underestimation of population exposure estimates in established methods

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HARMO21, Tuesday 27th September 2022, Aveiro (PT)

2 APCG

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human exposure to air pollutants …

… can be defined as the product of **time spent by a person in different locations** & the **air pollutant concentrations** in these locations.

(Ott, 1982, Watson et al., 1988)

emission sources → **concentrations outdoors + indoors** → **intake** → **uptake** → **dose** → **health effects**

well-known problems

Environment International, Vol. 7, pp. 179–196, 1982
Printed in the USA.

CONCEPTS OF HUMAN EXPOSURE TO AIR POLLUTION

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U.S. Environmental Protection Agency, Office of Research and Development (RD-680), Washington, DC 20460, USA

(Received 3 September 1980; Accepted 6 November 1981)

Conclusions

[…]

These estimates also often ignore the fact that employed persons, and many others as well, usually spend considerable time each day away from their residences, and therefore they are located even further away from the monitoring station that is supposed to represent their exposure. Perhaps more important, these estimates almost always ignore indoor air quality levels, despite the fact that measurements have shown that indoor levels differ from outdoor levels for a variety of air pollutants, including CO, lead, respirable particulates, and NO_2. Thus, it appears unlikely that "exposure," as defined by these investigators, will be truly representative of the concentrations actually reaching members of the population and entering their lungs.

In this paper, several new definitions are suggested. An "exposure" has been defined as occurrence of the

challenges for representative exposure estimates in 1982 (Ott 1982)

1. fixed monitoring sites
2. static populations
3. indoor air quality levels

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(our) hypothesis

human exposure to air pollution is underestimated in established approaches

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agenda

1. overview established approaches (global, regional, urban)
2. overcoming challenges at the urban scale
3. approaching challenges at the regional scale

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1. Overview established approaches (global, regional, local)

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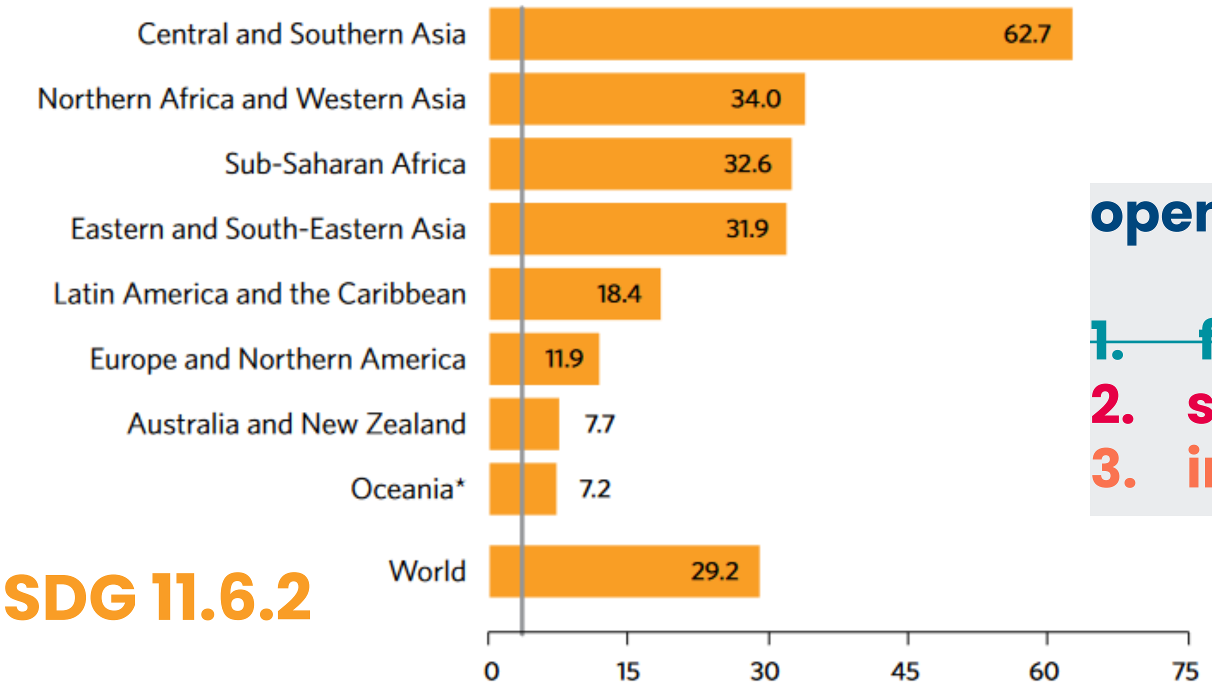
11 SUSTAINABLE CITIES AND COMMUNITIES

MAKE CITIES AND HUMAN SETTLEMENTS INCLUSIVE, SAFE, RESILIENT AND SUSTAINABLE

99% OF THE WORLD'S URBAN POPULATION BREATHE POLLUTED AIR

ACCORDING TO NEW WORLD HEALTH ORGANIZATION AIR QUALITY GUIDELINES OF $PM_{2.5}$ <5 UG/M^3

Annual exposure to particulate matter ($PM_{2.5}$) in urban areas, three-year average from 2017 to 2019 (micrograms per cubic metre)



* Excluding Australia and New Zealand.

Note: The vertical line represents WHO's new air quality guidelines value for particulate matter ($PM_{2.5}$) of 5 micrograms or less per cubic metre.

SDG 11.6.2

open challenges:

1. ~~fixed monitoring sites~~
2. static populations
3. indoor air quality levels

EEA regional exposure estimates (EEA 2018)

European Environment Agency

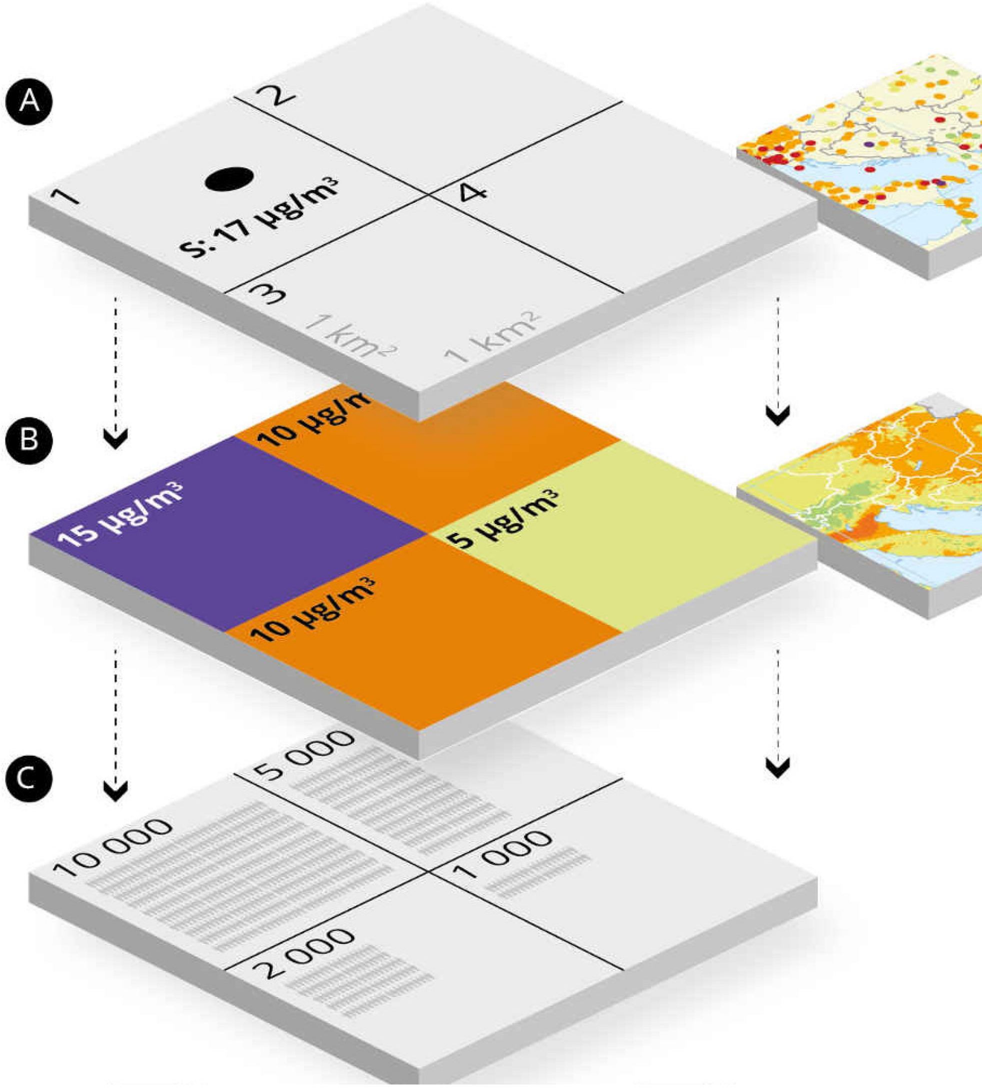
A) Station data – monitoring stations (S) in 1x1 km² grid

B) Concentration map – mapped monitoring station (S) combined with EMEP concentrations results in annual mean concentration grids

C) Population exposure – gridded residential addresses

open challenges:

1. ~~**fixed monitoring sites**~~
2. **static populations**
3. **indoor air quality levels**



© EEA2018 – *Assessing the risks to health from air pollution*

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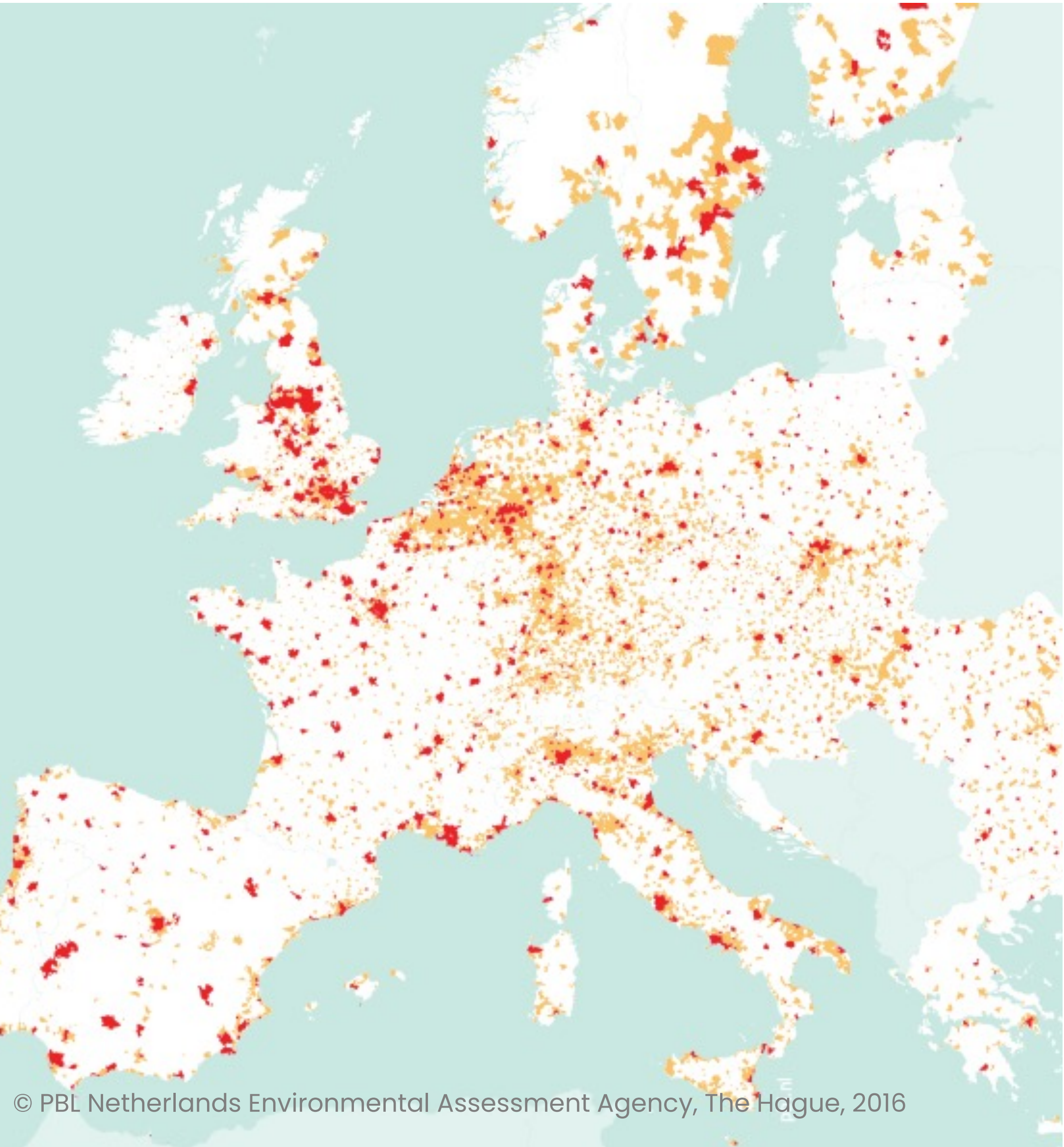
EEA urban exposure estimates (EEA2020)

European Environment Agency



1. definition of urban core (Urban Audit, 2014)
2. **EEA measurement stations** (*urban/suburban traffic/background (no industrial)*) spatially joined with urban core
3. urban population = **residential addresses** in urban core (%pop lives <100m from major roads ➔ traffic stations)
4. one exposure value per urban area

open issues:

1. **fixed monitoring sites**
2. **static populations**
3. **indoor air quality levels**

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established approaches exposure estimates

open challenges 40 years after W. Ott (1982):

~~1. fixed monitoring sites~~
2. static populations
3. indoor air quality levels

ambient pollutant concentrations (e.g. NO_2, O_3, $PM_{2.5}$)

static population activity (e.g. home, work, traffic)

population exposure

air quality studies → exposure assessments → health effect studies

- monitoring networks
- numerical modelling
- land-use regression
- satellite data

- population density
- residential addresses

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2. overcoming challenges at the urban scale

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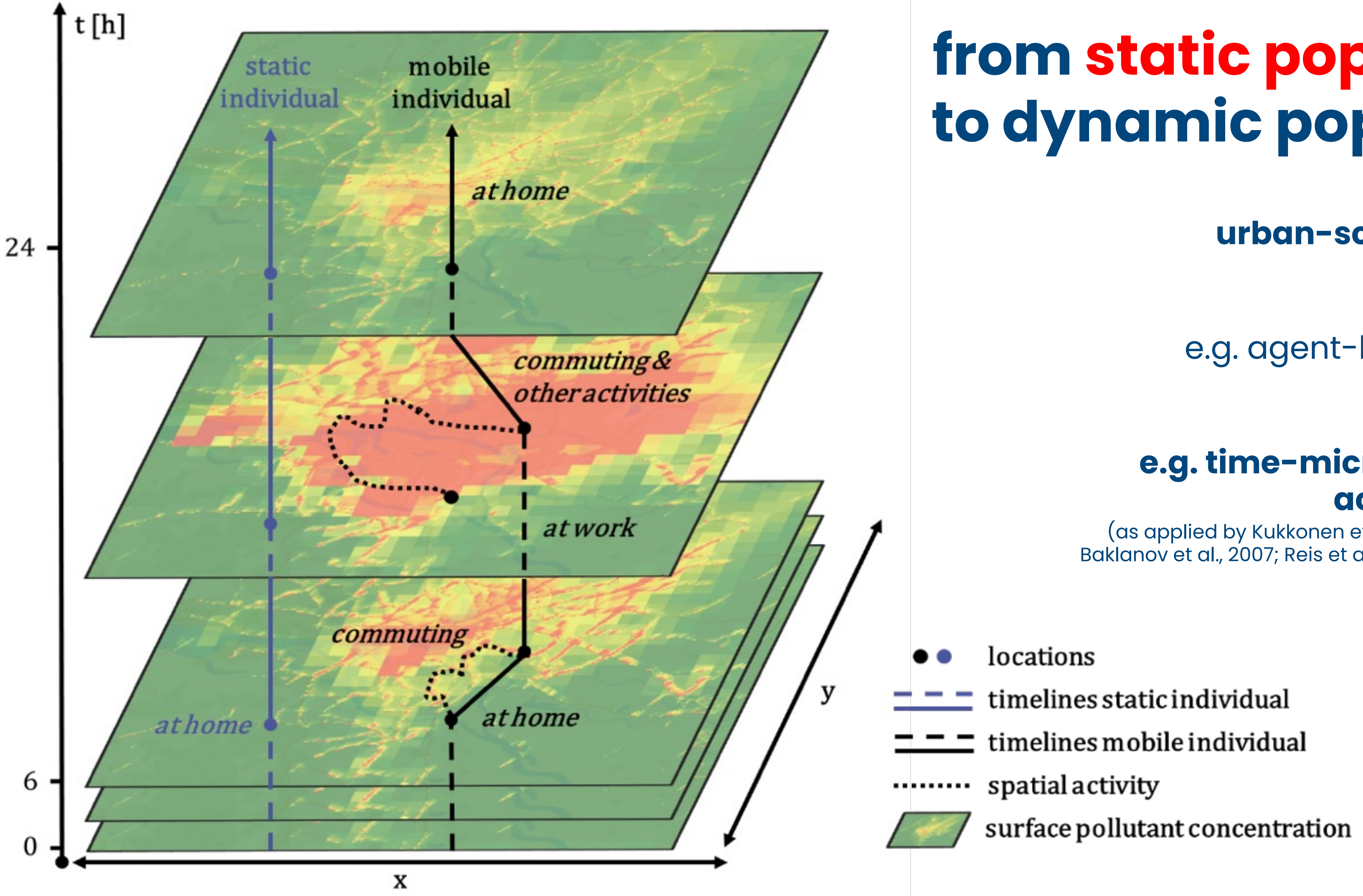

from static populations to dynamic populations

urban-scale approaches

individuals
e.g. agent-based modelling

populations
e.g. time-microenvironment-activity approach
(as applied by Kukkonen et al. 2016; Soares et al., 2014; Baklanov et al., 2007; Reis et al., 2018; Singh et al., 2020; …)

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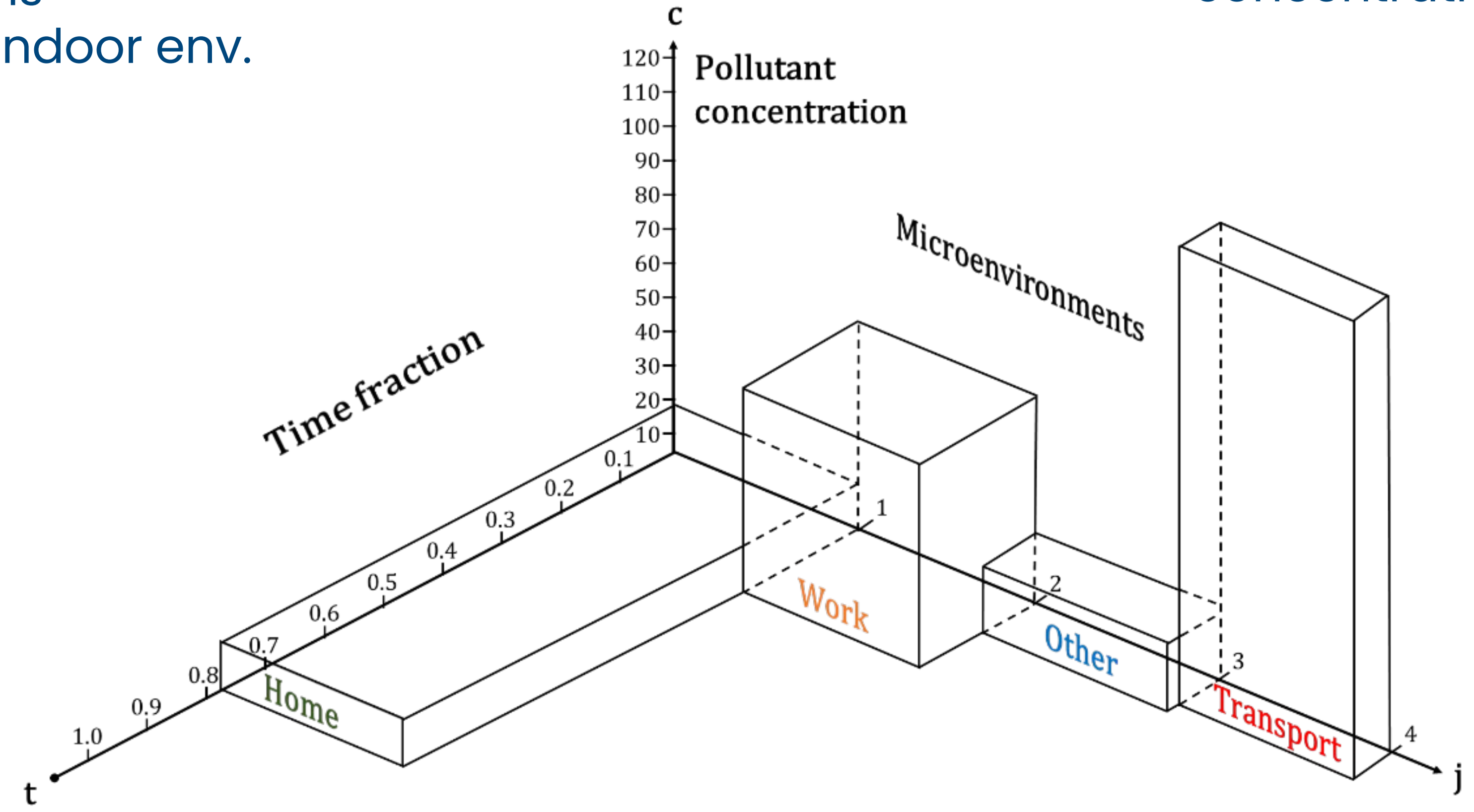
microenvironments

<u>microenvironment (ME):</u>
a location in which human exposure takes place, containing a relatively uniform concentration.

<u>microenvironment concept enables:</u>
- spatial distribution of populations
- temporal distribution of populations
- outdoor concentration infiltrating indoor env.

1. fixed monitoring sites
2. static populations
3. indoor air quality levels



Reproduced figure based on Watson et al. (1988)

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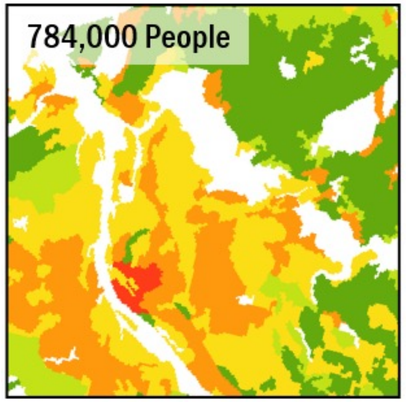
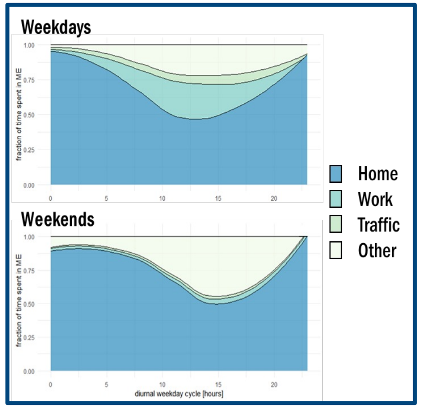
urban dynamic exposure estimates (UNDYNE) Ramacher et al. 2019

time-microenvironment-activity approach
(as applied by Kukkonen et al. 2016, Soares et al., 2014; Baklanov et al., 2007; Reis et al., 2018; Singh et al., 2020, …)

population dataset
Copernicus UrbanAtlas

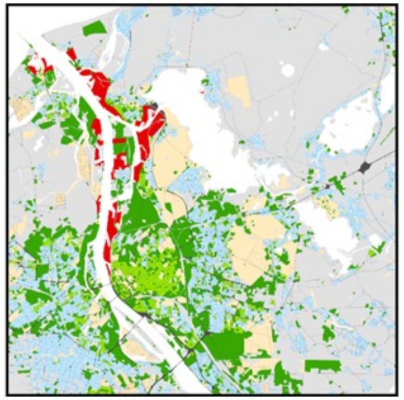




temporal distribution
diurnal activity profiles

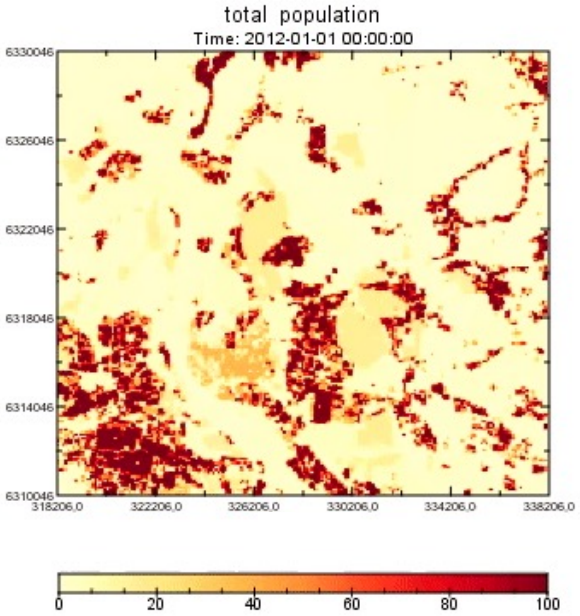
additional data:

- **infiltration factors**
- commuting
- labor statistics
- …



spatial distribution
Copernicus UrbanAtlas & OSM

Number & spatial distribution of persons per hour for each microenvironment



UNDYNE model
UrbaN DYNamic Exposure model
https://github.com/martinottopaul/UNDYNE

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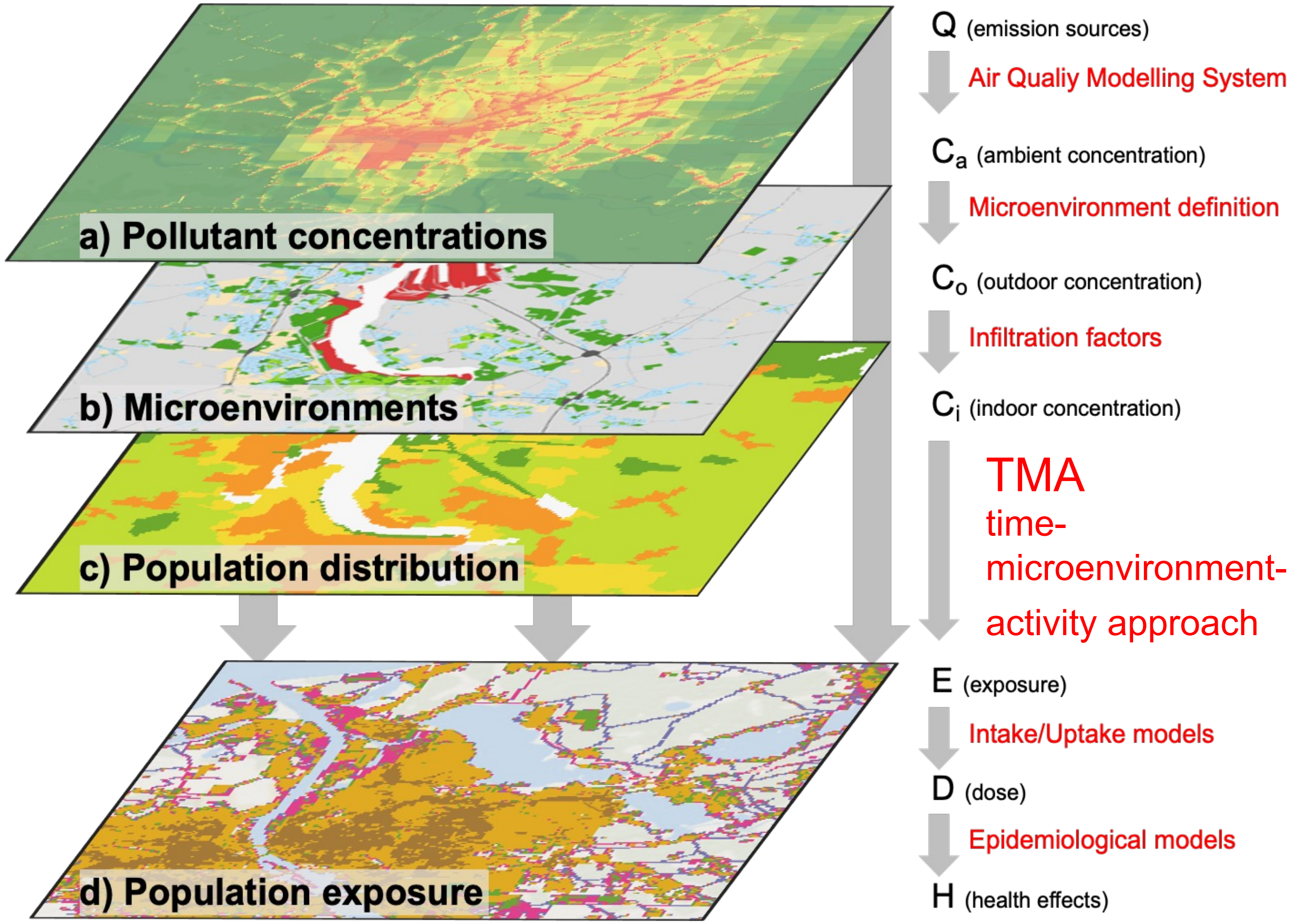
findings from state-of-the-science urban-scale exposure estimates



UNDYNE model (Ramacher, 2021)
UrbaN DYNamic Exposure model
https://github.com/martinottopaul/UNDYNE

applying dynamic population activity
›› higher exposure in urban areas!
›› **3-13% higher NO_2 exposure***
›› **7-21% higher $PM_{2.5}$ exposure***

***compared to static population activity (Ramacher et al. 2019, 2021, 2022)**

Athens (GR), Gdansk-Gdynia (PL), Hamburg (DE), Liège (BE), Marseille (FR), Riga (LV), Rostock (DE)

~~open issues:~~

1. **~~fixed monitoring sites~~**
2. **~~static populations~~**
3. **~~indoor air quality levels~~**

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3. approaching challenges at the regional scale

can we up-scale the urban approach?

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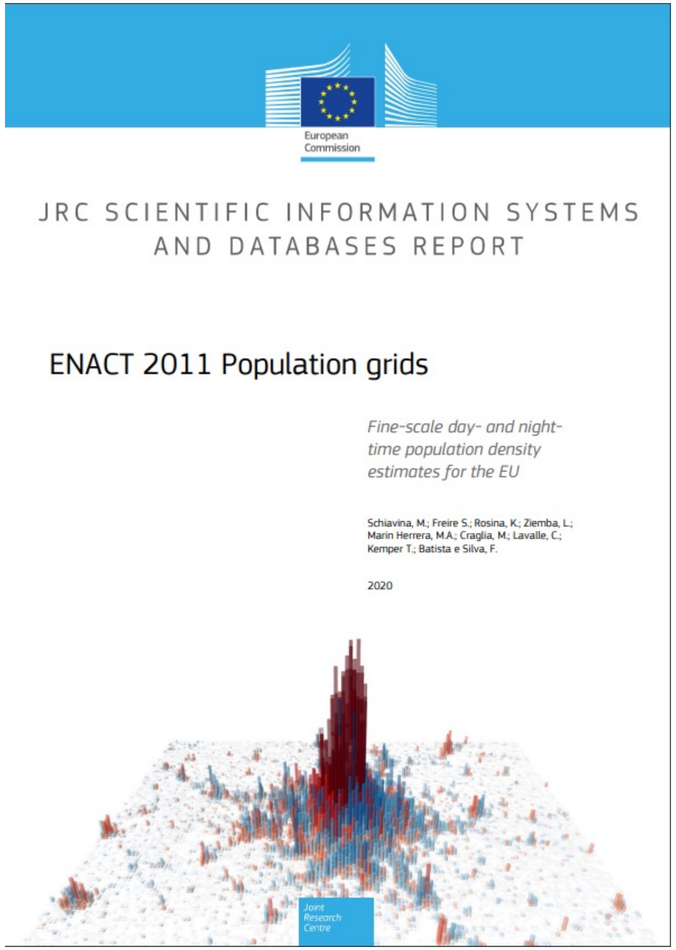
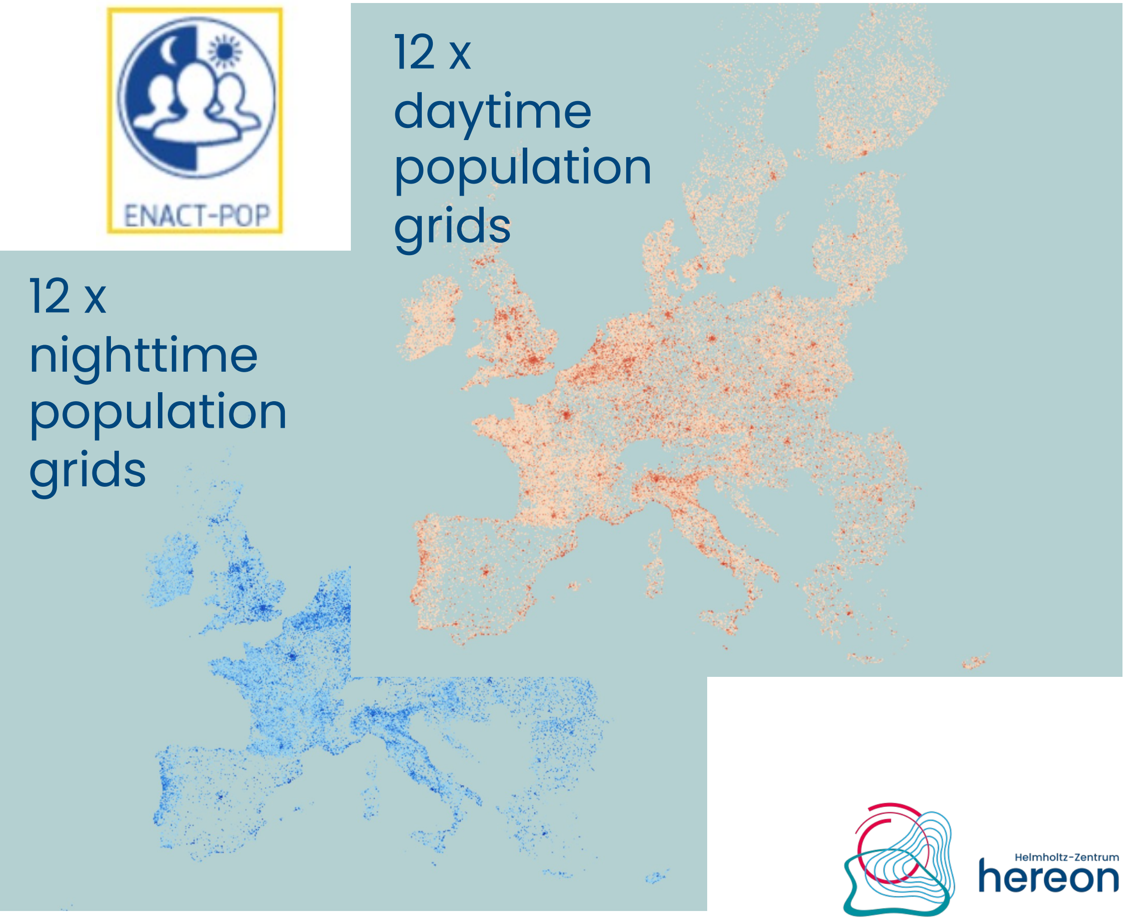
ENACT day/night time populations (Schiavina et al. 2020, …)

The ENACT grids are a set of 24 consistent and multi-temporal population density grids for the European Union that take **into account major daily and monthly population variations!**





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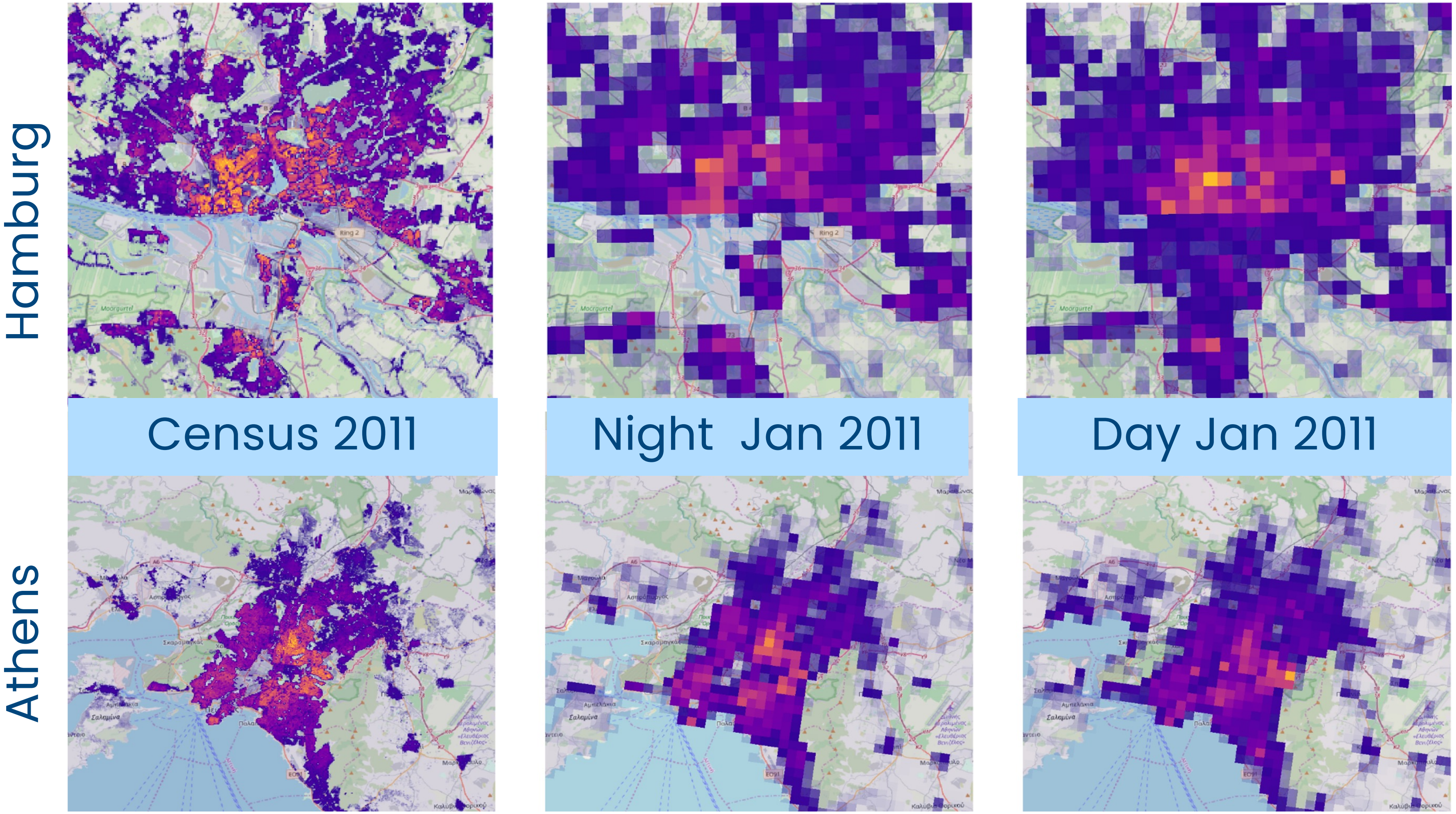
impact on urban exposure estimates



+6% NO_2
+9% $PM_{2.5}$

change in exposure due to day/night time pop. grids

+3% NO_2
+4% $PM_{2.5}$

https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/enact-2011-population-grids

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high-resolution mapping of CAMS AQ data

GAUSS
GENERATING ADVANCED USAGE OF EARTH OBSERVATION FOR SMART STATISTICS

https://eo4smartstats.com/

Rationale: Utilize a variety of EO platforms (CAMS Regional Ensemble Reanalysis, in-situ low cost $PM_{2.5}$ sensors, columnar NO_2 from Sentinel-5p) on top of the current regulatory AQ network to produce reports of the Air Quality Directive at an increased spatial resolution.

1x1 km² air quality data

high-resolution mapping of CAMS AQ data

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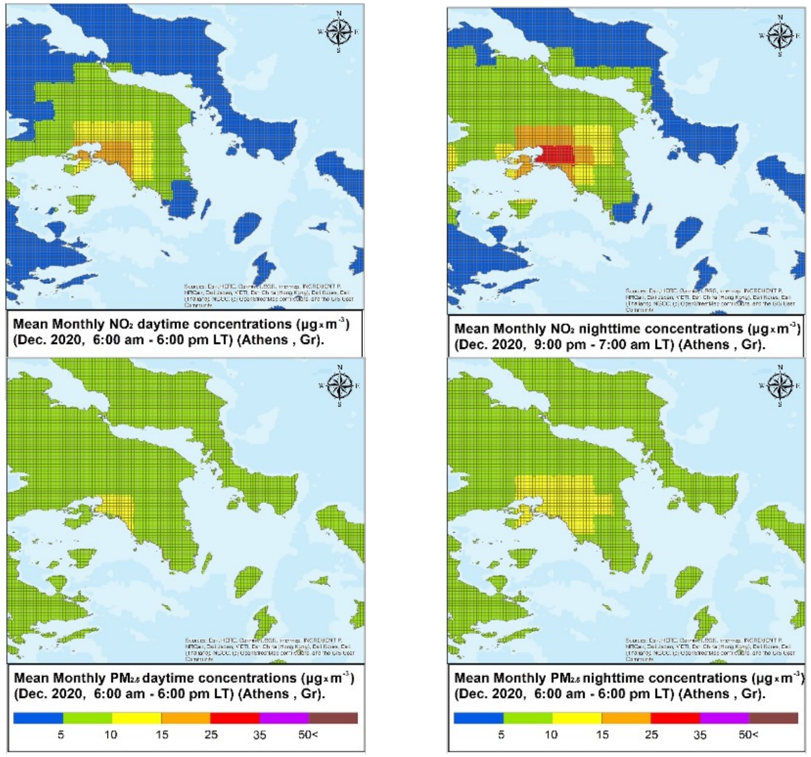
https://eo4smartstats.com/

Copernicus/CAMS European air quality reanalysis ensemble data (aprox. 10kmx10km)

- **regrid to the GHSL (1km x 1km) grid**
- **offline assimilation of in situ AQ data, low cost and regulatory (in progress)**
- **Use S5P NO2 retrievals to derive surface information for episodic events (in progress)**
- **Provide an equivalent CAMS product (1km x 1km)“corrected” by in situ and remote sensing measurements for creating IPR reports (final output)**

daytime, nighttime & monthly averaged NO_2, $PM_{2.5}$ etc. in 1x1km^2

1x1 km^2 air quality data for Greece Dec2020



preliminary results

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(very) preliminary (first) results of ENACT population grids with 1x1 km² AQ data for Greece

<u>**Changes in absolute exposure of all population**</u>
(based on 1 monthly mean value for Dec. 2020)

NO_2 daytime mean for Dec. 2020 = **+0.5%**
NO_2 nighttime mean for Dec. 2020 = **+1%**

$PM_{2.5}$ daytime mean for Dec. 2020 = **+1.5%**
$PM_{2.5}$ nighttime mean for Dec. 2020 = **+2.5%**

small indication for higher exposure estimates when applying ENACT population grids

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3. approaching challenges at the regional scale

can we up-scale the urban approach?

day/night time population activity available at 1km for Europe
AQ data (soon) available at 1km for Europe

ENACT-POP

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GENERATING ADVANCED USAGE OF EARTH OBSERVATION FOR SMART STATISTICS

solid starting point for development of dynamic regional exposure assessments

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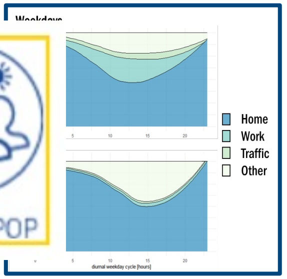
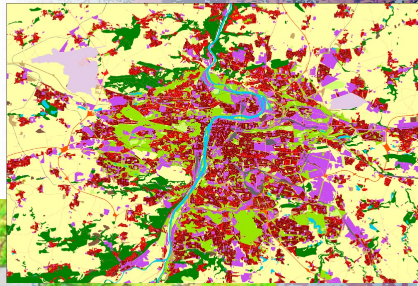
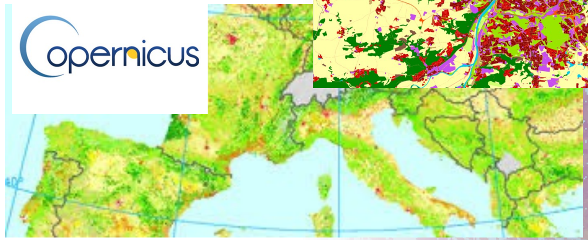
… ongoing work on dynamic exposure estimates at the regional-scale

- ENACT profiles to adjust daily activity patterns for Europe
- Copernicus data (CORINE, UrbanAtlas) for spatial definition of microenvironments
  - allows for spatial/temporal distribution at regional scale
  - allows for consideration of O/I infiltration

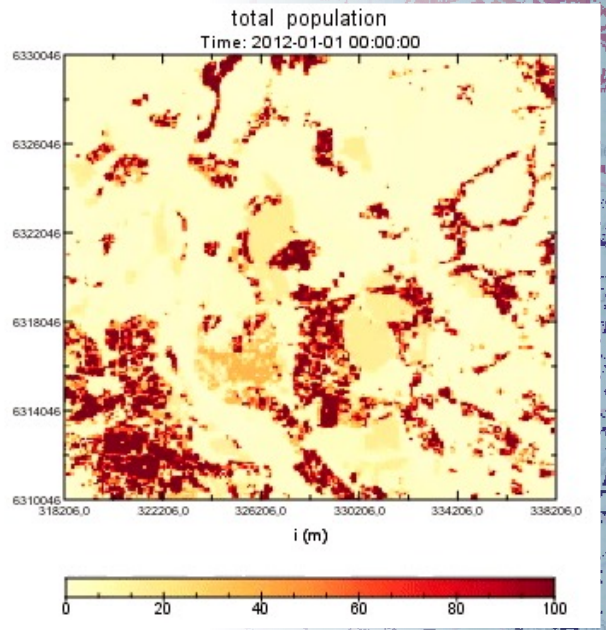






will tackle all … **challenges for representative exposure estimates in 1982** (Ott 1982)

1. **fixed monitoring sites**
2. **static populations**
3. **indoor air quality levels**



in a nutshell

- since the 80s challenges for reliable exposure estimates are known

- today in established methods for regulatory purposes:
  - methods to derive air pollutant concentrations have improved
  - population activity & indoor air pollution <u>are open problems</u>

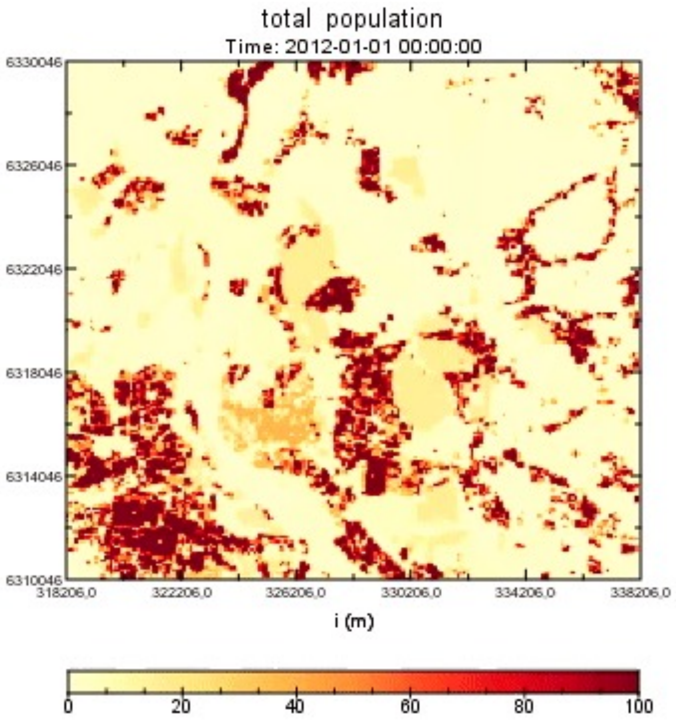
- urban-scale studies overcoming challenges show <u>3-13% higher NO_2</u> and 7-21% higher $PM_{2.5}$ exposure estimates in EU cities

- day/night time populations (ENACT) combined with 1x1 km^2 AQ data are a starting point for dynamic regional-scale exposure estimates
  - small indication for underestimation of exposure estimates on regional-scale (preliminary results)

<u>**New challenges:**</u>
- methods to derive health effects
- indoor air pollution (sources)
- ...

thank you for your attention!

https://www.researchgate.net/profile/Martin-Ramacher



www.hereon.de

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Annex

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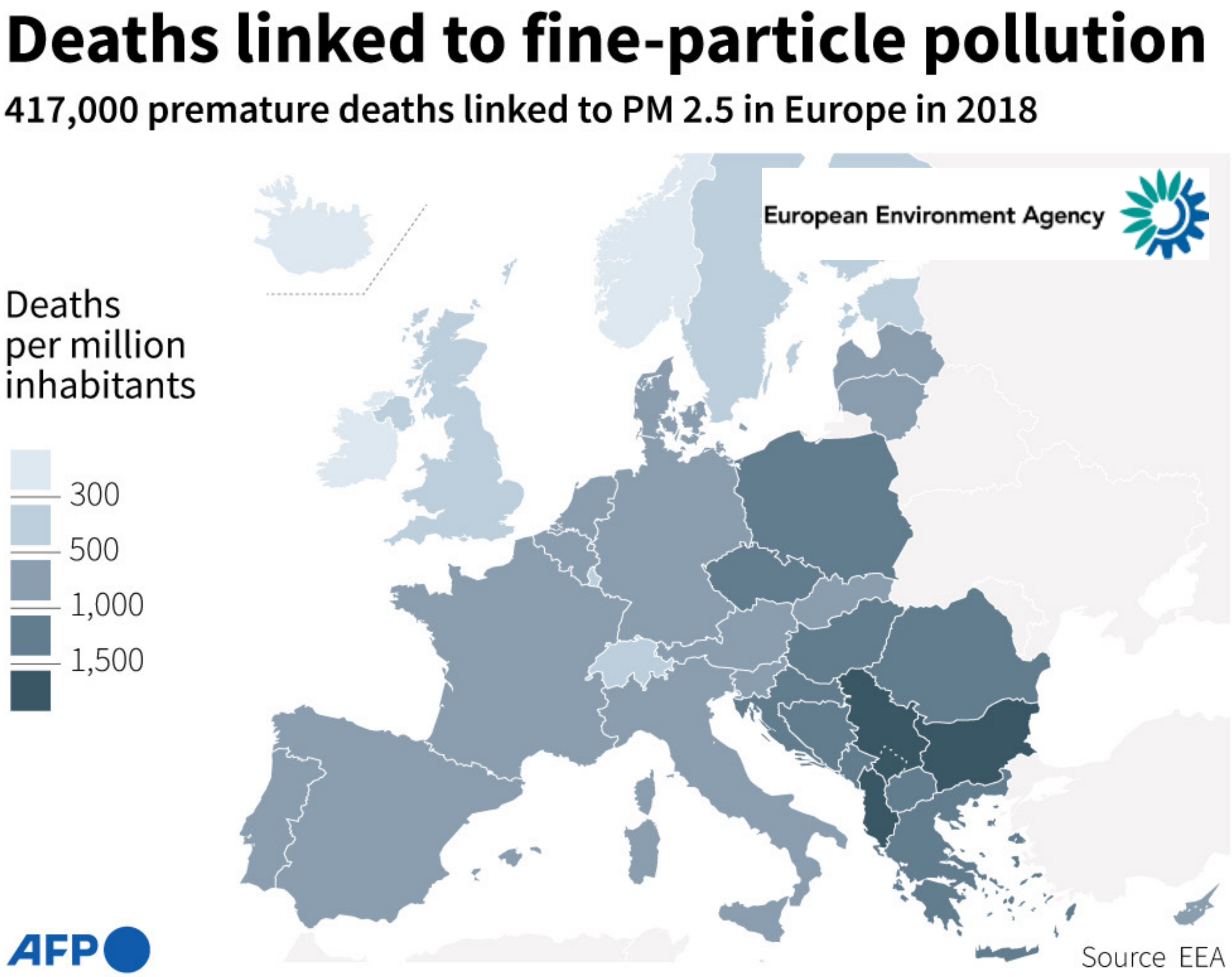
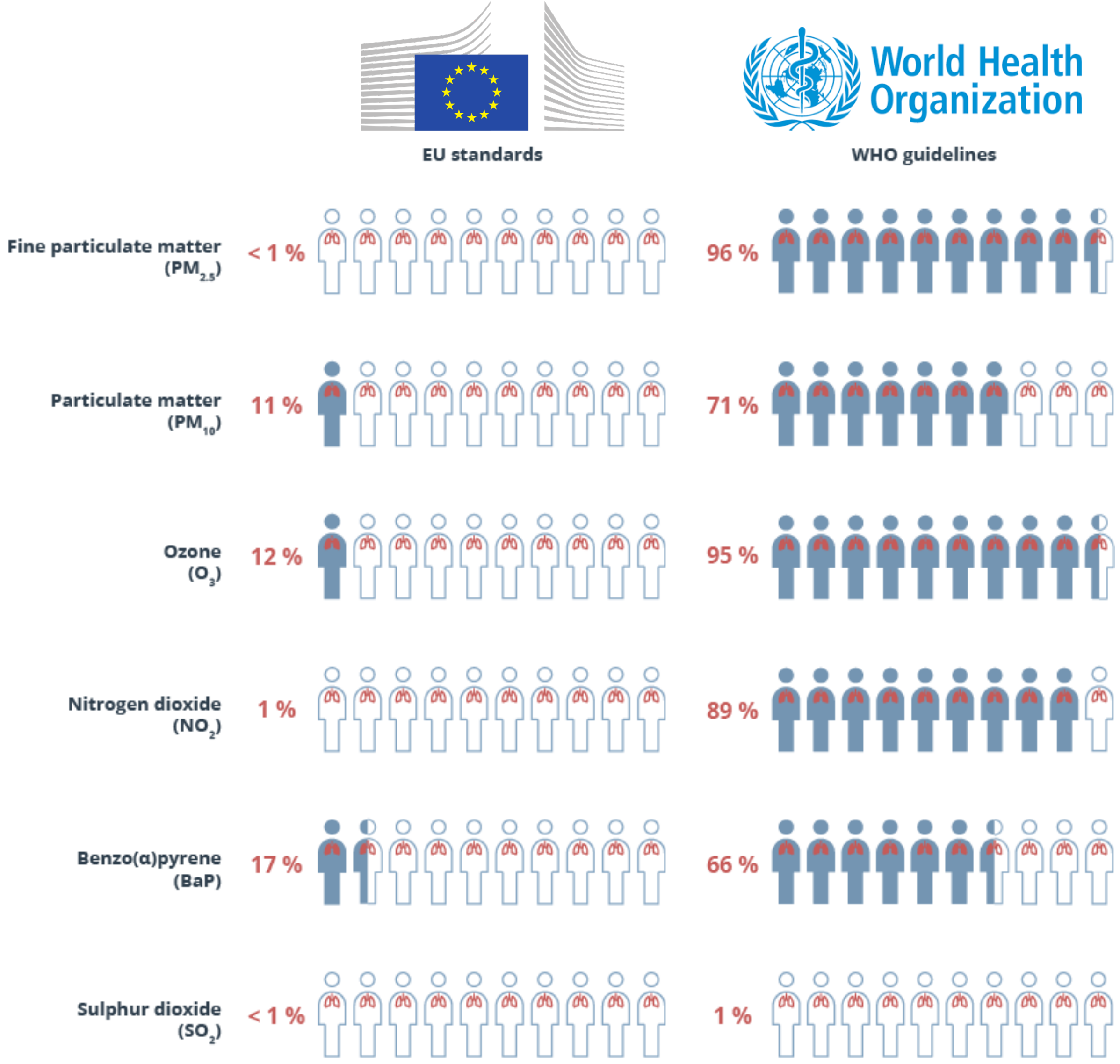
EEA method for regional exposure estimates



EEA urban exposure estimates (EEA2020)

European Environment Agency



Share of the EU urban population exposed to air pollutant concentrations above EU standards and WHO guidelines in 2020

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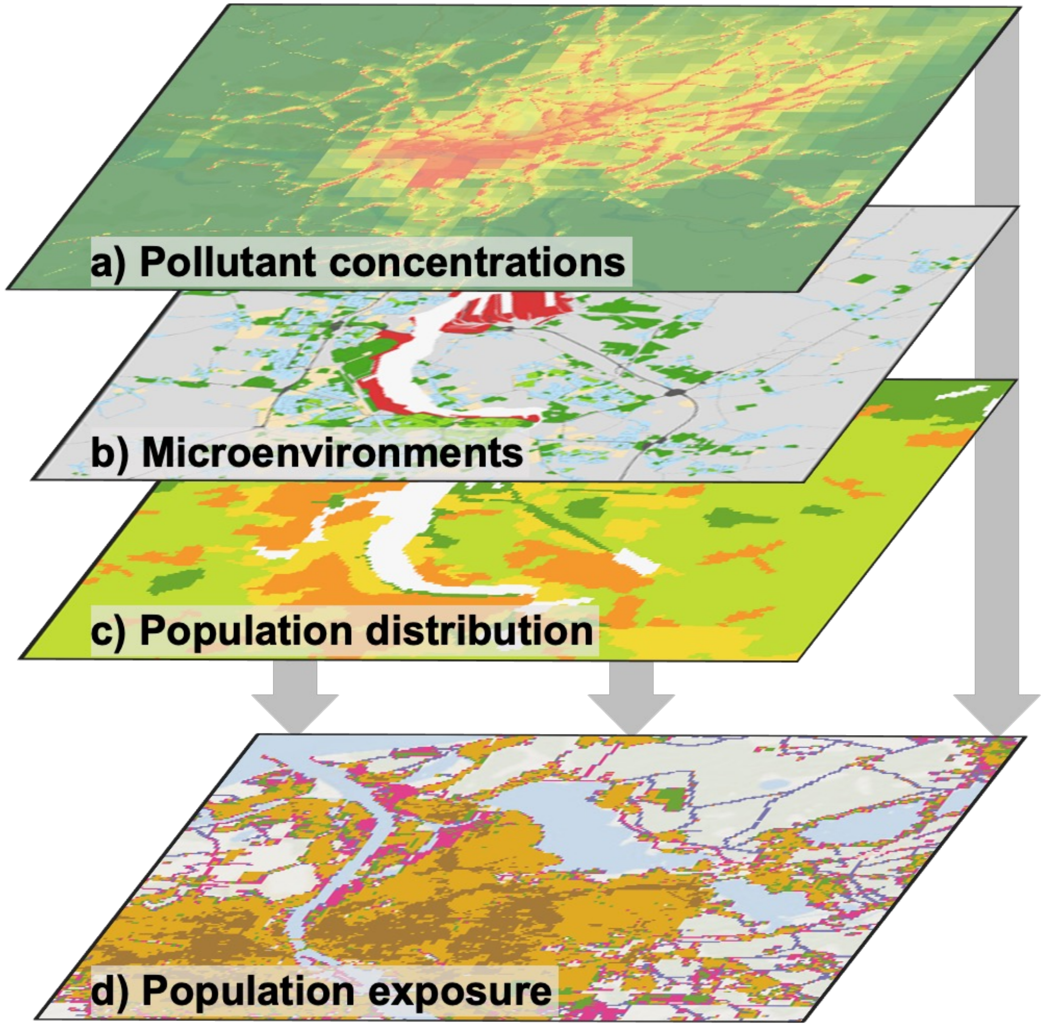
Source: https://www.eea.europa.eu/ims/exceedance-of-air-quality-standards

Urban dynamic exposure estimates (UNDYNE) Ramacher et al. 2019



Q (emission sources)
Air Qualiy Modelling System
C_a (ambient concentration)
Microenvironment definition
C_o (outdoor concentration)
Infiltration factors
C_i (indoor concentration)
TMA
time-microenvironment-activity approach
E (exposure)
Intake/Uptake models
D (dose)
Epidemiological models
H (health effects)

$$E_i = C\, t_i$$

E_i = time-weighted integrated exposure for receptor i
t_i = time that receptor i spends in the polluted environment

>> m >> spatially mapped with ***Copernicus UrbanAtlas***

>> F_j >> specific by season & microvenvironment

>> $t_{i,j}$ >> microenvironment specific temporal distribution with ***diurnal activity profiles for Europe (weekday & weekend)***

$$E_i = \sum_{j=1}^{m} F_j C_{i,jo}\, t_{i,j}$$

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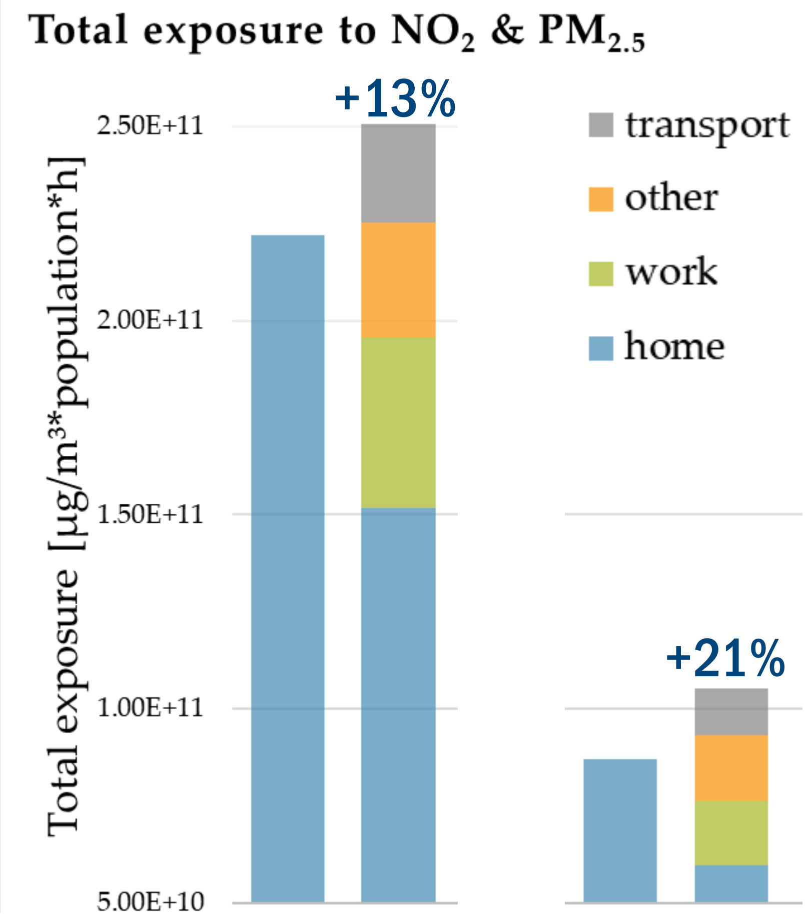
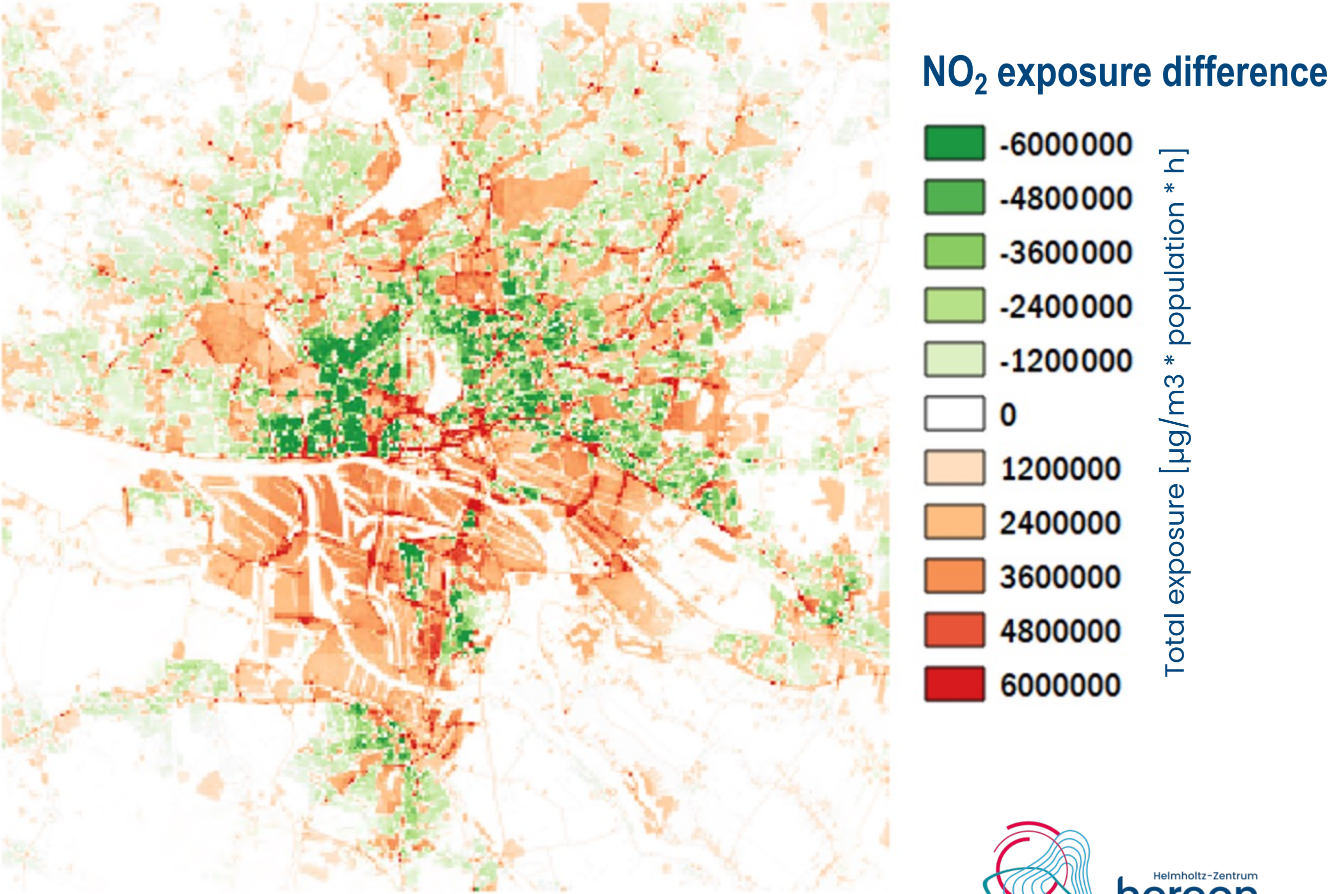
Static populations lead to underestimation of exposure estimates at the urban-scale

Hamburg 2016 (DE)



Hamburg 2016 (DE)

dynamic approach – static approach



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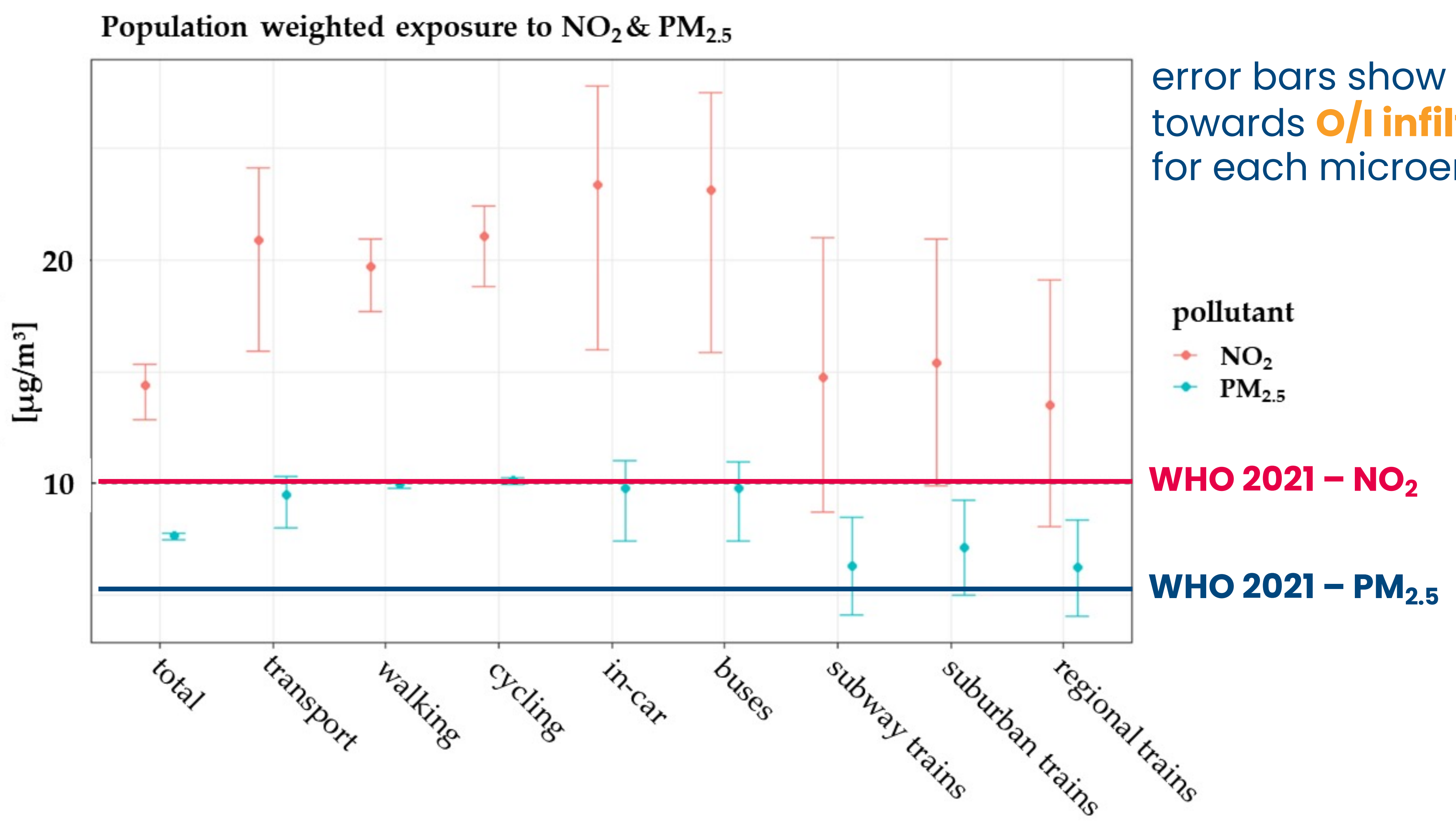
static vs. dynamic populations & impact of infiltration factors



error bars show sensitivity towards **O/I infiltration factors** for each microenvironment

Ramacher et al. 2020, **https://doi.org/10.3390/ijerph17062099**

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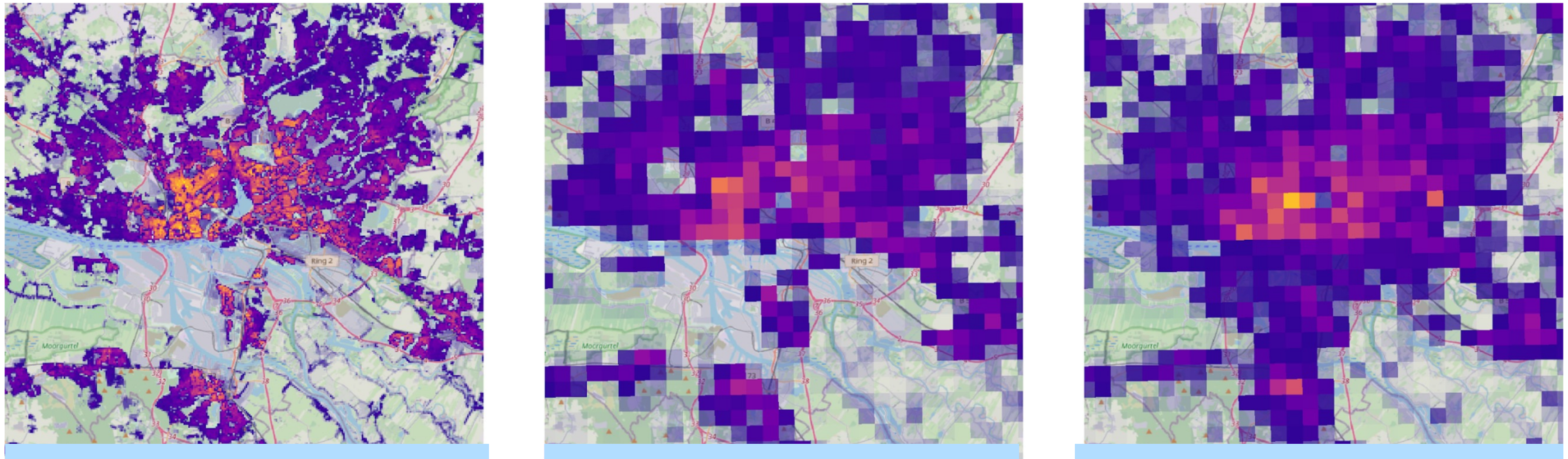
ENACT day/night time populations (Schiavina et al. 2020)

day/night time population grids

Hamburg



Census 2011 | Night Jan 2011 | Day Jan 2011

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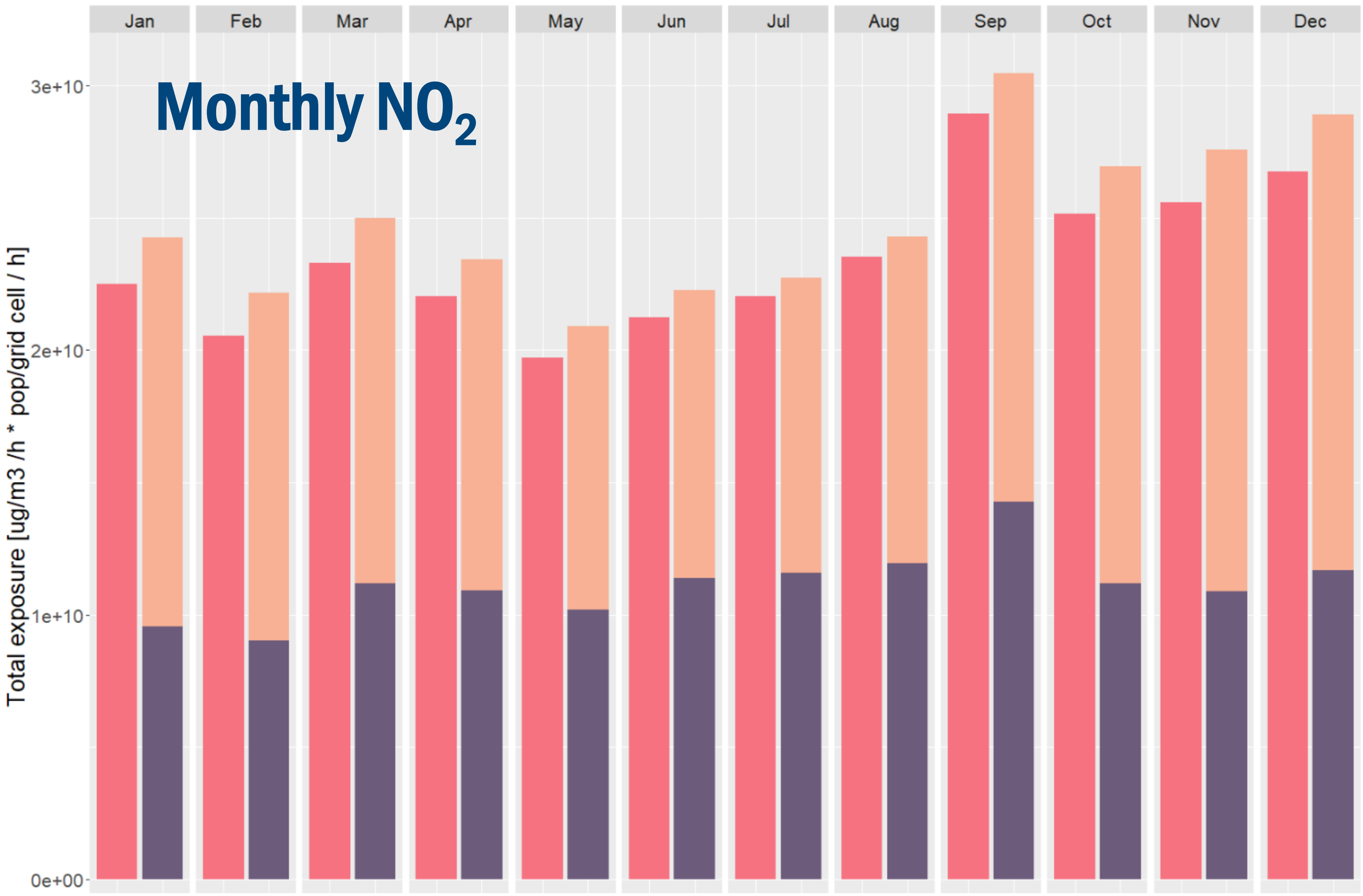
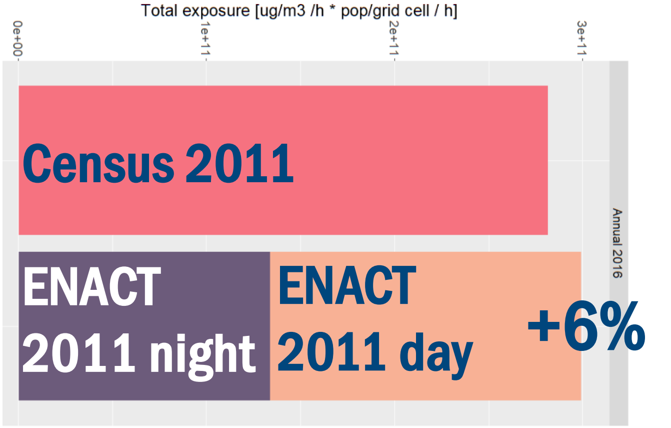
IMPACT OF MONTHLY DAY/NIGHT TIME POPULATION ON TOTAL STATIC EXPOSURE ESTIMATES – HAMBURG

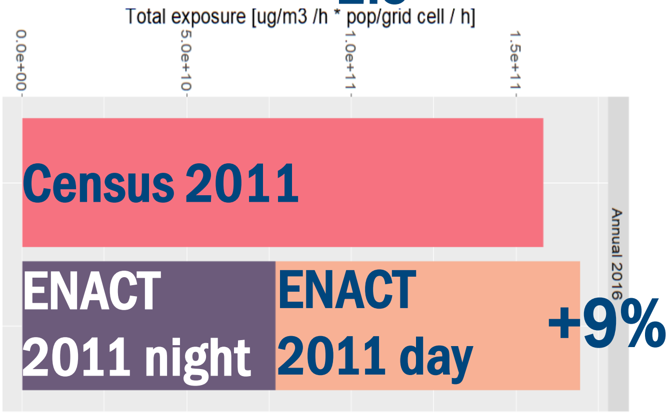
Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research



Annual NO_2



Annual $PM_{2.5}$



(very) preliminary (first) results of ENACT population grids with 1x1 km² AQ data for Greece

Changes in absolute exposure of all population
(based on 1 monthly mean value for Dec. 2020)

NO_2 daytime mean for Dec. 2020 = **+0.5%**
NO_2 nighttime mean for Dec. 2020 = **+1%**

$PM_{2.5}$ daytime mean for Dec. 2020 = **+1.5%**
$PM_{2.5}$ nighttime mean for Dec. 2020 = **+2.5%**

small indication for higher exposure estimates when applying ENACT population grids

Population exposed to different limit values

[% of GR pop.]	GHSL-Pop	ENACT day	ENACT night
NO_2 EU annual limit value (40 µg/m³)	0%	0%	0%
NO_2 WHO daily AQG value (25 µg/m³)	2.4%	0%	2.6%
NO_2 WHO annual AQG (10 µg/m³)	42.2%	41.8%	43.2%
$PM_{2.5}$ EU annual limit value (25 µg/m³)	0%	0%	0%
$PM_{2.5}$ WHO daily AQG value (15 µg/m³)	2.4%	0%	2.6%
$PM_{2.5}$ WHO annual AQG (5 µg/m³)	4.8%	0.2%	5.4%

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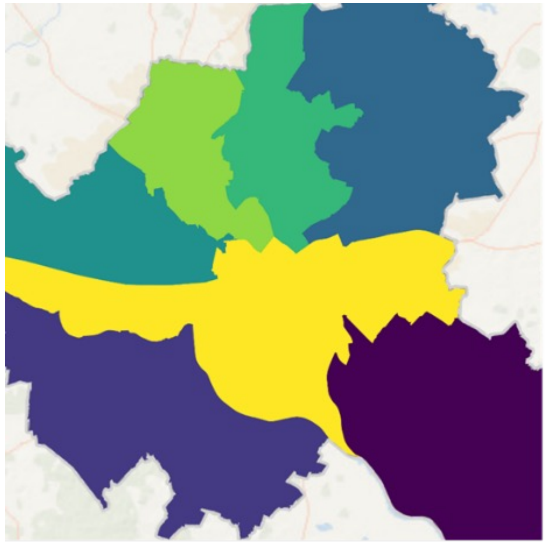
SMURBS ERA-PLANET

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

UN SDG INDICATOR 11.6.2

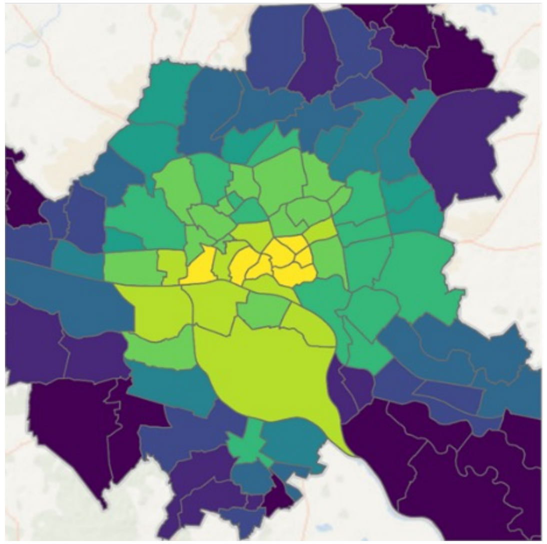
...contribution to urban-specific sustainable development goal inidicator

Scale	SDG 11.6.2 approach	Description / underlying assumptions & data
Country-scale	SMURBS city (FUA) algorithm	Country-level calculation of population-weighted concentration based on one country's different cities (**inter-urban**) • Average PM2.5 conc.: CAMS • Urban area definition: CLMS FUA / GHSL urban-centre • Population data: CLMS FUA / GHSL GHS-Pop
Urban-scale	SMURBS intra-urban algorithm	City-level calculation of population-weighted concentration based on one city's different areas (**intra-urban**). • Average PM2.5 conc.: CityChem • Urban area definition: GHSL urban-centre / Municipality • Population data: GHSL GHS-Pop / Municipality
Pixel-scale	SMURBS urban-pixel algorithm	Pixel-level calculation of population-weighted concentration based on one city's grid-cell resolution (**pixel-level**). • Average PM2.5 conc.: CityChem • Urban area definition: GHSL urban-centre / Municipality • Population data: GHSL GHS-Pop / Municipality



SDG11.6.2 PM2.5 Hamburg 2012
µg/m³ per district
≤9,101
≤9,342
≤9,648
≤10,544
≤10,710
≤10,954
≤11,831

District mean: 10.425 µg/m³



SDG11.6.2 PM2.5 Hamburg 2012
µg/m³ per neighborhood
≤8,937
≤9,273
≤9,538
≤9,875
≤10,303
≤10,847
≤11,538
≤12,417
≤13,534
≤14,954

Neighborhood mean: 10.802 µg/m³

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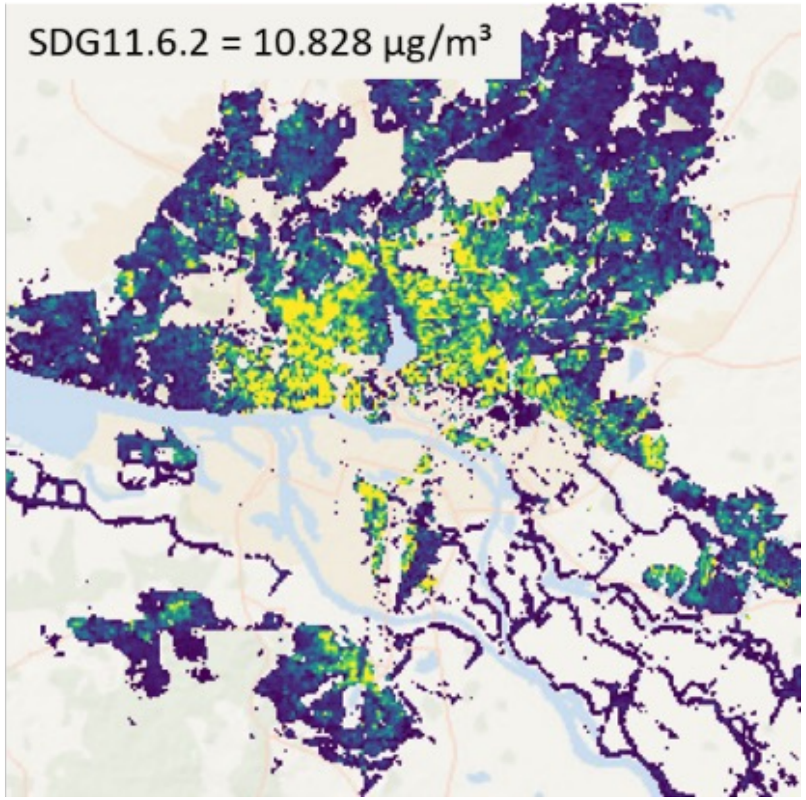

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Table S4-1. Infiltration ratios for $PM_{2.5}$ in different microenvironments from literature

Microenvironment	Min	Mean	Max	Location	Season	Reference
Transport	-	1	-	London	annual	Smith et al. (2016), Singh et al. (2020)
Car	0.2	-	0.9	Hangzhou	winter	Tong et al. (2019)
Car	0.6	0.92	1	Los Angeles	spring	Fujita et al. (2014)
Car	0.3	-	0.98	North Raleigh	summer	Jiao and Frey (2013)
Car	0.43	-	0.99	NA	NA	Liu and Frey (2011)
Bus	-	0.91	-	Nanjing	annual	Shen and Gao (2019)
Subway		0.37		Beijing	spring	Jia et al. (2018)
Subway	0.56	-	0.66	Hongkong	winter	Li et al. (2018)
Subway	-	0.94	-	Taipei	NA	Shen and Gao (2019)
Subway	-	0.81	-	Seoul	NA	Shen and Gao (2019)
Subway	-	0.82	-	Los Angeles	NA	Shen and Gao (2019)
Subway	-	0.18	-	Naples	NA	Shen and Gao (2019)
Subway	-	0.79	-	Singapore	NA	Shen and Gao (2019)
Buildings	0.37	0.57	0.7	Helsinki	annual	Soares et al. (2014)
Residential	0.35	0.56	0.86	London	annual	Smith et al. (2016)
Residential	0.42	0.59	0.76	Europe	annual	Hänninen et al. (2004)
Work	0.23	0.47	0.71	Europe	annual	Hänninen et al. (2004)
Residential	-	0.7	-	Athens. Greece	Winter	Hänninen et al. 2011
Residential	-	0.63	-	Basle. Switzerland	Winter	Hänninen et al. 2011
Residential	-	0.59	-	Helsinki. Finland	Winter	Hänninen et al. 2011
Residential	-	0.61	-	Prague. Czech	Summer	Hänninen et al. 2011
Residential	-	0.53	-	Florence	Winter	Hänninen et al. 2011
Residential	-	0.7	-	Riverside. USA	-	Ozkaynak et al. (1993)*
Residential	-	0.56	-	Riverside. USA	-	Ozkaynak et al. (1993)*
Residential	-	0.62	-	Chongju. Korea	-	Lee et al. (1997)*
Residential	-	0.66	-	Birmingham. USA	-	Lachenmyer and Hidy (2000)*
Residential	-	0.35	-	Baltimore. USA	-	Landis et al. (2001)*
Residential	-	0.7	-	Boston, USA	-	Long et al. (2001)*

conclusions I

established exposure estimates are still biased due to well-known (since the 80s) problems/challenges

- methods to derive air pollutant concentrations have improved

- but there is a lot of evidence that exposure estimates in established approaches on regional and global scales are underestimated due to open challenges:

- population activity
- indoor air pollution

Urban-scale studies with state-of-the-science methods can take into account population activity and outdoor-indoor infiltration and show 3-13% higher NO_2 exposure and 7-21% higher $PM_{2.5}$ exposure

conclusions II

Up-scaling of urban-scale approaches to the regional scale becomes more and more realistic due to

- **ENACT day/night time population datasets**
- **1x1 km2 AQ data (e.g. derived in GAUSS project)**

Preliminary results with these datasets show small indication of underestimated exposure estimates.

Methods/data/development in progress can finally tackle all

challenges for representative exposure estimates in 1982 (Ott 1982)

1. **fixed monitoring sites**
2. **static populations**
3. **indoor air quality levels**