



HAL
open science

Balancing positive and negative environmental impacts of urban greening considering future climate: A case study in the Paris region, France

Robin Monnier, Erwan Personne, Patrick Stella, Laura Ferraz de Paula, Patrick Schalbart, Charlotte Roux, Bruno Peuportier

► **To cite this version:**

Robin Monnier, Erwan Personne, Patrick Stella, Laura Ferraz de Paula, Patrick Schalbart, et al.. Balancing positive and negative environmental impacts of urban greening considering future climate: A case study in the Paris region, France. *City and Environment Interactions*, 2026, 29, pp.100277. <10.1016/j.cacint.2025.100277>. <hal-05444489>

HAL Id: hal-05444489

<https://hal.science/hal-05444489v1>

Submitted on 4 Feb 2026

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License



Research Articles

Balancing positive and negative environmental impacts of urban greening considering future climate: A case study in the Paris region, France

Robin Monnier^a, Erwan Personne^b, Patrick Stella^b, Laura Ferraz de Paula^b, Patrick Schalbart^a, Charlotte Roux^{a,*}, Bruno Peuportier^a

^a Mines Paris, PSL University, Centre for Energy Environment and Processes (CEEP), 75006 Paris, France

^b UMR ECOSYS, INRAE, AgroParisTech, Université Paris-Saclay, 91120 Palaiseau, France

ARTICLE INFO

Keywords:

Building
Vegetation
Overheating
Mitigation
Adaptation
DALY

ABSTRACT

Urban greening enhances summer thermal comfort in cities; however, vegetation requires watering and reduces solar gains on buildings, potentially increasing energy consumption for heating. A methodology was developed to investigate whether the positive effects of urban trees on human health offset the increased water and energy consumption impacts. This method involves four steps: 1. Modelling the urban microclimate based on regional climatic data, accounting for vegetation effects; 2. Evaluating indoor temperatures and possible overheating using building thermal simulation; 3. Deriving the damage of overheating on human health, and 4. Performing a life cycle assessment.

This process was applied to a case study on an urban greening project, including renovating an existing social housing building. According to the results, urban greening thanks to a decrease in outdoor air temperature around 1.7 °C (median value, 1.3 °C and 2.0 °C for 10th and 90th percentile, resp.) and a decrease in indoor temperature around 0.4 °C (median value; 0.25 °C and 0.55 for 10th and 90th percentile, resp.) during the five weeks heat wave period. Some life-cycle environmental impacts were reduced, particularly those related to damage to human health (−12.5 %), with limited impact transfer. The impact reduction due to energy savings from building renovation is higher.

While many cities invest in urban greening projects, the importance of energy renovation is often overlooked. This prioritisation may be questioned, and the analysis presented in this article could serve as a valuable tool in guiding decision-making. By using the same indicator (Disability-Adjusted Life Years, DALY) to express life cycle and overheating-related impacts, this approach enables the integration of mitigation and adaptation in decision-making processes.

Introduction

Buildings significantly contribute to environmental impacts, particularly in terms of greenhouse gas emissions. These impacts can be evaluated by applying life-cycle assessment (LCA) [1]. Mitigation measures in the building sector have been studied over the last 30 years, thanks to life cycle approaches. Thanks to more available data and the development of specific methodologies and tools, different scales have been assessed, from the building scale [2] to the district [3,4] and even to the city scale [5].

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [6], adverse impacts from human-caused climate change are expected to continue intensifying, necessitating the

implementation of adaptation measures. Passive strategies at the building scale, regarding, e.g., solar protection and thermal insulation, have been evaluated in various contexts such as Taiwan (K.-T. Huang & Hwang, 2016), Europe (Pajek & Košir, 2021; van Hooff et al., 2016), or China [7]. They have been estimated to be more efficient than, e.g., cool roofs [8]. Adaptation measures can reduce overheating in buildings but may also increase environmental impacts, which are often overlooked in adaptation-focused studies. For instance, air conditioning increases energy consumption and releases heat into the streets, thereby exacerbating the urban heat island effect. Additionally, thermal insulation has environmental impacts related to its production. To integrate the effects of adaptation measures on human health in addition to their environmental impacts, [9] have developed a methodology based on life cycle

* Corresponding author at: Mines Paris, PSL University, Centre for energy efficiency of systems (CES), 75006 Paris, France.

E-mail address: charlotte.roux@minesparis.psl.eu (C. Roux).

<https://doi.org/10.1016/j.cacint.2025.100277>

Received 18 March 2025; Received in revised form 26 September 2025; Accepted 1 December 2025

Available online 6 December 2025

2590-2520/© 2025 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

analysis (LCA) based on the Recipe Impact Assessment Method updated by Huijbregts et al. [10] and taking into account the impacts on human health due to overheating, energy and materials, which helps designers to minimise a total indicator of human health, evaluated in DALYs (Disability Adjusted Life Years) [11]. Various adaptation measures were considered and evaluated (Monnier et al., 2024), except for the urban greening around the studied building, which should complement the improvement of the building's energy performance.

Indeed, indoor overheating is influenced by outdoor microclimatic conditions around the studied building. At an urban scale, the urban heat island effect was already accounted for in the relevant literature [12,13]. The effects of urban vegetation on mitigating the urban heat island effect have also been widely studied [14,15,16,17,18,19,20,21,22]. Outdoor thermal comfort has been widely explored [23], and several indicators have been developed to evaluate outdoor thermal stress in thermo-physiological models for human-biometeorology research [24]. Nevertheless, previous studies mainly focused on the impact of vegetation or cool pavement on outdoor thermal conditions and outdoor human thermal comfort [25]. However, some studies were interested in the effect of green infrastructures on indoor environment (e.g., [26] and the effect of building shading by trees on indoor thermal conditions (e.g., [27]; the effect of canopy layer urban heat island mitigation on indoor thermal comfort has not been explored. Huang et al. [28] studied the link between mortality data and the heat island effect, focusing solely on external temperature, as the primary objective was not to examine the ecodesign of buildings but instead to evaluate the most vulnerable areas to heat waves. To our knowledge, the consequences of such urban revegetation measures on indoor thermal comfort have not been addressed. Furthermore, a common metric must be used to comprehensively evaluate all environmental consequences of adaptation measures, including both positive and negative effects, such as improving health by reducing overheating, but at the expense of using more water and/or more energy.

This paper, therefore, proposes a holistic methodological framework for assessing the benefits of urban greening, incorporating building life-cycle assessment and climate projections. It proposes an innovative modelling framework to evaluate the impact of urban greening on indoor thermal comfort. A unified indicator based on human health is proposed to bridge mitigation and adaptation strategies, ensuring holistic decision-making processes. This modelling framework integrates the reduction of damage to human health due to overheating in buildings, the influence of vegetation (here, urban trees) on building energy use (both positive and negative), and the increase in water use resulting from watering urban trees.

The method, based on i/ the modelling of outdoor thermal conditions at the canyon scale with the TEB-Surfatm model [29], ii/ the methodology developed by Monnier et al. (2024) associated with thermal dynamic simulation and life-cycle assessment, is adaptable to a wide range of urban contexts and a combination of adaptation and mitigation measures.

The method is first described and then applied to a case study in the Paris region, France, within future climate conditions. The results are then displayed, followed by a discussion and further research perspectives.

Materials and methods

Methodological framework

The methodology relies on three models to evaluate environmental impacts. The Pleiades STD COMFIE model simulates indoor thermal temperatures, which are required for both estimating the health effects related to overheating and evaluating the building's energy use. This model requires standard meteorological inputs (radiation, temperature, and wind speed), which were typically averaged at the district or city scale in previous studies. In this study, to capture local microclimatic

specificities in the urban canyon, the outdoor temperature is instead estimated using a third model, TEB-Surfatm, which accounts for the influence of urban morphology and greening on microclimatic conditions. In Pleiades STD COMFIE, shading effects from nearby buildings and trees, as well as the surface albedo of the surroundings, are only considered through their direct influence on the studied building, not through potential impacts on outdoor temperature. An overview of the suggested four-step methodological framework is presented in Fig. 1, and the different steps and information concerning the models are further detailed in the text.

Hence, the first step involves calculating local outdoor microclimatic conditions (especially air temperature) within the urban street canyon using regional climatic data, including prospective scenarios (e.g., derived from IPCC global planetary scenarios at different time horizons and for varying heatwave severities). In this study, estimating the mean street canyon at the hourly time step for the entire year is required to apply the proposed methodology. In this first approach, the influence of vegetation on urban air flows is neglected, which would constitute a potential area for improvement. Hence, the TEB-Surfatm model [29] is used to estimate the outdoor air temperature (T_{out}) from the regional climatic data. It is a one-dimensional model that considers a district as an urban canyon. Vegetation is accounted for as a mean fraction coverage within the street at the ground level. It consists of an energy balance model for impervious surfaces (TEB) [30] and vegetation (Surfatm) [31], which calculates heat fluxes (i.e., sensible, latent, and conductive) for walls, roofs, ground, and vegetated surfaces. As a result, it firstly provides the mean microclimatic conditions within the street canyon. In addition, since it calculates transpiration from vegetation, it is also able to provide the water requirements for the vegetated surface based on the water balance given by the Surfatm model [32]. TEB-Surfatm only requires information on urban characteristics (e.g., building height, street width, and material thermal properties) and on urban vegetation (vegetation height and fraction, physiological characteristics, and soil properties).

Outdoor microclimatic data provided by the TEB-SurfAtm model (step 1) for different vegetation percentages were used as input in the thermal simulation (step 2), resulting in different indoor temperature profiles. Dynamic thermal simulation is performed using the Pleiades STD COMFIE model [33] to evaluate indoor temperatures. This tool was selected due to its integration with an LCA tool, and its thermal model reliability has been assessed through multiple validation studies [34,35]. The building is represented using multiple thermal zones, defined as spaces assumed to maintain a uniform temperature. This approach is similar to other models, such as TRNSYS multizone building and EnergyPlus. The proposed methodology could be applied using any validated building energy simulation tool. More details on the dynamic thermal simulation modelling and hypothesis are available in Monnier (2024). Dynamic thermal simulation also uses other inputs from the prospective climatic data, such as solar irradiation, which are not modified by step 1. Tree shading is accounted for in this step (2).

Steps 1 and 2 enabled the evaluation of heating loads and overheating degree-hours (DH) in accordance with the EN 16798-1 standard [36]. At each hour of the considered year, a comfort threshold is defined in the standard in terms of the average outdoor temperature for the previous day. The difference D between the indoor temperature and the comfort threshold is calculated. The DH indicator is the sum of hourly D over the year. It accounts for both the severity of overheating periods (excess temperature compared to the comfort threshold) and their duration.

In step 3, the approach of Monnier et al. (2024) enables the evaluation of the health effects of overheating in buildings, integrating the benefits of outdoor urban greening on human health. This method is based on data from the 2003 heat wave in France, where the number of excess deaths was used to evaluate the corresponding DALYs (noted DALY2003). These DALYs were related to the product of DH by net areas (NA) of archetype buildings constituting the modelled building stock in

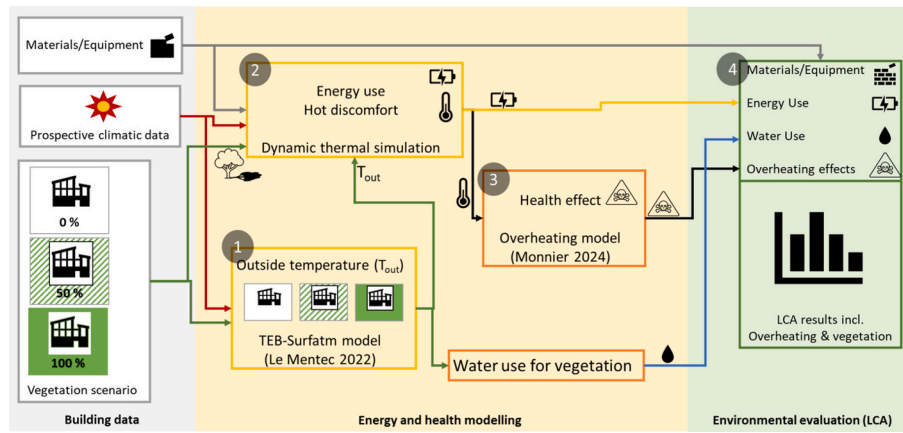


Fig. 1. Overview of the 4-step methodological framework.

the same year. The sum of $DH \times NA$ of all archetypes is noted as $DH \times NA_{stock}$. Proportionality is considered between DALY and $DH \times NA$, leading to Eq. (1), from which the DALY of the studied building is calculated according to the DH and the net area of this building.

$$DALY_{building} = CF_{overheating} \times DH_{building}$$

$$where CF_{overheating} = \frac{DALY_{2003}}{DH_{2003stock} \times NA_{2003stock}} = 1.35E^{-8} DALY \cdot m^{-2} \cdot DH^{-1}$$

(1)

In step 4, all parameters are combined in a life-cycle perspective, integrating the reduction of overheating, the influence of outdoor urban greening on energy use, and water use. LCA was performed using the Pleiades LCA Equer [37] and the ecoinvent v3.4 LCA database [38], with a contextualization process (particularly regarding electricity production in France). Environmental indicators are shown in Table 1. They include damage indicators on ecosystems, expressed in PDF.m².year (potential disappeared fraction of species over an area and during a period of time), and on human health, expressed in Disability-Adjusted Life Years (DALYs). LCA hypotheses specific to the case study are detailed in the next section (functional unit, system boundaries, etc.).

Although the approach has been applied to a specific case study corresponding to an existing building in France, detailed hereafter, it is worth noting that it can be applied to other buildings, including new construction and greening scenarios, in other countries and prospective scenarios.

This four-step framework, to our knowledge, is the first to consistently link future urban microclimatic conditions (including the effect of vegetation), indoor overheating simulation, and life cycle assessment within a single workflow, thereby enabling an integrated evaluation of

urban greening strategies at the building scale. The original coupling of the TEB-SurfAtm model with the health impact model developed by Monnier et al. (2024) represents a key innovation. Furthermore, the explicit integration of vegetation necessitated the addition of specific features—such as tree shading effects and water consumption—that were not previously considered in studies related to this work.

Description of the case study and life cycle assessment hypothesis

An existing social housing building situated near Paris is studied. It includes 52 apartments on four floors above an unheated ground floor (Fig. 2). The net heated floor area is 4,375 m². The facades, roof, and floors are made of 20 cm concrete. In this case study, the facades are supposed to be renovated with an external insulation layer made of 20 cm of rock wool. Similarly, the roof is considered insulated with 20 cm of polyurethane over the concrete layer. The existing single-glazed windows are intended to be replaced with triple-glazed windows, featuring a heat loss coefficient of 1.095 W/(m² · K) and a solar factor of 0.41.

The considered lifespan of the building after renovation is 100 years, which aligns with the default value reported by Palacios-Munoz et al. [39]; the number of inhabitants is 175.

The main modelling hypotheses are described in Table 2.

In the renovation project without adding vegetation, the following elements are included in the studied system:

- End of life of the replaced single-glazed windows,
- Fabrication, transport, installation, replacement, and end-of-life of new triple-glazed windows, façade and roof insulation,

Table 1

List of considered environmental indicators.

Indicator	Unit	Method
Climate	kg CO ₂ eq.	GWP100 [58]
Energy	MJ	Addition of energy flows from life-cycle inventory results
Water	m ³	Addition of net water flows, from life-cycle inventory results
Biodiversity	PDF.m ² .an	ReCiPe, 2016 [10]
Human health	DALY	Hierarchist perspective ReCiPe, 2016 [10]
Resources	kg antimony eq.	Hierarchist perspective ReCiPe, 2016 [10]
Waste	kg	Addition of waste flows, from life-cycle inventory results
Radioactive waste	kg	Addition of different radioactive waste flows, from life-cycle inventory results



Fig. 2. Picture of the studied building (Photo B. Peuportier – 09/12/2002).

Table 2
Main modelling hypotheses.

Heating system	District heating system (43 % gas, 57 % wood fuel) T° set point: 21 °C
Water consumption	Cold water: 100 L per day per person Hot water: 40 L per day per person
Specific electricity	22.7 kWh/m ² /year
Air renewal rate	Mechanical ventilation: 0.36 ACH (air change per hour) Infiltration: 0.14 ACH
Summer thermal comfort control	Window opening at night (if overheating) resulting in 10 ACH (dual-aspect apartment, see [59]) 80 % of solar gain reduction with shadings in summer (external roller blinds)

- District heat consumption for heating and domestic hot water,
- Electricity consumption for lighting and domestic appliances,
- Water consumption and wastewater treatment,
- Impacts on human health due to overheating.

Impacts related to the construction of the building, which occurred more than 60 years ago, are not accounted for because they cannot be changed and do not vary according to the renovation project or the vegetation percentage. The impacts of electricity consumption are evaluated considering an average hourly production mix over 100 years, using a consequential LCA approach [40].

The methodology was applied to prospective weather data corresponding to Paris in the distant future (2080–2100) under an extreme heat wave, i.e., the 95th quantile of all simulated heat waves [41]. The very high greenhouse gas emissions of the IPCC scenario RCP8.5 (Representative Concentration Pathway, radiative forcing 8.5 W/m²) were considered. These climate projections were generated through the dynamic downscaling of global models (GCMs, or General Circulation Models or Global Climate Models) from the CMIP5 coupled model intercomparison project [42]. The typical future climate conditions used in this study are based on a statistical analysis of a set of climate projections produced by regional climate models from the EURO-CORDEX ensemble [43]. Hourly meteorological data under future climate conditions are derived from the high-resolution regional climate model AROME, the climate version of the numerical weather prediction model developed by Météo-France and CNRM [44]. This level of spatial and temporal resolution is necessary for the thermal dynamic simulation of buildings, which was unavailable for France in the CMIP6.

On the other hand, three urban greening scenarios around the building were considered. They consisted of 0 %, 50 %, and 100 % of the ground area covered by 6 m height temperate deciduous trees with LAI equal to 4 m².m⁻², representative of the Ile-de-France region with a ground grass layer. The physiological parameters of the trees and grass, as reported by Simpson et al. [45] and Le Mentec et al. [29], respectively, were used. In this study, it was considered that the vegetation did not suffer from water limitation in order to evaluate the maximum cooling effect of urban greening. To this aim, water supply was applied

each time the soil water content reached the threshold for triggering the stomatal control by hydric stress. It also allowed for estimating the maximum additional water needs to ensure maximum cooling by vegetation.

Results

Outdoor temperature

To illustrate the impact of urban greening on outdoor cooling, the effect of greening scenarios on the mean street canyon outdoor air temperature is shown during the period from June 30th to August 14th (Fig. 3). This latter corresponds to the heat wave during which diurnal outdoor air temperatures reach up to 40–45 °C and only decrease to 20–25 °C during nighttime (Fig. 3a).

Urban greening allows for a decrease in outdoor air temperature. This cooling increases with the percentage of vegetation (Fig. 3), is minimal in the early morning (i.e., at around 8:00), and is maximal in the late afternoon (i.e., at around 18:00) (Fig. 3b). With 50 % vegetation, the minimum cooling is usually around 0.25 °C in the early morning, but it increases until late afternoon to around 1 °C before decreasing during early evening and nighttime to its minimum. With this amount of vegetation, the cooling ranges between 0 and 1 °C (10th and 90th percentiles, respectively) during nighttime and can reach 1.3 °C (90th percentile) in late afternoon. Considering the 100 % vegetation scenario, although the minimal cooling in the early morning is similar to that with 50 % vegetation, it allows for a decrease in outdoor air temperature, typically around 1.7 °C (which can reach 2 °C, 90th percentile) in the late afternoon (Fig. 3b).

Indoor temperature

The impact of outdoor greening on indoor temperature is illustrated in the following by considering, on the one hand, the same period as previously and, on the other hand, the top western zone of the building, which corresponds to its warmest zone in summer. Indeed, the southern façade receives less solar radiation in the summer at noon, when the solar height and, therefore, the incidence angle of direct radiation are high. The western zone receives the highest solar radiation in the afternoon, when the outside temperature is at its maximum, inducing high indoor overheating.

The indoor temperature increases significantly during the heat wave, reaching up to 28 °C at nighttime and 33 °C during the daytime (Fig. 4a). Outdoor greening allows for indoor cooling, which increases with the amount of vegetation, similar to the effect on outdoor cooling (Fig. 4). Nevertheless, due to several effects (insulation, thermal mass), the cooling magnitude and its variations at the daily scale are weaker than those of the outdoor temperature. The indoor cooling is approximately 0.4 °C (median value; 0.25 °C and 0.55 °C for 10th and 90th percentiles, respectively) in the case of 50 % vegetation. For the 100 % vegetation scenario, the indoor temperature decrease varies between

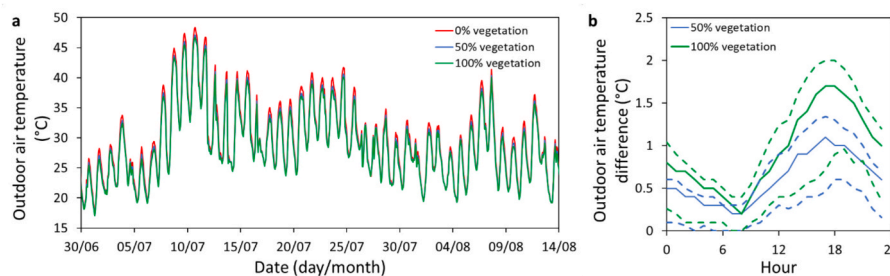


Fig. 3. (a) Time series of outdoor air temperature with 0 % (red line), 50 % (blue line), and 100 % (green line) vegetation. (b) Hourly medians (filled lines) and 10th and 90th percentiles (dotted lines) of the outdoor temperature difference without and with vegetation (50 % in blue, 100 % in green). The period considered is from June 30 to August 14. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

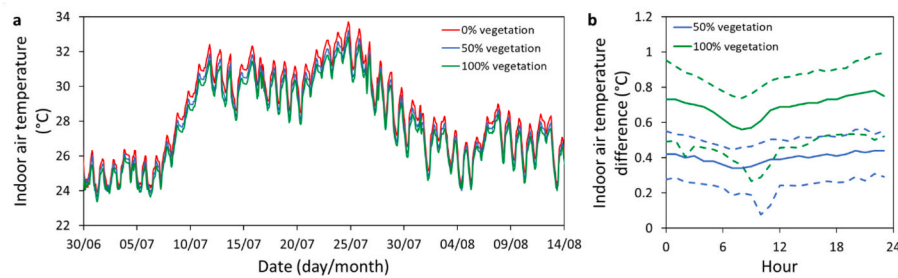


Fig. 4. (a) Time series of indoor air temperature with 0 % (red line), 50 % (blue line), and 100 % (green line) vegetation. (b) Hourly medians (filled lines) and 10th and 90th percentiles (dotted lines) of the indoor temperature difference without and with vegetation (50 % in blue, 100 % in green). The period considered is from June 30 to August 14. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.6 °C and 0.8 °C (median value), but can reach 1 °C during nighttime (90th percentile) (Fig. 3b).

Impacts of overheating on human health

Indoor temperature profiles obtained through dynamic thermal simulation enabled the calculation of overheating degree hours (DH) in each thermal zone. The overheating threshold is set between 26 and 28 °C, according to an adaptive comfort approach based on the standard EN 16798-1 [36]. An average for the whole building is then calculated by weighting the indicator DH of each zone by the net zone area. The method defined by Monnier et al. (2024) was applied in order to evaluate the corresponding damage to human health, expressed as a DALY indicator. The result is shown in Table 3. The renovation halves the overheating and vegetation scenario, which could allow an additional decrease of up to 15.5 %.

Evaluation of the water supply for vegetation

To ensure outdoor thermal cooling, vegetation requires sufficient water accessible in the soil for its root system to avoid plant water stress, leading to a reduction in transpiration. This need has been evaluated by calculating the amount of water supply required, in addition to natural precipitation, throughout the year to prevent stomatal closure due to low soil water content. It has been evaluated that the maximum annual water supply required to maintain maximum evapotranspiration, and therefore maximum cooling, is 280 mm and 560 mm for the 50 % and 100 % vegetation scenarios, respectively. This water supply is necessary from June to October. Considering that the vegetated area is 3,300 m², this water supply accounts for an additional water requirement of 924 m³ and 1,848 m³ annually for 50 % and 100 % vegetation, respectively.

Life cycle assessment

The LCA study aims to evaluate the environmental impact reduction of the renovation project, considering the three urban greening scenarios mentioned above (0 %, 50 %, and 100 %). The functional unit corresponds to the entire building, i.e., the function is to provide dwelling space for 175 persons in 52 apartments for 100 years. The

Table 3
Overheating degree days and DALY indicator in terms of the vegetation %.

	Before renovation	After renovation		
	0 % vegetation	0 % vegetation	50 % vegetation	100 % vegetation
Overheating DH (K.h)	2383	1162	945	792
μDALY (over one year)	141	69	56	47

considered thermostat set point, occupancy, internal gains, and ventilation schedules result in heating loads as indicated in Table 4. The amount of vegetation influences shading and, therefore, solar gains and heating needs.

The environmental impacts of the use stage are reduced by the renovation owing to heating energy savings. Overall, the impacts over the life cycle are reduced (see Fig. 5) except regarding water consumption (this indicator is not being influenced by thermal renovation) and depletion of mineral resources (impact due to the materials used for thermal insulation and new windows is approximately compensated by impact reduction thanks to energy saving). Considering the impact of overheating on the DALY indicator for human health, the benefits of renovation are accentuated. Fig. 5 illustrates the relative impact reduction for each environmental indicator, considering the reference values prior to renovation. For instance, the impact on climate change is reduced by 30 % after renovation.

Adding vegetation reduces the overheating and related impact on human health (see §3.3 above), but water is consumed for watering the trees (see §3.4 above). Also, trees shade the building facades, which increases the heating needs (see Table 4). Fig. 6 illustrates the reduction in impacts on human health resulting from overheating, as well as the negligible increase in impacts due to water and energy consumption. As this latter is negligible, e.g., lower than 1 μDALY/m²/year (an increase from 19.6 μDALY in the 0 % scenario to 20.2 μDALY in the 100 % scenario), it does not appear in Fig. 6. The human health indicator in DALYs is expressed per year and per square meter of net heated area.

The radar graph in Fig. 7 shows the comparison across all indicators. It shows a reduction of around 12.5 % in damage to human health, but a very weak variation in other indicators. Water consumption related to vegetation represents approximately 8 L per day and per person for 100 % vegetation (resp. 4 L for 50 %), compared to the 100 L of cold water and 40 L of hot water consumed per day and per person. Impacts on ecosystems (biodiversity) are also slightly increased, which is due, following a contribution analysis, to increased use of water and heating energy.

The case study presented above corresponds to a single residential building; however, the method could be applied to an urban project that includes several buildings and possibly various uses (e.g., tertiary), assuming that appropriate occupancy scenarios are defined.

Table 4
Heating needs of the building (distant future year 2080–2100 with extreme heat wave in Paris area).

	Before renovation	After renovation		
	0 % vegetation	0 % vegetation	50 % vegetation	100 % vegetation
Heating needs (kWh/m ² /year)	61,1	15,2	15,7	16,6

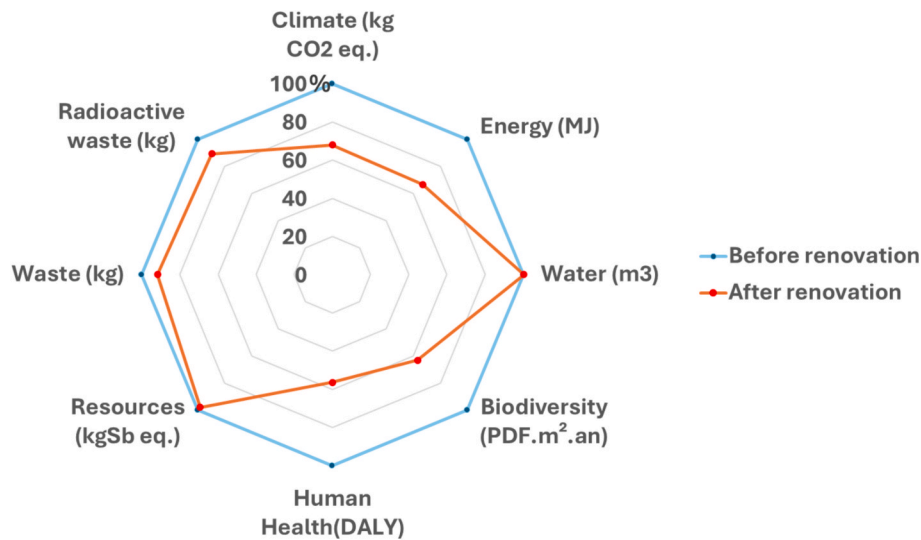


Fig. 5. Comparison of environmental impacts before and after renovation (no vegetation).

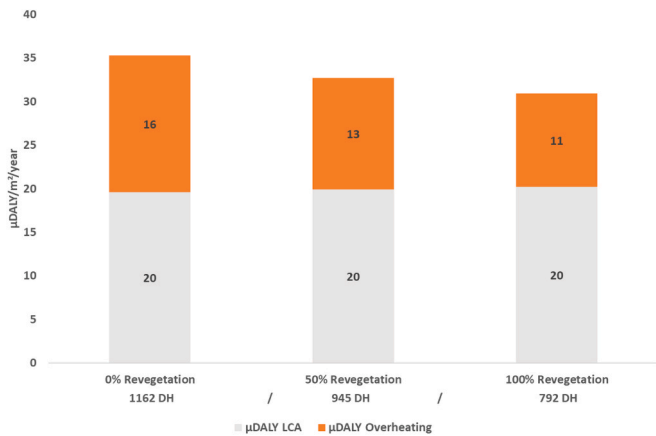


Fig. 6. Human Health indicator (in $\mu\text{DALY}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$) after renovation in terms of vegetation %. 1162, 945 and 792 DH are the overheating according to the EN 16798–1 standard in Degree.Hour for each vegetation scenario.

Discussion

Even if other solutions and strategies exist to mitigate the heat island, such as modifying the albedo of surfaces and improving the structure of buildings [46], as found in previous studies, urban greening allows for a decrease in outdoor air temperature. For instance, Tan et al. [47] reported that street trees allowed for air cooling ranging from 0.2 to 1.5 °C, depending on the amount of vegetation, urban morphology, and the time of day in Hong Kong. Similar results were found by Calhoun et al. [48] for a case study in the USA. For the Paris region during the 2003 heat wave, De Munck et al. [49] estimated that converting 75 % of the available ground surface to green spaces with deciduous trees would provide a median cooling of around 0.5 °C over the whole studied domain, which could reach up to 2 °C. However, measurements performed by Parison et al. [50] indicated that the air temperature decreased by 0.2 °C during nighttime to 1.3 °C during late afternoon after converting an asphalt-concrete parking lot to a small urban forest in the Paris region.

The cooling effect provided by vegetation is linked to several processes: the modification of the radiative and thermal properties of the surface, the evapotranspiration, and, concerning trees, the shading

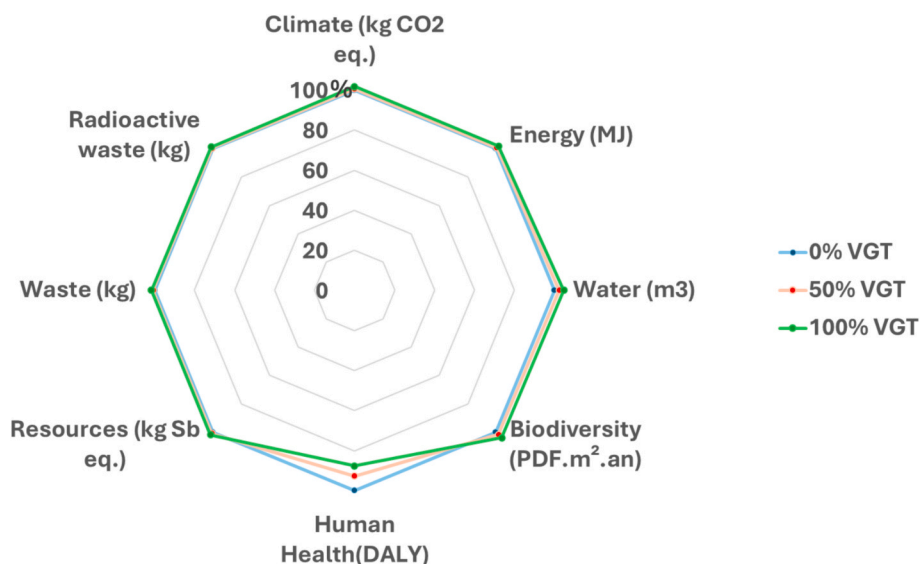


Fig. 7. Comparison of environmental impacts after renovation for three vegetation percentages.

effect provided by the canopy [51,21]; Rahman et al., 2020a). These processes are primarily responsible for the diurnal variations in the cooling effect provided by vegetation. From early morning to early afternoon, evapotranspiration increases, thereby increasing the cooling provided by vegetation. From early afternoon to late afternoon, although the evapotranspiration progressively decreases, the effect of shading and the thermal properties of vegetated surfaces (i.e., heat capacity and heat conductivity) allow a decrease in the temperature below the tree surface and less heat storage, explaining that the cooling effect provided by vegetation still increases until late afternoon. Finally, during nighttime, the cooling effect provided by the vegetation is linked to its faster cooling due to its lower heat capacity and larger heat conductivity. However, the cooling magnitude provided by vegetation progressively decreases during nighttime, as the impervious surface becomes progressively cooler, even if it is a slow process. Nevertheless, the relative contribution of each process, as well as its magnitude in the cooling effect provided by the vegetation, is strongly dependent on local conditions, such as microclimate, vegetation characteristics, or urban morphology. For instance, Shashua-Bar & Hoffman [52] calculated that shading accounted for approximately 80 % of the cooling effect at 3:00 p.m. during summer (in Tel-Aviv), making this process the dominant factor compared to evapotranspiration. However, the *meta*-analysis performed by Rahman et al. [53] highlighted a higher contribution of transpiration for trees grown in Oceanic and Continental climates compared to those grown in Mediterranean climates.

A possible improvement would be to integrate CFD models (e.g., ENVI-met, SOLENE) better to capture the influence of vegetation on urban airflow and, consequently, on indoor conditions. However, such an approach was not feasible here, as our focus on year-long simulations would have required excessive computational resources. Using these models under specific conditions could nevertheless provide an interesting research perspective to better assess the uncertainties related to local airflow modelling.

For evapotranspiration, vegetation requires water, implying an additional water supply, especially during the summer months. Indeed, Kunert et al. [54] reported transpiration rates in natural forest stands ranging from 2.51 ± 0.21 mm/day (during the dry season) to 2.64 ± 0.30 mm/day (during the wet season). For urban trees, the rate ranged from 0.9 to 4 mm/day, according to Kjelgren & Montague [55], for a Norway maple tree. Zheng et al. [56] reported values ranging from 1.6 to 4.7 mm/day for different deciduous trees, depending on the meteorological conditions. These transpiration rates indicate that the amount of water required by trees ranges from 135 mm to 705 mm over five months, reflecting substantial variability due to species and local pedoclimatic conditions. For the distant future under an extreme heat wave scenario considered in this study, the cumulated rainfall over these five months is 203 mm (June = 32 mm; July = 48 mm; August = 53 mm; September = 22 mm; October = 41 mm), meaning a theoretical water supply required of a maximum 502 mm. For our case study, the water supply estimated is therefore realistic, even if it represents the maximum water supply, given that the threshold for triggering water supply is set to avoid water stress for the plant. However, considering that each apartment is inhabited by two adults and two children and assuming a mean annual water consumption of $40 \text{ m}^3/\text{adult}/\text{year}$ and $20 \text{ m}^3/\text{child}/\text{year}$, this annual water supply for plants accounts for 30 % and 15 % of the annual water requirement of the considered building for 100 % and 50 % vegetation scenario, respectively. A solution could be to use greywater from housing. This could help reduce the demand for freshwater in maintaining green areas near buildings; however, it does not entirely eliminate the environmental impact. Greywater is typically treated and returned to natural ecosystems (e.g., rivers), meaning that its diversion still constitutes a withdrawal of resources that would otherwise support ecological functions. Nevertheless, it is essential to note that greening also benefits the entire district, not just the considered building, meaning that, in reality, the water needs for plants are lower in relation to the district's overall water consumption. In all cases,

water supply for vegetation, whether with fresh or grey water, must be associated with plant selection. The choice of local species adapted to local pedoclimatic conditions and also drought-resistant is an important lever to ensure sustainable greening in the urban context associated with climate change.

This study aims to evaluate the maximum impact of urban greening on outdoor and subsequent indoor temperatures. It has been hypothesised that there will be no hydric stress, which is not realistic under heat wave conditions. Even if the water supply necessary to ensure vegetation hydric comfort has been evaluated, more work is needed to refine these estimates according to the vegetation considered (e.g., Mediterranean vs temperate species), the soil water availability under highly specific non-natural soil conditions, and/or the amount of water that can be allocated to vegetation irrigation. Last but not least, this case study, being for a distant future under an extreme heat wave scenario, is, by definition, highly uncertain and maximised. The estimates of water supply, in addition to natural precipitation, are therefore an order of magnitude.

This study was conducted considering that residential buildings are not typically equipped with active cooling devices. This is the most common situation in France today, but it may evolve rapidly due to climate change. Active cooling is an efficient way to mitigate building overheating, but it increases energy consumption, as evaluated in Monnier et al. (2024). Moreover, the massive integration of cooling devices in buildings can also have an unwanted effect on the urban climate, increasing outdoor temperature [57]. Considering the potential of urban greening and building renovation to delay the need for active cooling—and thereby reduce the associated energy consumption—is an interesting perspective emerging from this work.

Several sources of uncertainty can be listed in this study e.g., prospective climate data with their variability, parameters of the vegetation model (e.g. leaf area index and its seasonal variation), the microclimate model (e.g. optical properties of surfaces such as albedo and emissivity of impervious ground surface, walls and roofs; the thermal characteristics of the buildings such as thermal capacity and thermal conductivity of walls and roofs), the building thermal simulation model (e.g. air flow rate when windows are open), the overheating related DALY evaluation (simplified building stock model), the life cycle assessment (e.g. building life span), and life cycle impact assessment (e.g. regionalisation). Performing a sensitivity analysis on key input parameters—such as vegetation characteristics (e.g., leaf area index, type), building thermal envelope properties, or occupancy-related internal gains—would help identify which variables most influence the results. Defining uncertainty intervals on these influential parameters would then allow for a more robust quantification of the overall uncertainty in the environmental and health impact indicators.

Some models, inducing the highest uncertainty, could be refined. Particularly, the evaluation of overheating DALYs could benefit from using data related to more recent heatwaves, as well as various climatic contexts, including regions where humidity influences damage to human health. Vegetation influences not only ambient temperatures but also humidity and air quality. Accounting for such combined effects will need further investigation.

Biogenic carbon storage in trees was not accounted for because reducing climate change would require long-lasting carbon storage, which is difficult to guarantee. Trees planted in such urban contexts may suffer from droughts, storms, pollution, diseases, and parasites. Tree pruning may produce waste that can be treated in several ways (e.g., pellet production, heat recovery from incineration), leading to different effects on the climate and, therefore, on human health.

Vegetation provides ecosystem services that have positive effects on local biodiversity, but this was not accounted for in this study. Urban greening also has additional benefits, related to stormwater retention, noise reduction, and social impacts, which were previously disregarded due to the difficulty of integrating them into an LCA framework. Although social impacts may be more challenging to quantify in an LCA approach, expanding the system boundaries to include noise and

stormwater retention presents an interesting perspective on this work. Maintenance costs of green spaces have also been disregarded in this study.

Conclusions and perspectives

A process was developed to evaluate the environmental impacts of buildings and urban projects, accounting for some effects of urban greening, and applied in a case study regarding the renovation of an existing residential building. According to the results of this case study, urban greening can reduce some impacts, particularly those related to human health, with a limited transfer of impact (resulting in a slight increase in water and energy use).

The impact reduction resulting from energy saved through building renovation (in this case, façade and roof insulation, and window replacement) is significantly higher than the impact reduction and transfer associated with urban greening.

Many cities focus on urban greening projects but pay little attention to energy renovation. Such priority setting could be questioned, and the analysis proposed in this article may constitute a first step to aid decision-making in this field. Several improvement perspectives are outlined to enhance the reliability of the proposed evaluation process. Expressing life cycle and overheating-related impacts using the same DALY indicator allows the integration of both mitigation and adaptation in decisions.

The primary perspectives of this work include conducting in-depth sensitivity analyses on the most influential parameters, integrating the positive impact of urban greening on local biodiversity, and considering specific building solutions, such as active cooling, to mitigate overheating. Research activities are planned to study the evolution of mortality associated with heat waves, using more recent data.

CRedit authorship contribution statement

Robin Monnier: Writing – original draft, Methodology, Investigation, Formal analysis. **Erwan Personne:** Writing – review & editing, Methodology, Conceptualization. **Patrick Stella:** Writing – review & editing, Conceptualization. **Laura Ferraz de Paula:** Investigation, Formal analysis. **Patrick Schallbart:** Writing – review & editing, Conceptualization. **Charlotte Roux:** Writing – review & editing, Writing – original draft. **Bruno Peuportier:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Bruno Peuportier reports financial support was provided by VINCI through Fondation des Ponts (in-dustrial chair). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was performed with the financial support of the French Environment Agency (ADEME), and the chair lab recherche environnement VINCI ParisTech.

Data availability

Data will be made available on request.

The authors declare that the main data supporting the findings of this study are available within the paper. Details on very specific thermal dynamic simulations or LCA hypotheses are available on request. Considering thermal dynamic simulation, the commercial software Pléiades® was used, but open-source tools such as EnergyPlus (<https://energyplus.net/>) could also be used.

References

- [1] Jolliet O, Saadé-Sbeih M, Shaked S, Jolliet A, Crettaz P. *Environmental Life Cycle Assessment* (CRC Press). CRC Press; 2015.
- [2] Cabeza, L. F., Bai, Q., Bertoldi, P., Kihila, J. M., Lucena, A. F. P., Mata, É., Mirasgedis, S., Novikova, A., & Saheb, Y. (2022). Buildings. In IPCC (Ed.), *Climate Change 2022—Mitigation of Climate Change Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Pradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.011* (pp. 953–1048). <https://doi.org/10.1017/9781009157926.011>.
- [3] Arceo A, Touchie M, O'Brien W. Beyond density: examining overlooked drivers of housing and neighborhood greenhouse gas emissions. *Sustain Cities Soc* 2025;120: 106131. <https://doi.org/10.1016/j.scs.2025.106131>.
- [4] Brozovsky J, Gustavsen J, Gaitani N. Zero emission neighbourhoods and positive energy districts – a state-of-the-art review. *Sustain Cities Soc* 2021;72:103013. <https://doi.org/10.1016/j.scs.2021.103013>.
- [5] Dorr E, François C, Poulhès A, Wurtz A. A life cycle assessment method to support cities in their climate change mitigation strategies. *Sustain Cities Soc* 2022;85: 104052. <https://doi.org/10.1016/j.scs.2022.104052>.
- [6] Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., ... Péan, C. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. (First)*. Intergovernmental Panel on Climate Change (IPCC). <https://doi.org/10.59327/IPCC/AR6-9789291691647>.
- [7] Chi F, Borys I, Jin L, Zhu Z, Bart D. The strategies and effectiveness of climate adaptation for the thousand pillars dwelling based on passive elements and passive spaces. *Energy Build* 2019;183:17–44. <https://doi.org/10.1016/j.enbuild.2018.10.029>.
- [8] Porritt S, Shao L, Cropper PC, Goodier CI. Adapting dwellings for heat waves. *Sustain Cities Soc* 2011;1(2):81–90. <https://doi.org/10.1016/j.scs.2011.02.004>.
- [9] Monnier R, Schallbart P, Roux C, Peuportier B. Integrating effects of overheating on human health into buildings' life cycle assessment. *Int J Life Cycle Assess* 2024. <https://doi.org/10.1007/s11367-024-02353-3>.
- [10] Huijbregts MAJ, Steinmann JZN, Elshout PMF, Stam G, Verones F, Vieira M, et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 2017;22(2):138–47. <https://doi.org/10.1007/s11367-016-1246-y>.
- [11] Murray CJL, Aravkin AY, Zheng P, Abbafati C, Abbas KM, Abbasi-Kangevari M, et al. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the global burden of disease study 2019. *Lancet* 2020;396(10258):1223–49. [https://doi.org/10.1016/S0140-6736\(20\)30752-2](https://doi.org/10.1016/S0140-6736(20)30752-2).
- [12] Mavrogianni A, Davies M, Batty M, Belcher S, Bohnenstengel S, Caruthers D, et al. The comfort, energy and health implications of London's urban heat island. *Build Serv Eng Res Technol* 2011;32(1):35–52. <https://doi.org/10.1177/0143624410394530>.
- [13] Tomlinson CJ, Chapman L, Thornes JE, Baker CJ. Including the urban heat island in spatial heat health risk assessment strategies: a case study for Birmingham. *UK International Journal of Health Geographics* 2011;10(1):42. <https://doi.org/10.1186/1476-072X-10-42>.
- [14] Alexandri E, Jones P. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Build Environ* 2008;43(4):480–93. <https://doi.org/10.1016/j.buildenv.2006.10.055>.
- [15] Bowler DE, Buyung-Ali L, Knight TM, Pullin AS. Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landscape Urban Plan* 2010;97(3):147–55. <https://doi.org/10.1016/j.landurbplan.2010.05.006>.
- [16] Feyisa GL, Dons K, Meilby H. Efficiency of parks in mitigating urban heat island effect: an example from Addis Ababa. *Landscape Urban Plan* 2014;123:87–95. <https://doi.org/10.1016/j.landurbplan.2013.12.008>.
- [17] Gillner S, Vogt J, Tharang A, Dettmann S, Roloff A. Role of street trees in mitigating effects of heat and drought at highly sealed urban sites. *Landscape Urban Plan* 2015; 143:33–42. <https://doi.org/10.1016/j.landurbplan.2015.06.005>.
- [18] Gunawardena KR, Wells MJ, Kershaw T. Utilising green and bluespace to mitigate urban heat island intensity. *Sci Total Environ* 2017;584–585:1040–55. <https://doi.org/10.1016/j.scitotenv.2017.01.158>.
- [19] Kim J, Yeom S, Hong T. Analyzing the cooling effect, thermal comfort, and energy consumption of integrated arrangement of high-rise buildings and green spaces on urban heat island. *Sustain Cities Soc* 2025;119:106105. <https://doi.org/10.1016/j.scs.2024.106105>.
- [20] Lemonsu A, Masson V, Shashua-Bar L, Erell E, Pearlmutter D. Inclusion of vegetation in the town energy balance model for modelling urban green areas.

- Geosci Model Dev 2012;5(6):1377–93. <https://doi.org/10.5194/gmd-5-1377-2012>.
- [21] Qiu G, Li H, Zhang Q, Chen W, Liang X, Li X. Effects of Evapotranspiration on mitigation of urban temperature by vegetation and urban agriculture. *J Integr Agric* 2013;12(8):1307–15. [https://doi.org/10.1016/S2095-3119\(13\)60543-2](https://doi.org/10.1016/S2095-3119(13)60543-2).
- [22] Zhang Y, Ge J, Wang S, Dong C. Optimizing urban green space configurations for enhanced heat island mitigation: a geographically weighted machine learning approach. *Sustain Cities Soc* 2025;119:106087. <https://doi.org/10.1016/j.scs.2024.106087>.
- [23] Kumar P, Sharma A. Study on importance, procedure, and scope of outdoor thermal comfort – a review. *Sustain Cities Soc* 2020;61:102297. <https://doi.org/10.1016/j.scs.2020.102297>.
- [24] Migliari M, Babut R, De Gaulmyn C, Chesne L, Baverel O. The metamatrix of thermal comfort: a compendious graphical methodology for appropriate selection of outdoor thermal comfort indices and thermo-physiological models for human-biometeorology research and urban planning. *Sustain Cities Soc* 2022;81:103852. <https://doi.org/10.1016/j.scs.2022.103852>.
- [25] Zhang T, Fu X, Qi F, Shen Y, Xu P, Tao Y, et al. Optimizing pedestrian thermal comfort in urban street canyons for summer and winter: tree planting or low-albedo pavements? *Sustain Cities Soc* 2025;120:106143. <https://doi.org/10.1016/j.scs.2025.106143>.
- [26] Wang Y, Bakker F, De Groot R, Wörtche H. Effect of ecosystem services provided by urban green infrastructure on indoor environment: a literature review. *Build Environ* 2014;77:88–100. <https://doi.org/10.1016/j.buildenv.2014.03.021>.
- [27] Morakinyo TE, Dahanayake KWD, Kalani C, Adegun OB, Balogun AA. Modelling the effect of tree-shading on summer indoor and outdoor thermal condition of two similar buildings in a Nigerian university. *Energy Build* 2016;130:721–32. <https://doi.org/10.1016/j.enbuild.2016.08.087>.
- [28] Huang Y, Mao F, Xu Y, Qi J, Zhang W, Li C, et al. Association between urban heat islands and heat-related mortality in 70 pairs of adjacent urban-rural counties among 8 topographic regions in China. *Sustain Cities Soc* 2025;121:106182. <https://doi.org/10.1016/j.scs.2025.106182>.
- [29] Le Mentec S, Stella P, Najjar G, Kastendeuch P, Saudreau M, Ngao J, et al. Coupling the TEB and surfatm models for heat flux modelling in urban area: comparison with flux measurements in Strasbourg (France). *Front Environ Sci* 2022;10. <https://www.frontiersin.org/articles/10.3389/fenvs.2022.856569>.
- [30] Masson V. A physically-based scheme for the urban energy budget in atmospheric models. *Bound-Lay Meteorol* 2000;94(3):357–97. <https://doi.org/10.1023/A:1002463829265>.
- [31] Personne E, Bedos C, Lichiheb N, Loubet B, Stella P. SURFATM: a model for the exchanges of energy, ammonia, ozone, and pesticides between soil, vegetation, and atmosphere at the field scale. *Software Impacts* 2024;19:100600. <https://doi.org/10.1016/j.simpa.2023.100600>.
- [32] Personne E, Loubet B, Herrmann B, Mattsson M, Schjoerring JK, Nemitz E, et al. SURFATM-NH3: a model combining the surface energy balance and bi-directional exchanges of ammonia applied at the field scale. *Biogeosciences* 2009;6(8):1371–88. <https://doi.org/10.5194/bg-6-1371-2009>.
- [33] Peuportier B, Blanc Sommeux I. Simulation tool with its expert interface for the thermal design of multizone buildings. *Int J Solar Energy* 1990;8(2):109–20. <https://doi.org/10.1080/01425919008909714>.
- [34] Brun, A., Spitz, C., & Mora, E. W. and L. (2009). Behavioural comparison of some predictive tools used in a low-energy building. 11th IBPSA Conference, Glasgow, Scotland, July 27-30. <https://www.aivc.org/resource/behavioural-comparison-some-predictive-tools-used-low-energy-building>.
- [35] Munaretto F, Recht T, Schalbart P, Peuportier B. Empirical validation of different internal superficial heat transfer models on a full-scale passive house. *J Build Perform Simul* 2017;1–22. <https://doi.org/10.1080/19401493.2017.1331376>.
- [36] CEN. (2019). *Standard EN 16798-1 Energy performance of buildings—Ventilation for buildings—Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics—Module M1*.
- [37] Polster B, Peuportier B, Blanc Sommeux I, Diaz Pedregal P, Gobin C, Durand E. Evaluation of the environmental quality of buildings towards a more environmentally conscious design. *Sol Energy* 1996;57(3):219–30. [https://doi.org/10.1016/S0038-092X\(96\)00071-0](https://doi.org/10.1016/S0038-092X(96)00071-0).
- [38] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* 2016;21(9):1218–30. <https://doi.org/10.1007/s11367-016-1087-8>.
- [39] Palacios-Munoz B, Peuportier B, Gracia-Villa L, López-Mesa B. Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: a new approach. *Build Environ* 2019;160:106203. <https://doi.org/10.1016/j.buildenv.2019.106203>.
- [40] Frapin M, Roux C, Assoumou E, Peuportier B. Modelling long-term and short-term temporal variation and uncertainty of electricity production in the life cycle assessment of buildings. *Appl Energy* 2021;118141. <https://doi.org/10.1016/j.apenergy.2021.118141>.
- [41] Lemonsu, A., & Le Roy, B. (2021). *Résilience – Livrable 3. Rapport descriptif des données climatiques* (p. 27 pages). ADEME. <https://bibliothèque.ademe.fr/changement-climatique-et-energie/6409-resilience.html>.
- [42] Taylor KE, Stouffer RJ, Meehl GA. An overview of CMIP5 and the experiment design. *Bull Am Meteorol Soc* 2012;93(4):485–98. <https://doi.org/10.1175/BAMS-D-11-00094.1>.
- [43] Jacob D, Petersen J, Eggert B, Alias A, Christensen OB, Bouwer LM, et al. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Reg Environ Chang* 2014;14(2):563–78. <https://doi.org/10.1007/s10113-013-0499-2>.
- [44] Seity Y, Brousseau P, Malardel S, Hello G, Bénard P, Bottier F, et al. The AROME-France convective-scale operational model. *Mon Weather Rev* 2011;139(3):976–91. <https://doi.org/10.1175/2010MWR3425.1>.
- [45] Simpson D, Benedictow A, Berge H, Bergström R, Emberson LD, Fagerli H, et al. The EMEP MSC-W chemical transport model – technical description. *Atmos Chem Phys* 2012;12(16):7825–65. <https://doi.org/10.5194/acp-12-7825-2012>.
- [46] Gago EJ, Roldan J, Pacheco-Torres R, Ordóñez J. The city and urban heat islands: a review of strategies to mitigate adverse effects. *Renew Sustain Energy Rev* 2013;25:749–58. <https://doi.org/10.1016/j.rser.2013.05.057>.
- [47] Tan Z, Lau K-K-L, Ng E. Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. *Energy Build* 2016;114:265–74. <https://doi.org/10.1016/j.enbuild.2015.06.031>.
- [48] Calhoun ZD, Willard F, Ge C, Rodriguez C, Bergin M, Carlson D. Estimating the effects of vegetation and increased albedo on the urban heat island effect with spatial causal inference. *Sci Rep* 2024;14(1):540. <https://doi.org/10.1038/s41598-023-50981-w>.
- [49] De Munck C, Lemonsu A, Masson V, Le Bras J, Bonhomme M. Evaluating the impacts of greening scenarios on thermal comfort and energy and water consumptions for adapting Paris city to climate change. *Urban Clim* 2018;23:260–86. <https://doi.org/10.1016/j.uclim.2017.01.003>.
- [50] Parison S, Chaumont M, Koukoku-Arnaud R, Long F, Bernik A, Da Silva M, et al. The effects of greening a parking lot as a heat mitigation strategy on outdoor thermal stress using fixed and mobile measurements: case-study project “tertiary forest. *Sustain Cities Soc* 2023;98:104818. <https://doi.org/10.1016/j.scs.2023.104818>.
- [51] Jiao M, Jenerette GD, Zhou W, Wang J, Zheng Z. Adaptive shading: how microclimates and surface types amplify tree cooling effects? *Urban For Urban Green* 2024;101:128546. <https://doi.org/10.1016/j.ufug.2024.128546>.
- [52] Shashua-Bar L, Hoffman ME. Vegetation as a climatic component in the design of an urban street. *Energy Build* 2000;31(3):221–35. [https://doi.org/10.1016/S0378-7788\(99\)00018-3](https://doi.org/10.1016/S0378-7788(99)00018-3).
- [53] Rahman MA, Stratopoulos LMF, Moser-Reischl A, Zölch T, Häberle K-H, Rötzer T, et al. Traits of trees for cooling urban heat islands: a meta-analysis. *Build Environ* 2020;170:106606. <https://doi.org/10.1016/j.buildenv.2019.106606>.
- [54] Kunert N, Schwendenmann L, Potvin C, Holscher D. Tree diversity enhances tree transpiration in a Panamanian forest plantation. *J Appl Ecol* 2012;49(1):135–44. <https://doi.org/10.1111/j.1365-2664.2011.02065.x>.
- [55] Kjelgren R, Montague T. Urban tree transpiration over turf and asphalt surfaces. *Atmos Environ* 1998;32(1):35–41.
- [56] Zheng S, Guldmann J-M, Wang Z, Qiu Z, He C, Wang K. Experimental and theoretical study of urban tree instantaneous and hourly transpiration rates and their cooling effect in hot and humid area. *Sustain Cities Soc* 2021;68:102808. <https://doi.org/10.1016/j.scs.2021.102808>.
- [57] Vigiúé V, Lemonsu A, Hallegatte S, Beaulant A-L, Marchadier C, Masson V, et al. Early adaptation to heat waves and future reduction of air-conditioning energy use in Paris. *Environ Res Lett* 2020;15(7):075006. <https://doi.org/10.1088/1748-9326/ab6a24>.
- [58] IPCC. (2013). IPCC fifth assessment report, climate change 2013: The physical science basis. IPCC, 31–39.
- [59] Dupin N, Peuportier B, Duer, K., Cohen, M., Favre, B., Mejri, O., & Vorger, E. (2014, October). *Evaluation of ventilative cooling in a single family house – Characterization and modelling of natural ventilation*. Sustainable building conference, Sustainable building conference, Barcelona, 2014. <https://minesparis-psl.hal.science/hal-01459888>.