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Impacts of nature-based solutions on the urban atmospheric environment: a case study for Eindhoven, The Netherlands

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ABSTRACT

Nature-based solutions (NBS) can provide answers to the challenges that urban areas are currently facing, associated with urban densification and climate change. The benefits of NBS are recognized, and include improved quality of life, human health and air quality, amongst others. This study aims to assess how NBS can contribute to temperature attenuation and air quality improvement in the city of Eindhoven (The Netherlands), through the application of the state-of-the-art WRF-Chem online air quality modelling system. The city is thereby characterized in terms of air quality related data, such as climatology, atmospheric emissions and air pollutant concentrations. From this assessment, different NBS were selected according to city aspirations. The WRF-Chem model was applied for baseline and NBS scenarios over the study area with a spatial resolution of 1 km x 1 km and an hourly time resolution for August 2013. The baseline scenario (without NBS) was validated by comparing the model results with monitored data retrieved from the European air quality monitoring database, showing an adequate model performance. The scenario simulations (with NBS) were performed by changing the land use in the model setup, and results were compared with the baseline scenario. Reductions in hourly temperature values of approximately 1 °C and reductions in pollutant concentrations, namely nitrogen dioxide (NO_2), of approximately 10% were estimated after the application of the NBS in the Eindhoven study area. These results are particularly important to support public planners and decision-makers in understanding the effects and importance of NBS in their planning for more sustainable and resilient cities.

1. Introduction

The ever-growing global urban population and its environmental consequences are one of the major challenges of our time. Increased urbanization is resulting in a rapid expansion of impermeable surfaces and substantial loss of green spaces, leading to an increase in air temperature (urban heating island (UHI)) as well as carbon dioxide (CO_2) and air pollutant emissions, and a decrease in the amount of stored carbon (Bhatta, 2010; Liao et al., 2015). Air quality and climate change remains a major global concern in urban areas, threatening ecosystems and mankind. The expected higher temperatures, due to urbanization and climate change, could promote an increase in air pollution due to the increase in ozone formation and energy demands for cooling of buildings (Argüeso et al., 2014; Carvalho et al., 2010).

One of the answers to these problems are Nature-based solutions (NBS). The European Commission (EC, 2015) defines NBS as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions". Some examples of NBS are green parks, stormwater ponds, green roofs and walls, and permeable pavements. NBS have just recently started to be applied by policymakers and their effects include improving air quality and reducing local temperature (Borrego et al., 2012; Gunawardena et al., 2017; Rafael et al., 2016; Tallis et al., 2015), improving mental and physical health and well-being (Keniger et al., 2013), leading to urban compaction and increase in real-estate prices (Augusto et al., 2020; Roebeling et al., 2017; Saraiva et al., 2017) and enhancing the resilience of cities to climate change – serving as proactive adaptation options for municipalities (Borrego et al., 2017).

The NBS effects on the atmospheric environment have been shown in

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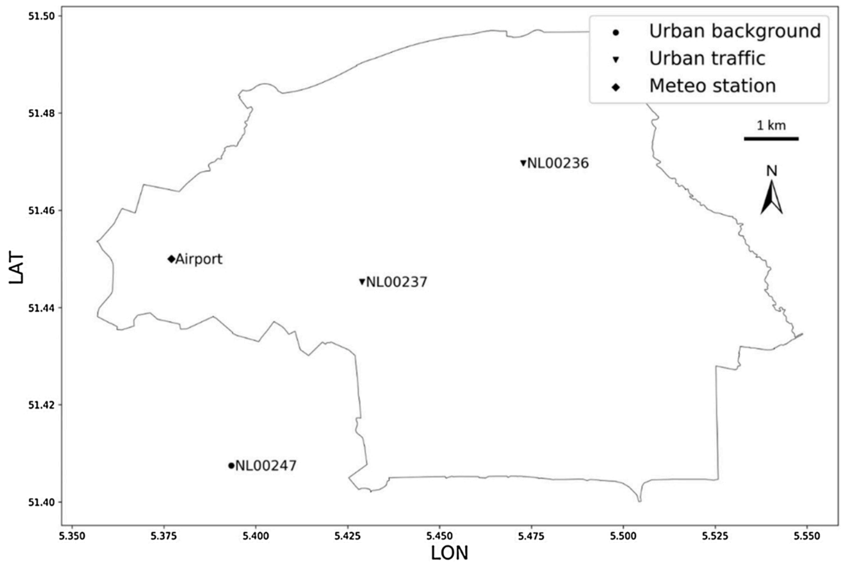

Fig. 1. Location of the air quality and meteorological monitoring stations in Eindhoven.

field campaigns (Setälä et al., 2013), wind-tunnel experiments (Rodrigues et al., 2018) and through numerical modelling (Augusto et al., 2020). Modelling systems are one of the best tools for quantifying the influences of NBS on urban climate and air quality, allowing the user to assess multiple impacts of NBS scenarios before implementation. They also provide results for a given modelling domain rather than a single point, helping to see a problem more broadly.

Models can be applied at different spatial scales, for instance, mesoscale chemical transport models (CTM) are currently being used to assess the impact of green infrastructures in urban areas (Miranda et al., 2017). The spatial resolution of mesoscale models allow the study of an entire urban region, while the higher resolution of computational fluid dynamics (CFD) models requires large computational capacity and only allows the study of a small area. Applying urban-mesoscale models with high resolution could be a way to shorten this gap, while still getting good quality results (Martilli, 2007; Mirzaei, 2015)

The implementation of NBS needs to be context-adapted, meaning that the same solution can have different effects depending on the case-study characteristics, like its land cover, population density and microclimate. Therefore, some studies have found that NBS can have negative effects on air quality (Arghavani et al., 2019; Fallmann et al., 2016; Rafael et al., 2019), while other studies found NBS to have a positive effect (Borrego et al., 2012; Tallis et al., 2015). However, there are still few modelling studies focusing on air quality and the majority of them are performed at microscale rather than assessing the entire urban area. Nonetheless, all studies highlight the need for further work on

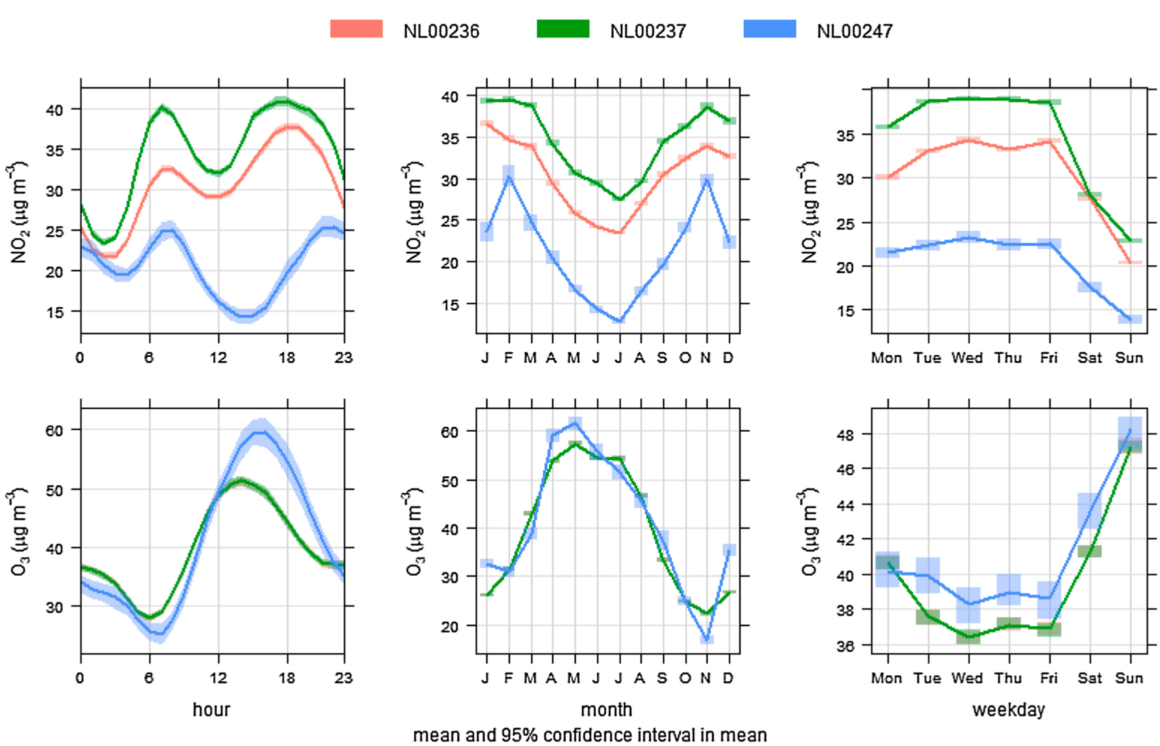

Fig. 2. Daily (left), monthly (center) and weekly (right) average profiles of NO_2 and O_3 concentrations observed at the three monitoring stations within Eindhoven region between 2008 and 2017 (based on: EEA, 2019a).

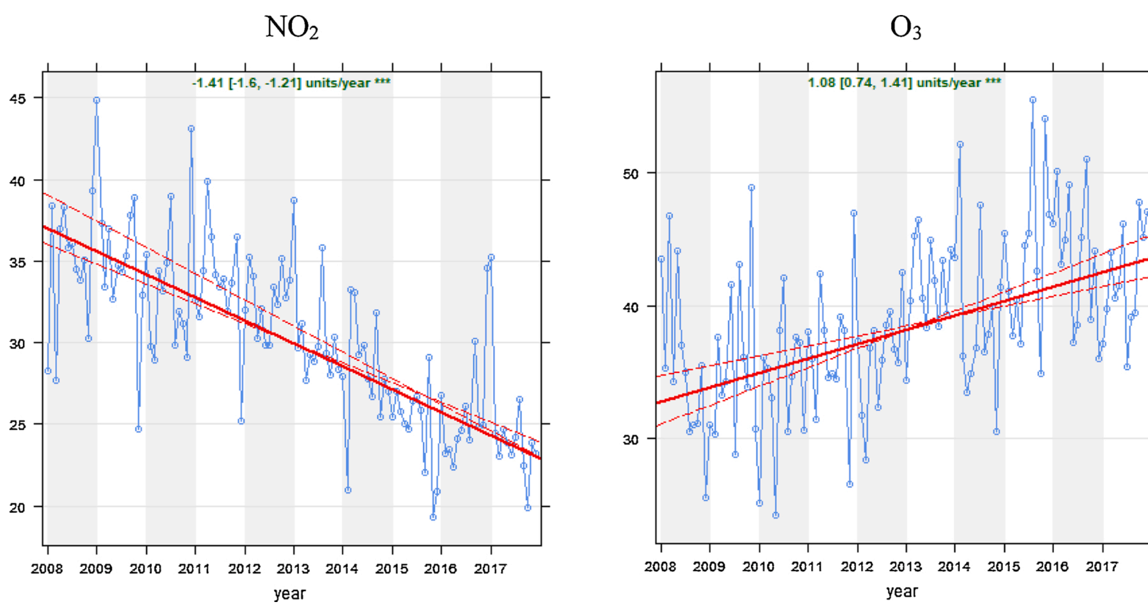

Fig. 3. Trends in NO_2 and O_3 concentrations at an urban traffic monitoring station within Eindhoven region, considering monthly values between 2008 and 2017. The solid line shows the trend estimate, and the dashed lines show the 95% confidence intervals for the trend based on resampling methods. The overall trend and the 95% confidence intervals in the slope are shown at the top of each plot. The *** are shown when the trend is significant to the 0.001 level. (Based on: EEA, 2019a).

modelling the NBS impacts on the urban atmospheric environment.

This paper aims to better understand the effect of NBS on temperature and air quality in an urban setting, contributing to the planning process of NBS undertaken by public planners and stakeholders. Three main variables were analysed: temperature (T), nitrogen dioxide (NO_2) and ozone (O_3). The online air quality modelling system WRF-Chem coupled with the Single-Layer Urban Canopy Model (SLUCM) was applied, with a spatial resolution of 1 km^2, to the city of Eindhoven, located in the southeast of The Netherlands, for a Summer month – August 2013. Although NBS are part of the planning strategies of the local authorities in Eindhoven, there are no scientific reports regarding their implementation and impacts on air quality.

The present work is organized as follows: Section 2 provides a short characterization of the city; Section 3 describes the air quality modelling system setup and its evaluation; NBS scenarios and modelling results are presented in Section 4; conclusions are drawn in Section 5.

2. Case study characterization

Eindhoven is the fifth-largest city in The Netherlands (89 km^2) and an example of economic and demographic growth (Westerink et al., 2017) with a population density of 2639 hab/km^2 (CBS, 2019). The city centre is composed of a mixture of residential and commercial buildings, mainly low-rise and a few high-rise buildings (Blocken et al., 2016). The climate is characterized by a temperate oceanic climate influenced by the North Sea and the Atlantic Ocean, with cool summers, moderate winters and typically high humidity. The average annual temperature is 9.4 °C and the yearly average rainfall is 776 mm (KNMI, 2019).

The air quality in the Netherlands has been improving, but there are still exceedances to the air quality limits established by the Air Quality Framework Directive 2008/50/CE, namely for nitrogen dioxide (NO_2), as road transport is one of the major emission sources in The Netherlands (EEA, 2019a, 2019b). The European Environmental Agency (EEA, 2019c) reported that, in 2016, the annual mean NO_2 exceedances in The Netherlands caused 1500 premature deaths and 14700 Years of Life Lost.

Taking a closer look at Eindhoven, 10 years of air quality data (2008-2017; EEA, 2019a) were analyzed for the urban background (Veldhoven-Europalaan; NL00247) and the two urban traffic (Eindhoven-Genovevalaan; NL00236 and Eindhoven-Noordbrabantlaan; NL00237) air quality monitoring stations in the city (Fig. 1). The predominant winds in Eindhoven come from the South-West, meaning that the background station is upwind of the main emission sources. The ozone target value for the protection of human health (120 μg/m^3; maximum daily eight-hour mean), established by the Air Quality Framework Directive, is exceeded 10 to 15 times every year, making O_3 one of the most problematic pollutants in the city. As NO_2 is one of the precursors to O_3, the pair was assessed (the hourly limit-value for NO_2 is 200 μg/m^3). Fig. 2 shows the daily, monthly and weekly profiles for NO_2 and O_3 for Eindhoven air quality stations; note that the NL00236 station does not monitor O_3 and the daily profiles are presented in local time.

NO_2 daily patterns exhibit a clear urban influence linked to the traffic diurnal profile, with peaks in the morning and late afternoon and a decrease of concentrations during the weekend. The increase in concentrations during the winter could be explained by atmospheric stability and an increase in emissions linked to heating processes. This pattern is more notorious in the background station (blue line), which indicates that this increase is not due to more traffic emissions.

O_3 patterns have a negative correlation with NO_2, explained by the photochemical reactions involving these compounds. Throughout the day, the increase in solar radiation and the presence of precursors (volatile organic compounds (VOC) and NO_2) promote ozone formation and concentrations increase. During the night, the accumulation of NO_2 leads to O_3 consumption. A similar pattern is observed during the year with hotter months having higher O_3 concentrations, with longer and higher intensity solar radiation.

The average O_3 concentrations during weekends are higher than during weekdays. This phenomenon is called the "weekend effect" (Pudasainee et al., 2006; Roberts-Semple et al., 2012). The negative correlation with NO_2 suggests that VOC contributed to elevated O_3 concentrations. Lower nitric oxide (NO) levels and VOC emissions during weekend mornings consume less O_3, which accumulates later by photochemical reactions. Weekday/weekend differences in O_3 are intricately related to interactions with its chemical precursors: nitrogen oxides (NOx) and VOC, respectively.

Similar conclusions can be derived from the trend analysis. Fig. 3 displays long-term temporal trends for NO_2 and O_3 concentrations estimated for mean monthly values based on data from the urban traffic monitoring station (NL00237). NO_2 shows a clear tendency for reduction, which could be the cause for the increasing O_3 trend. The reduction

Table 1
Main physical and chemical parametrizations adopted for WRF-Chem simulations.

Processes	Options
Microphysics	Morrison double-moment
Short-wave radiation	RRTMG scheme
Long-wave radiation	RRTMG scheme
Surface layer	MM5 Monin-Obukhov scheme
Land-surface	Unified Noah land-surface model
Urban canopy model	Single-layer, UCM
Boundary-layer	MYNN 2.5 level TKE scheme
Cumulus	Grell 3D ensemble scheme
Photolysis	Fast-J
Gas-phase mechanism	RADM2
Aerosol module	MADE/SORGAM
Aerosol-radiation feedback	Turned on
Aerosol optical properties	Volume approximation

Acronyms: MADE/SORGAM - Modal Aerosol Dynamics Model for Europe /Secondary Organic Aerosol Model; MYNN - Mellor-Yamada-Nakanishi-Niino; RADM2 - Regional Acid Deposition Model, 2nd generation;. RRTMG - Rapid Radiative Transfer Model for General Circulation Models; TKE - Turbulent Kinetic Energy.

in NO_x could promote higher O_3 concentrations during the night, as less O_3 is consumed. However further research is needed to fully explain this behaviour in Eindhoven.

In sum, Eindhoven's air quality is heavily influenced by traffic emissions and probably by heating processes emissions during winter time, and although NO_2 concentrations have been decreasing, this could be leading to an increase in ozone concentrations that are already high in the city.

3. The WRF-Chem modelling system setup

WRF-Chem is a mesoscale "online" model developed by Grell et al. (2005) that integrates the Weather Research and Forecasting (WRF) model with chemistry modules (Chem). The model version 3.6.1, coupled with the single-layer urban canopy model (SLUCM) (Kusaka & Kimura, 2004; Kusaka et al., 2001), was applied for 4 scenarios (baseline and 3 NBS scenarios).

The model was forced by ERA-Interim data from the European Centre for Medium-Range Weather Forecasts (ECMWF) global analysis (Dee et al., 2011), with a horizontal resolution of 1° x 1° and with a 6 -h temporal resolution. The anthropogenic emissions inventory EMEP was used (EMEP/CEIP, 2015) for all domains, after being pre-processed into the format required by the model, using the emissions interface built by Tuccella et al. (2012). Therefore, emissions were spatially disaggregated based on the land cover, and vertical distribution and time profiles by activity sector were applied considering the seasonality and day of week, as well as speciation and aggregation of emissions into WRF-Chem species. The biogenic emissions were provided by the MEGAN model (Guenther et al., 2006) within WRF-Chem. The initial and boundary conditions were taken from the MOZART model (Emmons et al., 2010), and orography and land use from the USGS 33 classes database. The main physical and chemical parametrizations adopted are compiled in Table 1. These options were chosen based on previous model applications (e.g. Kong et al., 2015; Kuik et al., 2016; Silveira, 2020) and adjusted to improve model performance.

Three online-nested domains with an increased resolution at a downscaling ratio of five were used, with D1 the coarser domain of 25 km^2 horizontal resolution (180 × 155 grid nodes) covering Europe and part of the North Atlantic Ocean, D2 with a horizontal resolution of 5 km^2 (96 × 91 grid nodes) covering The Netherlands, Belgium and part for Germany and France, and D3 the innermost domain of 1 km^2 horizontal resolution covering an area of 45 km x 35 km containing the Eindhoven city (Fig. 4). Each domain was resolved with 30 vertical levels extending up to 50 hPa, being the lowest level at approximately 28 m above the surface. The feedback from nest to its parent domain was activated through 2-way nesting.

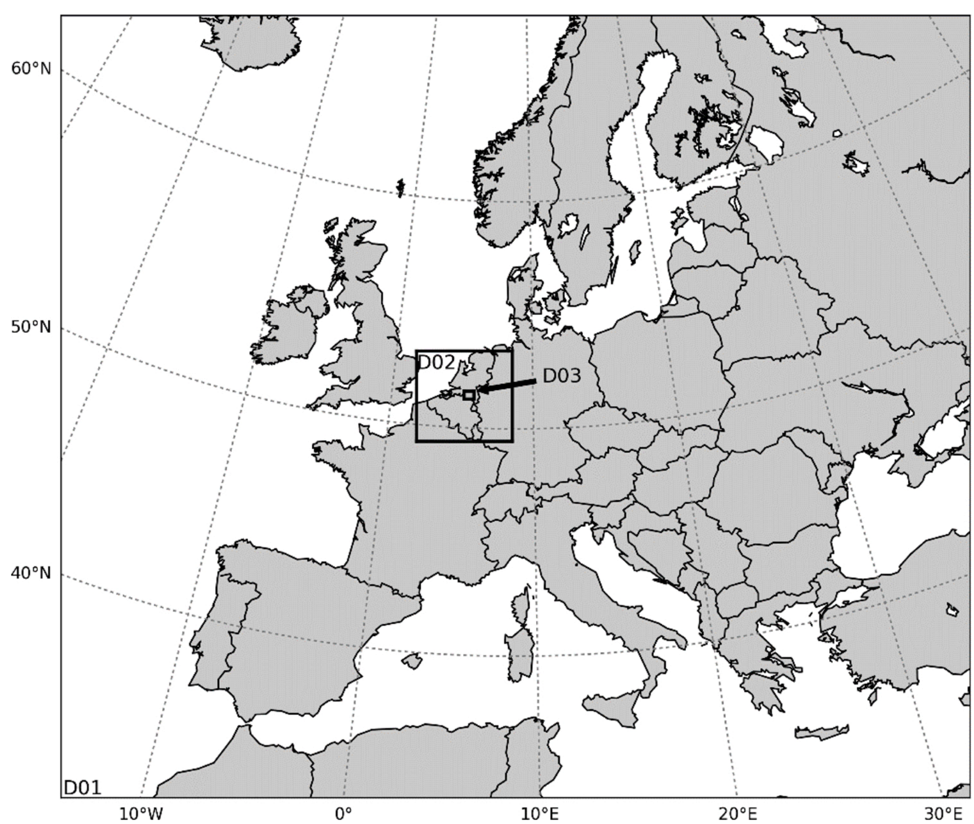

Fig. 4. Representation of the simulation domains used in the WRF-Chem air quality modelling system.

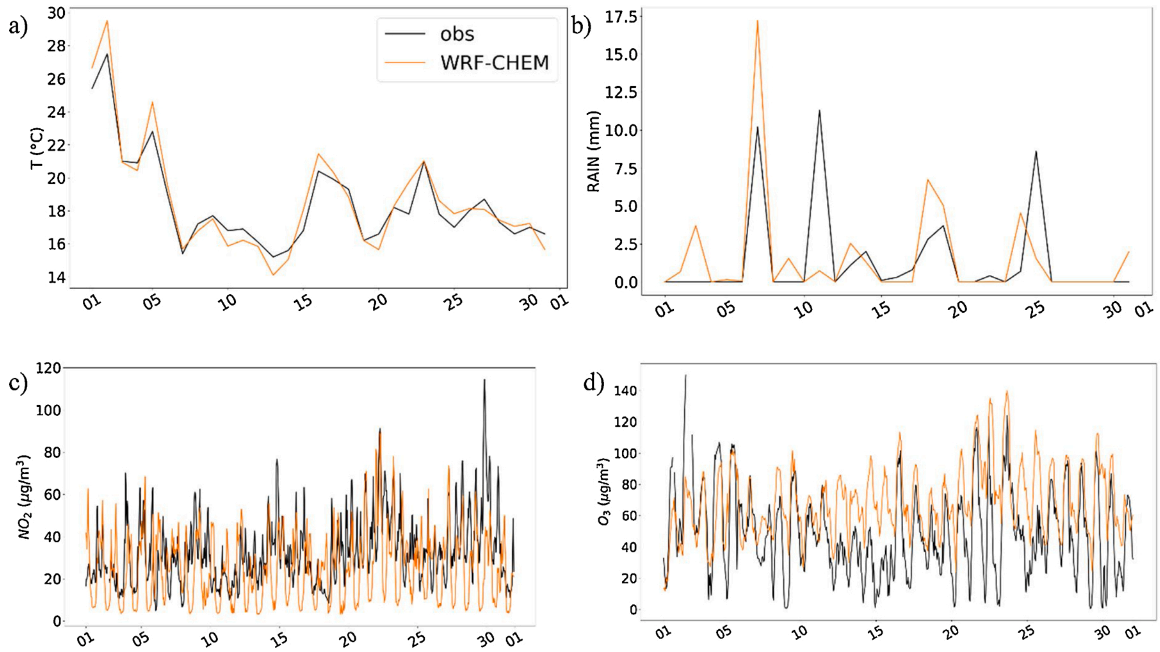

Fig. 5. Observed (black) and modelled (orange) values obtained for the simulated month of August 2013, for a) daily average temperature (°C), b) daily accumulated rainfall (mm), c) hourly NO_2 ($\mu g/m^3$) and d) hourly O_3 ($\mu g/m^3$), at the Airport meteorological station and at the NL00247 air quality station.

Table 2
The correlation coefficient (r), bias, RMSE and mean values for each variable.

	r	bias	RMSE	Mean observed	Mean modelled
Temperature (°C)	0.98	0.18	0.86	18.47	18.65
Precipitation (mm)	0.58	0.19	2.93	1.35	1.54
NO_2 ($\mu g. m^{-3}$)	0.35	- 7.60	20.15	32.74	25.11
O_3 ($\mu g. m^{-3}$)	0.68	19.00	27.86	48.24	67.73

The year 2013 was selected because it is the year with the lowest climate anomaly regarding the period 2012 to 2016 (representing the baseline current scenario). This was obtained from a careful analysis of the EURO-CORDEX data (Jacob et al., 2014). EURO-CORDEX is the European branch of the CORDEX initiative and produces ensemble climate simulations based on multiple dynamic and empirical-statistical downscaling models. Each year of the period 2012 to 2016 was analyzed, and the average for the period 2012-2016 was considered the reference value for the long-term average. This analysis was performed for temperature and precipitation; whereas for precipitation, seasonal and annual precipitation anomalies (in %) were calculated, for temperature, seasonal and annual anomalies (in °C) were calculated for the mean, minimum and maximum temperature.

The performance of the air quality modelling system was evaluated for August using the baseline simulation run. Meteorological and air quality results were compared with measured values retrieved from The Royal Netherlands Meteorological Institute (KNMI, 2019) and the EU e-reporting database (EEA, 2019a), respectively. The used monitoring stations were the Eindhoven's airport meteorological station and the urban background air quality station (NL00247). The model evaluation analysis was performed comparing results and monitored values for daily average temperature, daily accumulated rainfall, and hourly concentrations of NO_2 and O_3, based on the temporal resolution of the monitoring datasets. The modelled values are from the cells where the stations are located. Time-series plots for August 2013 are displayed in Fig. 5. Following the recommendations from Borrego et al. (2008), the statistical parameters correlation coefficient (r), bias and root mean square error (RMSE) were calculated to evaluate the model performance (Table 2).

The statistical parameters and the time series plots indicate an adequate performance of the WRF-Chem modelling system both for meteorology and air quality simulations. For meteorology, performance is better for temperature (slight overestimation of peaks; ~ 1 °C) than for the rainfall, but the model is able to predict some of the precipitation episodes during the simulation period. Regarding air quality, a better correlation with observations was found for O_3 (an overall overestimation of minimum and maximum values is observed) than for NO_2 (results show an overall underestimation of minimum values; possibly related to lack of accuracy in the emission profile). Several uncertainty modelling components (e.g. chemical mechanisms, boundary conditions or input data quality) can contribute to the quality of the modelling results (Borrego et al., 2008), but the emission inventories and data processing are probably the major source of uncertainty. Yet, the obtained performance indicator values are aligned with those achieved by similar modelling studies, either using WRF-Chem or other air quality models (see e.g. Mar et al., 2016; Monteiro et al., 2018).

4. Nature-based solutions scenario simulation

The NBS scenario simulations were performed for the first week of August, to reduce computational time and because it was the hottest week in August with measured daily temperatures surpassing 25 °C. The assessment of this period is particularly important as high O_3 production and critical UHI effects are associated with high temperatures, and it is when NBS need to be effective to protect citizens' well-being.

The selection of the scenarios was based on information provided by the municipality of Eindhoven, which consisted of the location of areas where, in the future, the municipality plans to implement NBS. For this study, a set of 3 NBS scenarios was considered: 1) "green parks scenario", implementation of green parks in areas identified as lacking in green; 2) "green roofs scenario", implementation of green roofs in the industrial areas of the city; 3) "green parks + roofs scenario", the combination of scenarios 1) and 2).

The modelling approach consisted in identifying every grid cell that overlaps with the areas indicated by the municipality, and then changing the land use classification to shrubs (to emulate an urban green park; scenario 1), and to grass (to emulate green roofs; scenario 2). Only the

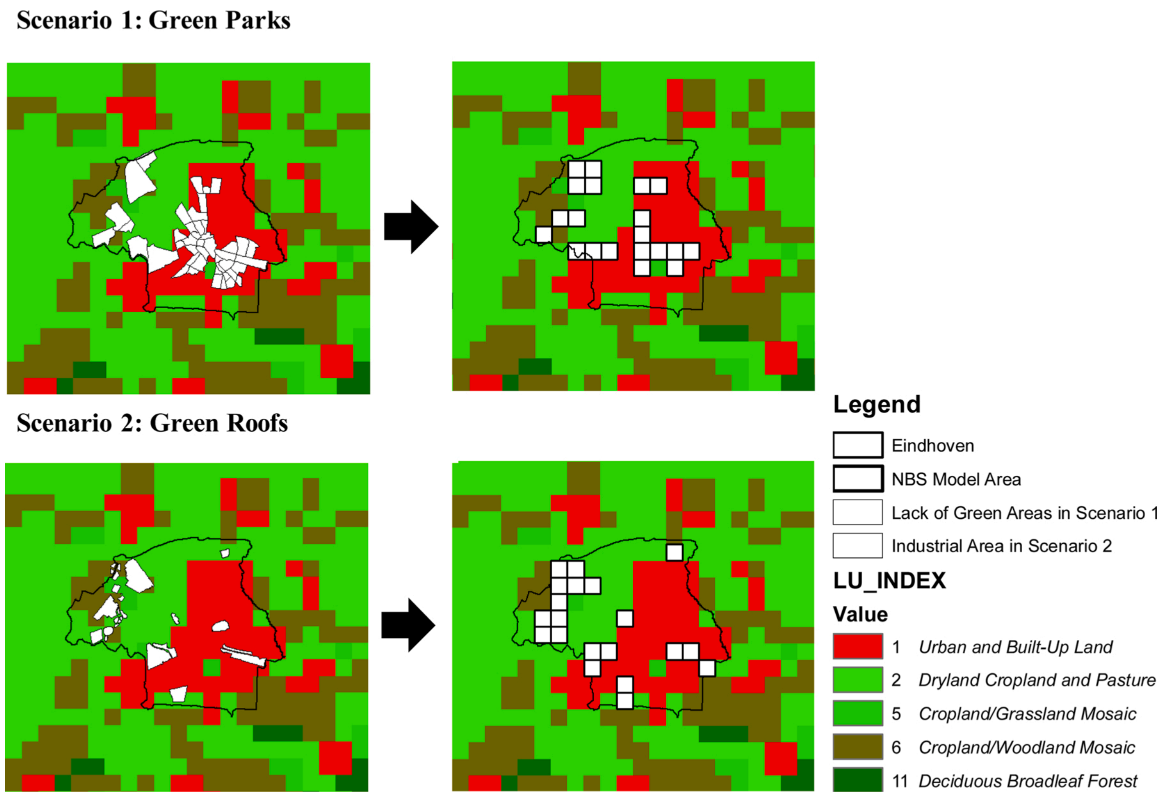

Fig. 6. Location of the areas lacking in green (upper left) and the industrial areas (lower left) and location of the changes applied to the model to simulate the NBS scenarios (right). The black line represents the limits of the municipality of Eindhoven.

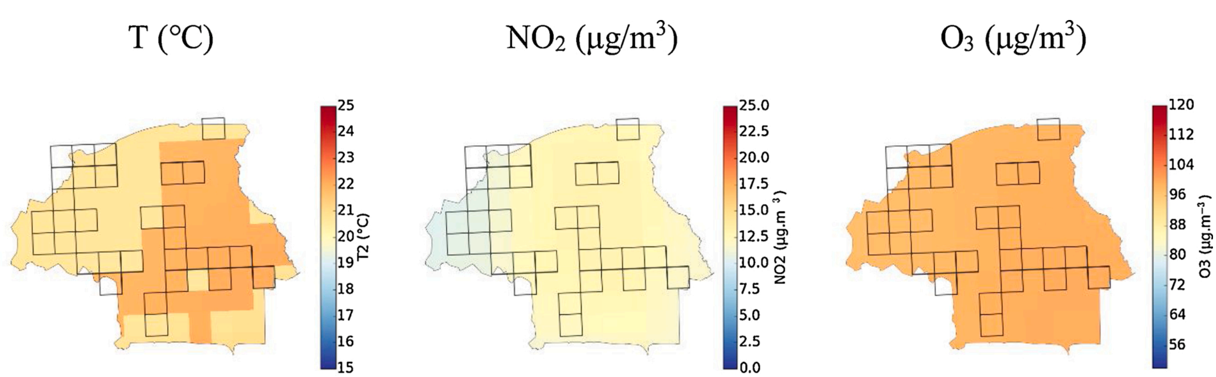

Fig. 7. Baseline scenario (without NBS); average values of temperature, NO_2 and maximum daily 8 h mean O_3 concentrations for the first week of August 2013. Black squares represent model cells which were altered.

land use was changed in the modelling setup and, consequently, associated variables depending on the WRF-Chem land use categories were automatically updated (such as the albedo values). A diagram explaining this method is shown in Fig. 6. Scenario 1 NBS implementation accounts for 22% of the Eindhoven municipality area, while in scenario 2 this is 20% and in scenario 3 this is 33%. In scenario 3, the overlapping cells were computed as green parks. Moreover, as urban surfaces were replaced by green land use, in scenario 1 and 3, anthropogenic emissions were also set to zero in the selected grid cells, leading to a decrease of 3% in the total NO_2 emissions in Eindhoven.

The baseline scenario (without NBS) results for the simulation period (1-8 of August) are presented in Fig. 7. Temperature and NO_2 levels are presented as an average while O_3 concentrations are presented as an average of the maximum daily 8 hours mean from hourly running 8 hours.

The spatio-temporal average temperature for the baseline scenario was approximately 21 °C. The higher values were obtained in urban and built-up areas, where average temperatures were 1 to 2 °C higher than in the surrounding areas. NO_2 concentrations were also higher in the urban area, where the average concentration was 13 µg.m^{-3}. Regarding O_3 concentrations, results show little spatial variation (between 96 and 99 µg.m^{-3}) and the average value was 97 µg.m^{-3}.

Fig. 8 shows the impact of the NBS scenarios for temperature, NO_2 and O_3 concentrations, presented as a mean difference between scenario and baseline, in percentage, for the first week of August.

All scenarios had a similar reduction impact on temperature; the green areas added to the city were able, on average, to reduce the temperature by 1.4 °C (6%). The maximum hourly difference obtained at one cell in the domain was -5 °C, and it was obtained during the night. Fig. 9 shows the average daily profile for baseline and NBS scenarios, and corresponding differences for the cells where NBS were applied. The strongest cooling effect was found during nighttime (between 7 p.m. and

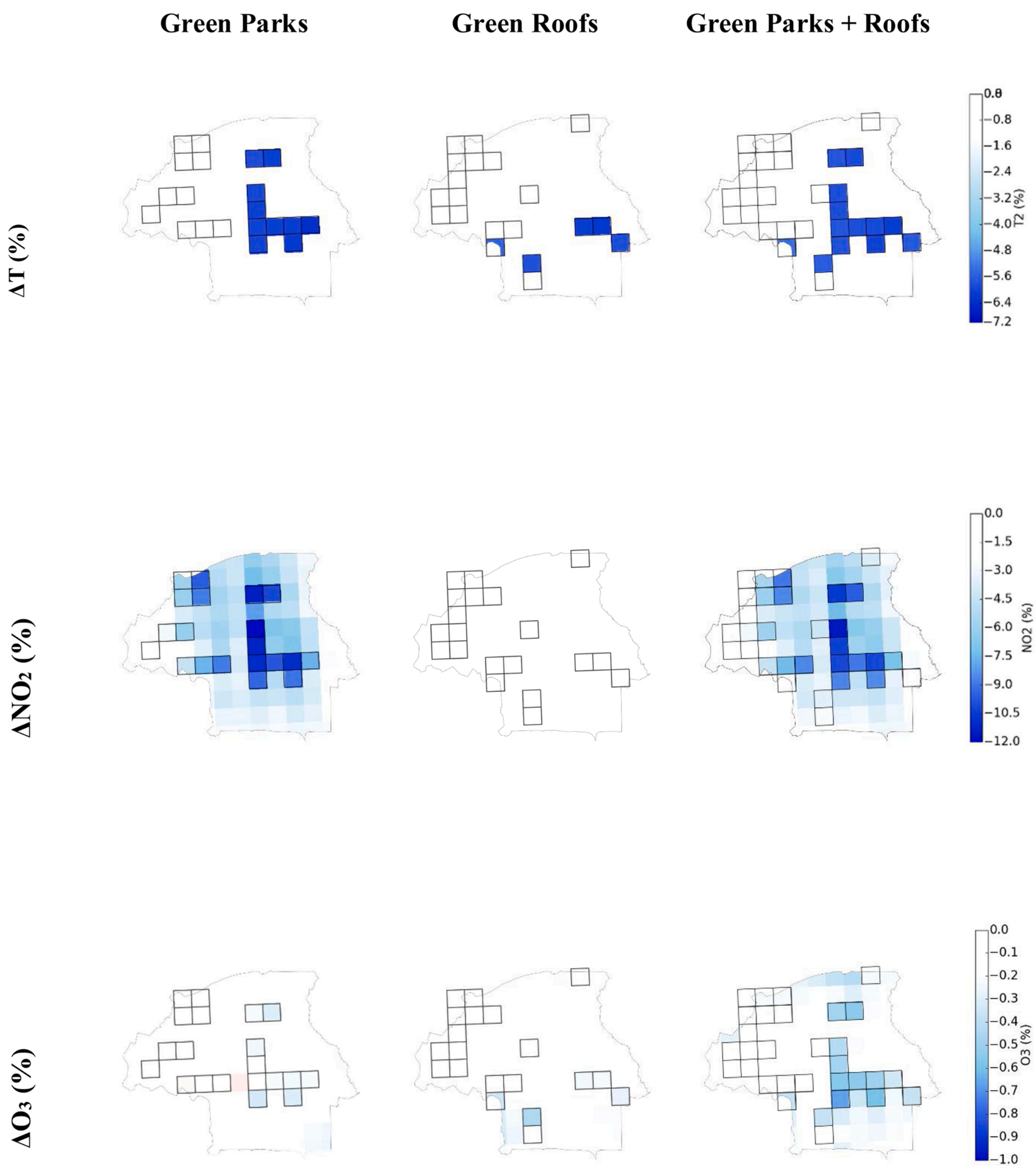

Fig. 8. Model results as percentual mean differences (NBS scenario – baseline) for temperature, NO_2 and O_3 concentrations. Black squares represent model cell which were altered.

5 a.m.) where, on average, the temperature was reduced between - 0.6 and -1.3 °C. This occurs due to the low albedo characteristics of urban surface materials (i.e., asphalt or concrete) that characterize the baseline scenario; these materials promote storage of energy during the day and its release as longwave radiation at night. The implementation of green parks implies that less energy is stored, which increases the temperature-reducing effects at this period. Similar conclusions were found by Lee et al. (2009).

Regarding air quality, NO_2 concentration values were reduced up to 1.6 μg.m^{-3} (12%) in scenarios 1 and 3, and no impact was observed for scenario 2. This decrease was mainly due to emission reductions. Fig. 10 shows the daily profile for NO_2 and O_3 for Baseline and NBS scenarios, as well as the corresponding differences, at the areas with NBS implementation. The major concentration decrease happens during the period with higher concentration values (at the beginning of the morning) caused by road traffic emissions resulting from citizens travelling to work. This could also be related to a lower dispersion capacity of the atmosphere near the surface due to the temperature reduction.

The ozone maximum daily 8 hours mean values were reduced by up to 0.45 μg.m^{-3} (0.6%), 0.40 μg.m^{-3} (0.5%) and 0.53 μg.m^{-3} (0.7%), for scenarios 1 to 3, respectively, which represents almost no impact in the city. The reduction in O_3 concentrations was promoted by the increase in dry deposition due to the gain in vegetation, though this reduction was very small and consistently occurred throughout the day, as shown in Fig. 10(b).

In summary, results show that NBS have a positive effect on the heat urban island and the air quality of the Eindhoven city during a hot summer period, and the combined scenario (green roof and green parks) was the one with bigger spatial impact and higher air pollutant abatement. However, the reduction in NO_2 concentrations was mainly due to

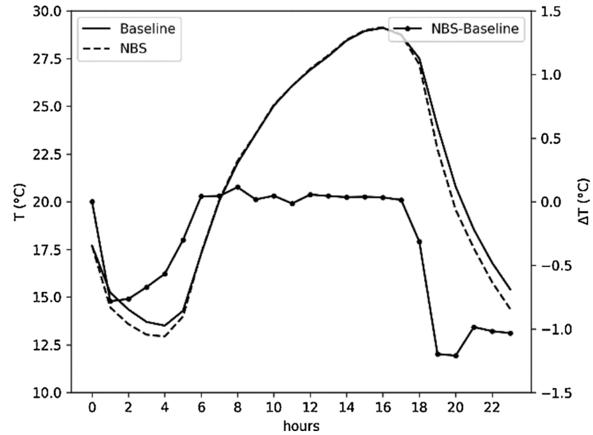

Fig. 9. Temperature average daily profile for Baseline and NBS scenarios and corresponding differences, averaged through the changed cells.

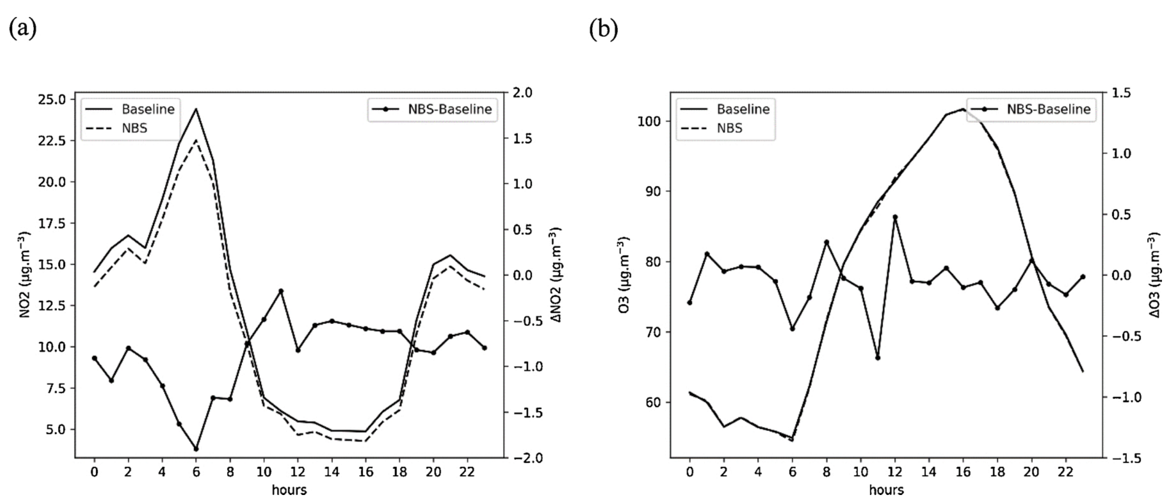

Fig. 10. Daily profile of Baseline and NBS scenarios and corresponding differences for (a) NO_2 and (b) O_3, averaged through the changed cells.

the removal of NO_2 emissions. How the NBS changes mobility and residential patterns (that is, the indirect impacts of NBS) is an interesting topic of research that is not well explored (see e.g. Augusto et al., 2020) and should be studied in future work. These are the first results of the NBS impact on air quality for the city of Eindhoven and must be extended, by simulating longer periods and testing further scenarios. Also, in future studies, more detailed and updated land use and emissions data should be used.

5. Conclusions

Nature-based solutions have the potential to reduce summer temperature and improve air quality in a city. This study contributes to the existing body of knowledge by testing three NBS scenarios for the city of Eindhoven in The Netherlands, with a high resolution mesoscale model. The major impact was observed in a scenario where the air quality model's land use was modified to emulate green parks in areas identified as lacking in green space and green roofs in industrial areas. A maximum 6% decrease in temperature and up to 12% reduction in NO_2 concentration was estimated for the areas with NBS.

This was a first modelling exercise for the city of Eindhoven, already indicating that green parks are effective NBS with a better potential to improve air quality in the city than green roofs for the same area of intervention. Future work will comprise more scenarios, with different types of NBS and improvements in the resolution and quality of input variables, namely a more detailed land use, to enable more realistic scenarios. Furthermore, it will be important to apply the model to longer periods and assess how the NBS impact changes according to meteorological conditions at different times of the year. The results presented in the current work are, however, particularly important to support public planners, stakeholder and decision-makers in understanding the effects and importance of NBS in their planning for more sustainable and resilient cities.

CRediT authorship contribution statement

Ana Ascenso: Conceptualization, Methodology, Software, Writing - original draft. **Bruno Augusto:** Writing - review & editing. **Carlos Silveira:** Software. **Sandra Rafael:** Writing - review & editing. **Sílvia Coelho:** Writing - review & editing. **Alexandra Monteiro:** Writing - review & editing. **Joana Ferreira:** Writing - review & editing. **Isilda Menezes:** Writing - review & editing. **Peter Roebeling:** Project administration, Writing - review & editing. **Ana I. Miranda:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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