuwenhuijsen, M., Orjuela, J.P., Rojas-Rueda, D., Standaert, A., Stigell, E., Gerike, R., 2018. European cyclists' travel behavior: differences and similarities between seven European (PASTA) cities. J. Transp. Heal. https://doi.org/10.1016/j.jth.2018.02.006.
Ridder, K.D., Lauwaet, D., Maiheu, B., 2015. Urban climate UrbClim – a fast urban boundary layer climate model. Urban Clim. 12, 21–48. https://doi.org/10.1016/j.uclim.2015.01.001.
Rojas-Rueda, D., de Nazelle, A., Tainio, M., Nieuwenhuijsen, M.J., 2011. The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. BMJ 343, 1–8.
Rojas-Rueda, D., de Nazelle, A., Teixidó, O., Nieuwenhuijsen, M.J., 2012. Replacing car trips by increasing bike and public transport in the greater Barcelona metropolitan area: a health impact assessment study. Environ. Int. 49, 100–109. https://doi.org/10.1016/j.envint.2012.08.009.
Rollero, C., 2013. The town in my mind: how place attachment and identification are linked to place perception. Estud. Psicol. 34, 309–314. https://doi.org/10.1174/021093913808349343.
Rowe, A.K., Powell, K.E., Flanders, W.D., 2004. Why population attributable fractions can sum to more than one. Am. J. Prev. Med. 26, 243–249. https://doi.org/10.1016/j.amepre.2003.12.007.
Rueda, S., 2018. Superblocks for the design of new cities and renovation of existing ones. Barcelona's case. In: Nieuwenhuijsen, M., Khreis, H. (Eds.), Integrating Human Health into Urban and Transport Planning. Springer International Publishing, pp. 135–154.
Tétreault, L., Perron, S., Smargiassi, A., 2013. Cardiovascular health, traffic-related air pollution and noise: are associations mutually confounded? A systematic review. Int. J. Public Health 58, 649–666. https://doi.org/10.1007/s00038-013-0489-7.
Thermo Analytics Inc, 2016. RadTherm Heat Transfer Software.
U.S. Environmental Protection Agency, 2009. Integrated Science Assessment for Particulate Matter, EPA/600/R-08/139F. Final Report. (Washington, DC).
United Nations, 2015. Transforming our World: The 2030 Agenda for Sustainable Development. New York. https://doi.org/10.1007/s13398-014-0173-7.2.
Van Kempen, E., Casas, M., Pershagen, G., Foraster, M., 2018. WHO environmental noise guidelines for the European region: a systematic review on environmental noise and cardiovascular and metabolic effects: a summary. Int. J. Environ. Res. Public Health 15, 379. https://doi.org/10.3390/ijerph15020379.
WHO, 2017. Health Economic Assessment Tool (HEAT) for Walking and for Cycling.

Methods and User Guide on Physical Activity, Air Pollution, Injuries and Carbon Impact Assessments. [WWW Document]. URL. http://www.euro.who.int/_data/assets/pdf_file/0010/352963/Heat.pdf?ua=1, Accessed date: 11 April 2019.
WHO, 2018. Environmental Noise Guidelines for the European Region. https://doi.org/10.3390/ijerph14080873.
Wolf, K.L., Robbins, A.S.T., 2015. Metro nature, environmental health, and economic value. Environ. Health Perspect. 123, 390–398.
Woodcock, J., Edwards, P., Tonne, C., Armstrong, B.G., Ashiru, O., Banister, D., Beevers, S., Chalabi, Z., Chowdhury, Z., Cohen, A., Franco, O.H., Haines, A., Hickman, R., Lindsay, G., Mittal, I., Mohan, D., Tiwari, G., Woodward, A., Roberts, I., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. Lancet 374, 1930–1943. https://doi.org/10.1016/S0140-6736(09)61714-1.
Woodcock, J., Franco, O.H., Orsini, N., Roberts, I., 2011. Non-vigorous physical activity and all-cause mortality: systematic review and meta-analysis of cohort studies. Int. J. Epidemiol. 40, 121–138. https://doi.org/10.1093/ije/dyq104.
Zapata-Diomedi, B., Barendregt, J.J., Veerman, J.L., 2018. Population attributable fraction: names, types and issues with incorrect interpretation of relative risks. Br. J. Sports Med. 52, 212–213. https://doi.org/10.1136/bjsports-2015-095531.
Zhang, K., Batterman, S., 2014. Air pollution and health risks due to vehicle traffic. Sci. Total Environ. 307–316. https://doi.org/10.1016/j.scitotenv.2013.01.074.Air.