Nature-Based Solutions for Urban Carbon Neutrality

Subjects: Construction & Building Technology | Green & Sustainable Science & Technology
Contributor: Zhe Xiao , Hua Ge , Michael A. Lacasse , Liangzhu (Leon) Wang , Radu Zmeureanu

The building sector is responsible for nearly 40% of the total global direct and indirect CO_2 emissions. Urban green infrastructure, which includes features such as urban trees, vegetation, green roofs, and green facades, are examples of nature-based solutions often employed as municipal climate mitigation and adaptation strategies. This approach offers a range of cost-effective strategies for reducing municipal CO_2 emissions and presents compelling public policy co-benefits such as improved urban livability and enhanced environmental conditions.

climate change | nature-based solutions | carbon neutral | carbon sequestration | resilient buildings and communities

1. Introduction

The assessment of the Intergovernmental Panel on Climate Change (IPCC) indicated that human activities are the primary cause of increasing concentrations of greenhouse gases (GHGs) in the atmosphere, which in turn leads to climate change [1]. Thus, emissions of carbon dioxide (CO_2), the most abundant of the GHGs, increasingly became an issue of concern for the different governments of nations around the globe. In the past few years, major carbon-emitting countries have developed plans and roadmaps to reduce or offset their CO_2 emissions in the coming decades in order to achieve a carbon neutral future [2][3][4]. The building sector is responsible for nearly 40% of total global direct and indirect CO_2 emissions [5]. Thus, the decrease in equivalent-CO_2 emissions from this sector could have a significant impact on climate change.

The urban green infrastructure, such as urban trees, vegetation, green roofs, and green facades, should be considered as nature-based solutions (NBS) for mitigating direct and indirect CO_2 emissions from buildings and communities, given that these NBS can, in accordance with the findings in many existing studies, potentially mitigate the urban heat island effect, lower the temperature of the surrounding environment and inside buildings, and sequester CO_2.

2. Reduction in Carbon Emissions

The use of NBS could result in direct and indirect contributions to the reduction in carbon emissions, both for buildings and communities. Such strategies include reducing the temperature of an urban area, improving the energy efficiency of buildings, and sequestering carbon from the atmosphere by way of photosynthesis.

2.1. Temperature Reduction for Urban Areas

The growth of urbanization has been driven by the growth of population and as well, the ever-increasing demand for new dwellings all over the world. According to the Population Reference Bureau [6], by 2022, the worldwide urban population was, on average, 57% of the entire population, and this percentage increased to 79% for developed countries. The UHI effect is an undesired side effect of urbanization and could considerably aggravate the outdoor air quality by intensifying pollutant concentration [7], increasing the energy demand for cooling buildings within urban centers [8], worsening the thermal comfort of pedestrians [9][10][11], as well as increasing the risks of occurrence of overheating in buildings which can be lethal to elderly, vulnerable people [12][13][14]. The increase in energy demand is correlated to CO_2 emissions, as the majority of energy is still generated through the burning of fossil fuels. A higher temperature in urban areas as compared to non-urban surroundings is a result of the absorption of shortwave and longwave radiation, heat emissions from buildings and vehicles, reduced air circulation, and less evapotranspiration as occurs from vegetation [15][16][17][18]. The NBS can contribute to mitigating elevated temperatures in urban areas by increasing surface shading and providing evaporative cooling [19][20][21][22][23] to reduce the surface temperature of the ground and buildings. The reduction in excessive temperatures in urban areas can also lead to improved thermal comfort and the mitigation of overheating in buildings.

Alexandri and Jones [24] investigated the thermal effects of vegetation on the building envelope for nine cities across the world with nine different types of climates and different configurations of the urban canyon and wind conditions using a two-dimensional, prognostic, micro-scale model. Ground-covering grasses and ivies were the types of vegetation covering green roofs and green walls, respectively. Simulations were conducted for a typical day of the hottest month in a given year. The maximum and average reduction in air temperature at the roof level were, respectively, 26 °C and 12.8 °C during the daytime. For the canyon, the corresponding maximum and average temperature reductions were, respectively, 11.3 °C and 9.1 °C. The effectiveness of vegetation was found to be increased for a hotter and drier climate but reduced for a wider canyon. Francoeur et al. [25] compared the performance of lawns located in Montreal, Canada, to another three types of urban NBS that had a low height, in terms of heat mitigation. It was concluded that the efficiency of NBS in mitigating urban heat could be improved by increasing the number of plant species. For a larger scale application, Bass et al. [26] investigated the effectiveness of green roofs to mitigate the UHI for the city of Toronto. The study was conducted using a Meso-scale Community Compressible simulation model at a 1 km resolution over a 48 h period. It was found that when the green roof area was 5% of the total area of the city, it could reduce the temperature by up to 0.5 °C at a height of 5 m above the ground. In addition, the cooling effects could be intensified by adding irrigated green roofs in high-density urban areas.

In another study, the effectiveness of cool, irrigated green roofs was compared to green roofs without irrigation in reducing the air temperature for the entire Berlin area [27]; the green roofs with irrigation were found to be able to reduce the average daytime and nighttime temperature by 0.71 °C and 0.26 °C, respectively. The study was conducted using the Weather Research and Forecasting (WRF) model coupled with the Urban Canopy Model. The evapotranspiration cooling effect was the primary factor considered when parameterizing the vegetation. No other information was provided on the implementation of vegetation in the model.

In the process of applying NBS to mitigate the excessive temperature in urban areas, the importance of different factors influencing the performance and efficacy of various NBS was explored in the vast majority of studies. In general, the number of NBS, their different types, and combinations of types with respect to the selection of vegetation were found to be significant in determining the degree of effectiveness of NBS in reducing urban temperature [20][21][28][29][30][31][32][33]. However, there was no consensus regarding the most effective vegetation type or combination of vegetation in reducing the urban temperature, given that the urban environment and local climatic conditions differed from one city to another. The implementation of NBS is evidently designed specifically for a particular city. Other considerations to be taken into account to achieve an optimal NBS design are the surrounding micro-climate and substrate, which acts as the foundation for vegetation to grow on. In general, extensive green roofs tend to have lower cooling and insulation properties compared to intensive systems due to their thinner substrate layer. On the other hand, intensive green roofs, with their thicker substrate layer and diverse plantings, provide enhanced insulation and cooling benefits, as well as the capability for carbon sequestration and storage. For instance, the vegetation is less effective in reducing the temperature in a wider urban canyon [24], and the effectiveness of a vertical greenery system is affected by its orientation [34]. The cooling effects of a green roof can be improved by situating the green roof within an urban area where there is a greater building density [26]. Moreover, the water content in the substrate is crucial to the performance of NBS as it provides the water resource for the evapotranspiration process, from which the heat from the surroundings is absorbed and thus cools the adjacent air [19][23][30][34]. It was also observed from these studies that the most commonly used numerical tools to undertake numerical simulations at an urban scale are the Weather Research and Forecasting (WRF) model coupled with the Single Layer Urban Canopy Model [27][35][36] and the ENVI-met model [28][29][37].

One major knowledge gap identified from these studies when assessing the performance of NBS in reducing air temperature was that it is still difficult to describe the mechanism of convective heat transfer between the plant and the ambient air. Qualitative and quantitative information were derived from statistical methods using mathematical models and empirical data, which were simultaneously affected by factors such as wind, humidity, microbiological factors, and other relevant factors. It is somewhat challenging to accurately isolate the effect of one particular factor and to extrapolate observations to a broader context [38]. Thus, it is also challenging to develop a reliable model that can accurately measure the effect of vegetation on temperature reduction. In addition, for studies at an urban scale, estimations of temperature reduction are performed primarily using numerical simulation tools, given the difficulty and complexity of obtaining accurate measurements before and after implementing the NBS with high resolution on such a large scale. Nevertheless, validation tests, i.e., validation of models using a smaller area and validation of parameters used in these models from experiments, can be conducted to improve the reliability of numerical models. It was also noted that many studies used scenarios with extreme weather, such as heatwave events, and the investigations were usually only conducted for a period of less than one month. The quantitative information obtained from such short periods may not adequately represent the usefulness of incorporating NBS over the long term, e.g., over a year. Thus, to permit further quantifying the reduction in CO_2 emissions due to the temperature reduction in urban areas, long-term simulations, i.e., one or multiple-year simulations, the results from which can potentially minimize the impact of seasonal climate factors and short-term extreme weather on the interpretation of results, are essential, although extensive computational resources may be required.

2.2. Improvement of Building Energy Efficiency

The NBS are effective in reducing the air temperature in urban areas. Less energy may be needed for the heating and cooling of buildings in such areas to maintain a comfortable indoor environment during the summer time and thus reduce anthropogenic CO_2 emissions. Meanwhile, the application of NBS on individual buildings may have a more significant impact on their energy efficiency. Specifically, heat flux through the building envelope can be reduced by the coverage of green walls and green roofs; insulation effects of green roofs and the increased thermal mass from green roof layers can moderate influences of outdoor temperature to the fluctuations of indoor temperature, which leads to improvements of building energy efficiency; lower wind speeds on the surface of buildings can be achieved from the buffer effect of NBS in proximity to, or on the surface of buildings, as such buffering reduces air infiltration across the building envelope and thus contributes to the reduction in heat loss or heat gain.

Shading and evapotranspiration are the two major cooling mechanisms that may be provided by NBS coverage [39]. The shading prevents a fraction of solar radiation from reaching and warming the underlying surfaces, and the evapotranspiration process absorbs heat from ambient air. As the number of leaf layers increases, the capacity for shading to reduce solar radiation is enhanced. Experiments from Ip et al. [40] indicated that 45% to 12% of solar radiation could transmit through 1 to 5 leaf layers of Parthenocissus Quinquefolia (Virginia creeper). In the numerical simulation conducted by Wong et al. [41], the heat transfer values of the building envelope were reduced by 0.59%, 21.2%, and 40.7% when the shading coefficients of species were 0.986, 0.500, and 0.041, respectively. Feng and Hewage [42] estimated the energy performance of a five-story high building located at the University of British Columbia (UBC), Okanagan, Canada, and having a LEED Gold standard for three green vegetation coverage scenarios, i.e., green building without a green roof, green building with full green roof, and green building with full green wall. These coverage scenarios were compared to the benchmark scenario using validated simulation models in Design Builder software. The results indicated that the full green roof and the full green wall could save 3.2% and 7.3% of the annual cooling energy, respectively. The function of vegetation was represented by a green roof energy balance model developed by Sailor [43].

In addition to energy savings over the summer time, it was noted that NBS are also beneficial to building energy savings over the winter time. In particular, the compositions of NBS structure can increase the thermal resistance of the building envelope by reducing its thermal conductivity and thus reduce the heat loss during the colder time periods. The analysis of the thermal performance of NBS during colder time periods should be divided into two phases. One phase is for the time period during which vegetation can still thrive. A second phase occurs when the temperature drops below freezing points, and most of the vegetation has withered.

In respect to Phase 1, for colder time periods in winter where vegetation can still thrive, Foustalieraki et al. [33] took measurements for temperature and humidity for a two-story commercial building located in Athens, Greece, during the winter time. The green roof increased indoor air temperature by up to 0.7 °C during the winter period, according to the simulation using Energy Plus, and energy reduction for heating attained a value of up to 11.4%.

Collins et al. [44] compared energy consumption for heated boxes installed with green roofs and bare roofs during the winter time in southern Finland. Prior to the freezing period, the energy loss of green roofs was 25% to 38% less than that of bare roofs. Cameron et al. [45] monitored the energy consumption to maintain 16 °C for a water tank surrounded by brick cuboids covered with different vegetation during winter time. The use of ivy or other foliage could reduce the heating energy consumption of the water tank by 21% to 37% in comparison to the bare cuboids surrounding the water tank. The energy efficiency was found to be further improved during periods of extreme weather.

In the previously discussed study of a LEED Gold standard building located in Kelowna, Canada, and conducted by Feng and Hewage [42], 20% of heat loss through walls and roofs could be reduced by completely covering them with vegetation during a typical week in the winter (i.e., 13 January 00:00 a.m. to 20 January 00:00 a.m.). However, the status of vegetation affected by the harsh winter environment was not considered in this study.

Serra et al. [30] found that the thermal conductance and transmittance of the substrate for a vertical greenery modular system (VGMS) located in Turin, Italy, was lower than that of the reference wall. Overall, the VGMS could have a beneficial effect on the reduction in heat loss during the winter period, despite its capacity to reduce the amount of absorbed solar radiation.

In respect to Phase 2, for which colder periods occur where the temperature drops below freezing and most vegetation has withered, it has been determined that the properties of substrates affected by ice and snow become the dominant factor when assessing the thermal performance of the building envelope. The process of water freezing could improve the energy efficiency of green roofs by reducing heat flux at the inner surface of the roof by up to 30% [32]. The thermal conductivity of the substrate affected by frost before and after freezing was, respectively, 0.41 W/m·k and 0.12 W/m·k [33]. The snow cover can be considered as an extra insulator to the building envelope [44][46][47]. Thus, it reduced the relative contribution of the green roof in saving heating energy.

In all the literature reviewed, no studies were found that investigated the variations in thermal performance of NBS over the long term, i.e., several years, and few studies were conducted to compare the performance of different types of NBS for buildings having different configurations. As well, the influence of NBS on the integrity of the building envelope over the long term is unknown. For instance, water leakage from blue–green roofs (green roofs incorporating a stormwater management system) may damage the roof membrane, which would have a negative impact on the thermal performance of the original roof. Consequently, the overall benefit of using a green roof would thereby become questionable. Moreover, in most studies, the net energy savings by considering the consumption of operational energy to maintain the NBS is not discussed, and neither were there any studies for which reductions in building energy correlated to carbon reductions.

2.3. Biological Carbon Sequestration and Storage

Urban vegetation has the capacity to store and sequester carbon in the atmosphere via its growth and photosynthesis processes. Nowak et al. quantified the carbon storage and sequestration by trees in the United States [48]. On average, the carbon storage density was 7.96 kg CO_2/m^2 per year of tree cover, and the carbon sequestration rate was 0.28 kg CO_2/m^2 per year of tree cover. The carbon storage density was estimated by calculating the ratio of total carbon storage, which was calculated using biomass equations, as given in Equation (1), to tree cover area [49], and the rate of carbon sequestration was estimated using the urban tree growth rate [50]. For the United States, the total annual urban net carbon sequestration was estimated at 18.9 million tonnes per year.

$$M=aD^b \quad (1)$$

where *M* is the oven-dry weight of the tree (kg), *D* is the diameter at breast height (DBH), *a* and *b* are parameters. Chen [51] quantified carbon storage and carbon sequestration by urban green infrastructures, i.e., urban green space developed for recreation, amenity, and ecological purposes, in 35 major Chinese cities that covered most types of climates in China from a review of existing studies for these locations. The average carbon storage density was 2.13 kg CO_2/m^2. The average carbon sequestration capability was 0.22 kg CO_2/m^2 per year, and the corresponding total amount of carbon sequestration was 1.9 million tonnes per year.

Gratani et al. [52] estimated the carbon sequestration capabilities, in smaller-scale studies, of four parks located in Rome, Italy, filled with different tree and shrub species. Carbon sequestration rates of these four parks varied from 0.664 to 0.998 kg CO_2/m^2 per year, which were found to be significantly correlated with the leaf area index. According to George and Palmyra [53], the carbon sequestration for a green roof was 1.22 kg CO_2/m^2 per year. In a study completed by Heusinger and Weber [54], a green roof contributed to 0.313 kg CO_2/m^2 per year of carbon sequestration. Luo et al. [55] compared the capability of different green roofs configurations located in Chengdu, China, for carbon sequestration, i.e., the degree of carbon sequestration provided by two different roof substrates, three different roof substrate depths, and various tree plant species. The mean carbon sequestration rate was estimated at 6.47 kg CO_2/m^2 per year, and the best-performing green roof had a carbon sequestration rate of 7.03 kg CO_2/m^2 per year. Kong et al. [56] estimated the contributions to carbon storage of an urban turfgrass system, located in Hong Kong, by considering grasses, soils, and carbon emissions from maintenance operations. The carbon storage capacity of grasses and soils were, respectively, 0.05 to 0.21 kg CO_2/m^2 and 1.26 to 4.89 kg CO_2/m^2, whereas the operational carbon emission was 0.17 to 0.63 kg CO_2/m^2 per year. Based on these numbers, it was concluded that the benefits of carbon storage for grasses and soils could be offset in 5 to 24 years.

Grossi et al. [57] considered a carbon sequestration rate of 0.575 kg CO_2/m^2 of tree coverage in the life-cycle assessment of an all-electric laboratory and a natural gas-powered single-detached house located in Montreal. The gardens of the laboratory, with an area of 410 m^2, and the single-detached house, with 505 m^2, featured full urban tree coverage; the total life cycle carbon emission for these two buildings was offset approximately 17% and 3%, respectively, from urban tree coverage.

The capability of carbon sequestration as can be achieved from NBS varies depending on numerous different aspects. The carbon sequestration rate of trees is affected by species, tree size, tree health, growth rates, and corresponding site conditions [48]. Regarding the carbon sequestration capability of green roofs, the roof plant species, depth, and moisture content of the substrate have a direct impact on the carbon sequestration and storage capability. Moreover, plants and substrates also affect each other's performance as the growth and survival of the roof plants rely on the substrate [58][59].

With respect to the carbon sequestration capability of vertical greenery systems, water content, percentage of dry matter, mortality of plants, and changes in the carbon storage rate of plants over the long term are factors that affect the carbon sequestration capability [60]. In addition to the biomass Equation (1), which was specifically applied to trees, the carbon sequestration of the vegetation is typically assessed by measuring the carbon content using an allometric equation and laboratory work in both the above and below-ground biomass (AGB); i.e., stems and leaves found above ground, and below-ground biomass (BGB), as is evident in the plant roots [61].

The initial step when applying an allometric equation is to assess the total dry weight (TDW) of the plant or biomass, followed by determining the total carbon weight (TCW), and, finally, the total CO_2 weight (TCO2W). The relationship between these parameters varies based on the species of vegetation. For instance, according to Othman and Kasim [62], the TCW is 0.5 times the TDW, and the TCO2W is 3.67 times the TCW for shrubs.

One of the major limitations of current studies when assessing the carbon sequestration capability of plants and vegetation is the uncertainty in the outcomes induced by the uncertainty in the input data. Further, many relevant studies have been undertaken, but only on a limited scale, and thus, their conclusions may not be generalizable to scenarios of a greater scale. Weissert et al. [63] indicated that there was a considerable amount of uncertainty in the currently available results for the evaluation of the potential of urban forests to reduce CO_2 emissions in urban areas. Lin et al. estimated uncertainties in input data, sampling methods, and models when using the i-Tree model to estimate carbon sequestration from the tree canopies of 15 American cities [64]. Bootstrap and Monte Carlo simulations were used for the estimation. Sampling methods were found to be the most significant factor contributing to the uncertainty associated with carbon sequestration, surpassing the accuracy of the models and input data. It was also noteworthy that for most studies, the degree of soil respiration as a means of offsetting the contribution made by NBS in carbon sequestration was not considered.

3. Design Guidelines

It is evident that NBS can deliver a number of benefits to the urban environment, including, but not limited to, mitigating urban heat island effects, saving energy, and sequestering carbon. However, given that numerous influencing factors need to be considered to determine the performance of NBS and considering the potential interactions between NBS and building components (e.g., green roof and building roof layers; vertical greenery system and building façade), design guidelines should be developed to facilitate the planning, design, construction, and maintenance of NBS. This allows practitioners to maximize the benefits of NBS whilst maintaining the integrity and functionality of the building to which the NBS is attached in different situations over a long-term period.

References

1. Stocker, T.F.; Qin, D.; Plattner, G.K.; Tignor, M.M.B.; Allen, S.K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P.M. Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, 2013; Volume 9781107057.
2. Government of Canada. Canadian Net-Zero Emissions Accountability Act; Government of Canada: Ottawa, ON, Canada, 2021.
3. IEA. An Energy Sector Roadmap to Carbon Neutrality in China; OECD Publishing: Tokyo, Japan, 2021.
4. Government of Spain Spain. 2050—Fundamentals and Proposals for a National Long-Term Strategy; Government of Spain: Madrid, Spain, 2021.
5. United Nations. Environment Programme 2022 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector; UN: Nairobi, Kenya, 2022.
6. Population Reference Bureau. World Population Data Sheet 2022; Population Reference Bureau: Washington, DC, USA, 2022.
7. Sarrat, C.; Lemonsu, A.; Masson, V.; Guedalia, D. Impact of Urban Heat Island on Regional Atmospheric Pollution. Atmos. Environ. 2006, 40, 1743–1758.
8. López-Guerrero, R.E.; Verichev, K.; Moncada-Morales, G.A.; Carpio, M. How Do Urban Heat Islands Affect the Thermo-Energy Performance of Buildings? J. Clean. Prod. 2022, 373, 133713.
9. Fahed, J.; Kinab, E.; Ginestet, S.; Adolphe, L. Impact of Urban Heat Island Mitigation Measures on Microclimate and Pedestrian Comfort in a Dense Urban District of Lebanon. Sustain. Cities Soc. 2020, 61, 102375.
10. Giridharan, R.; Emmanuel, R. The Impact of Urban Compactness, Comfort Strategies and Energy Consumption on Tropical Urban Heat Island Intensity: A Review. Sustain. Cities Soc. 2018, 40, 677–687.
11. Sanagar Darbani, E.; Monsefi Parapari, D.; Boland, J.; Sharifi, E. Impacts of Urban Form and Urban Heat Island on the Outdoor Thermal Comfort: A Pilot Study on Mashhad. Int. J. Biometeorol. 2021, 65, 1101–1117.
12. Teyton, A.; Tremblay, M.; Tardif, I.; Lemieux, M.-A.; Nour, K.; Benmarhnia, T. A Longitudinal Study on the Impact of Indoor Temperature on Heat-Related Symptoms in Older Adults Living in Non-

Air-Conditioned Households. Environ. Health Perspect. 2022, 130, 77003.

13. Tham, S.; Thompson, R.; Landeg, O.; Murray, K.A.; Waite, T. Indoor Temperature and Health: A Global Systematic Review. Public Health 2020, 179, 9–17.
14. Gupta, R.; Barnfield, L.; Gregg, M. Overheating in Care Settings: Magnitude, Causes, Preparedness and Remedies. Build. Res. Inf. 2017, 45, 83–101.
15. Santamouris, M.; Synnefa, A.; Karlessi, T. Using Advanced Cool Materials in the Urban Built Environment to Mitigate Heat Islands and Improve Thermal Comfort Conditions. Sol. Energy 2011, 85, 3085–3102.
16. Hamilton, I.; Stocker, J.; Evans, S.; Davies, M.; Carruthers, D. The Impact of the London Olympic Parkland on the Urban Heat Island. J. Build. Perform. Simul. 2014, 7, 119–132.
17. Kakoniti, A.; Georgiou, G.; Marakkos, K.; Kumar, P.; Neophytou, M.K.-A. The Role of Materials Selection in the Urban Heat Island Effect in Dry Mid-Latitude Climates. Environ. Fluid Mech. 2016, 16, 347–371.
18. Roth, M.; Lim, V.H. Evaluation of Canopy-Layer Air and Mean Radiant Temperature Simulations by a Microclimate Model over a Tropical Residential Neighbourhood. Build. Environ. 2017, 112, 177–189.
19. Cascone, S.; Coma, J.; Gagliano, A.; Pérez, G. The Evapotranspiration Process in Green Roofs: A Review. Build. Environ. 2019, 147, 337–355.
20. MacIvor, J.S.; Margolis, L.; Perotto, M.; Drake, J.A.P. Air Temperature Cooling by Extensive Green Roofs in Toronto Canada. Ecol. Eng. 2016, 95, 36–42.
21. Tiwari, A.; Kumar, P.; Kalaiarasan, G.; Ottosen, T.-B. The Impacts of Existing and Hypothetical Green Infrastructure Scenarios on Urban Heat Island Formation. Environ. Pollut. 2021, 274, 115898.
22. He, Y.; Lin, E.S.; Tan, C.L.; Tan, P.Y.; Wong, N.H. Quantitative Evaluation of Plant Evapotranspiration Effect for Green Roof in Tropical Area: A Case Study in Singapore. Energy Build. 2021, 241, 110973.
23. Wadzuk, B.M.; Schneider, D.; Feller, M.; Traver, R.G. Evapotranspiration from a Green-Roof Storm-Water Control Measure. J. Irrig. Drain. Eng. 2013, 139, 995–1003.
24. Alexandri, E.; Jones, P. Temperature Decreases in an Urban Canyon Due to Green Walls and Green Roofs in Diverse Climates. Build. Environ. 2008, 43, 480–493.
25. Francoeur, X.W.; Dagenais, D.; Paquette, A.; Dupras, J.; Messier, C. Complexifying the Urban Lawn Improves Heat Mitigation and Arthropod Biodiversity. Urban For. Urban Green. 2021, 60, 127007.

26. Bass, B.; Krayenhoff, S.; Martilli, A.; Stull, R. Mitigating the Urban Heat Island with Green Roof Infrastructure. In Proceedings of the Urban Heat Island Summit, Toronto, ON, Canada, 1–4 May 2002.
27. Wang, X.; Li, H.; Sodoudi, S. The Effectiveness of Cool and Green Roofs in Mitigating Urban Heat Island and Improving Human Thermal Comfort. Build. Environ. 2022, 217, 109082.
28. Wang, Y.; Ni, Z.; Hu, M.; Chen, S.; Xia, B. A Practical Approach of Urban Green Infrastructure Planning to Mitigate Urban Overheating: A Case Study of Guangzhou. J. Clean. Prod. 2021, 287, 124995.
29. Wang, Y.; Ni, Z.; Chen, S.; Xia, B. Microclimate Regulation and Energy Saving Potential from Different Urban Green Infrastructures in a Subtropical City. J. Clean. Prod. 2019, 226, 913–927.
30. Serra, V.; Bianco, L.; Candelari, E.; Giordano, R.; Montacchini, E.; Tedesco, S.; Larcher, F.; Schiavi, A. A Novel Vertical Greenery Module System for Building Envelopes: The Results and Outcomes of a Multidisciplinary Research Project. Energy Build. 2017, 146, 333–352.
31. Bartesaghi-Koc, C.; Osmond, P.; Peters, A. Quantifying the Seasonal Cooling Capacity of ‘Green Infrastructure Types’ (GITs): An Approach to Assess and Mitigate Surface Urban Heat Island in Sydney, Australia. Landsc. Urban Plan. 2020, 203, 103893.
32. Arkar, C.; Domjan, S.; Medved, S. Heat Transfer in a Lightweight Extensive Green Roof under Water-Freezing Conditions. Energy Build. 2018, 167, 187–199.
33. Foustalieraki, M.; Assimakopoulos, M.N.; Santamouris, M.; Pangalou, H. Energy Performance of a Medium Scale Green Roof System Installed on a Commercial Building Using Numerical and Experimental Data Recorded during the Cold Period of the Year. Energy Build. 2017, 135, 33–38.
34. Pan, L.; Wei, S.; Chu, L.M. Orientation Effect on Thermal and Energy Performance of Vertical Greenery Systems. Energy Build. 2018, 175, 102–112.
35. Imran, H.M.; Kala, J.; Ng, A.W.M.; Muthukumaran, S. Effectiveness of Vegetated Patches as Green Infrastructure in Mitigating Urban Heat Island Effects during a Heatwave Event in the City of Melbourne. Weather Clim. Extrem. 2019, 25, 100217.
36. Dardir, M.; Berardi, U. Development of Microclimate Modeling for Enhancing Neighborhood Thermal Performance through Urban Greenery Cover. Energy Build. 2021, 252, 111428.
37. Evola, G.; Nocera, F.; Costanzo, V.; Detommaso, M.; Bonaccorso, S.; Marletta, L. Greenery Systems for the Mitigation of the Urban Heat Island: A Simulation Experience for Southern Italy. In Innovation in Urban and Regional Planning: Proceedings of the 11th INPUT Conference; Springer: Berlin/Heidelberg, Germany, 2021; pp. 427–438.
38. Convertino, F.; Vox, G.; Schettini, E. Convective Heat Transfer in Green Façade System. Biosyst. Eng. 2019, 188, 67–81.

39. Koch, K.; Ysebaert, T.; Denys, S.; Samson, R. Urban Heat Stress Mitigation Potential of Green Walls: A Review. Urban For. Urban Green. 2020, 55, 126843.

40. Ip, K.; Lam, M.; Miller, A. Shading Performance of a Vertical Deciduous Climbing Plant Canopy. Build. Environ. 2010, 45, 81–88.

41. Wong, N.H.; Tan, A.Y.K.; Tan, P.Y.; Wong, N.C. Energy Simulation of Vertical Greenery Systems. Energy Build. 2009, 41, 1401–1408.

42. Feng, H.; Hewage, K. Energy Saving Performance of Green Vegetation on LEED Certified Buildings. Energy Build. 2014, 75, 281–289.

43. Sailor, D.J. A Green Roof Model for Building Energy Simulation Programs. Energy Build. 2008, 40, 1466–1478.

44. Collins, S.; Kuoppamäki, K.; Kotze, D.J.; Lü, X. Thermal Behavior of Green Roofs under Nordic Winter Conditions. Build. Environ. 2017, 122, 206–214.

45. Cameron, R.W.F.; Taylor, J.; Emmett, M. A Hedera Green Façade—Energy Performance and Saving under Different Maritime-Temperate, Winter Weather Conditions. Build. Environ. 2015, 92, 111–121.

46. Andenæs, E.; Kvande, T.; Muthanna, T.; Lohne, J. Performance of Blue-Green Roofs in Cold Climates: A Scoping Review. Buildings 2018, 8, 55.

47. Lundholm, J.T.; Weddle, B.M.; MacIvor, J.S. Snow Depth and Vegetation Type Affect Green Roof Thermal Performance in Winter. Energy Build. 2014, 84, 299–307.

48. Nowak, D.J.; Greenfield, E.J.; Hoehn, R.E.; Lapoint, E. Carbon Storage and Sequestration by Trees in Urban and Community Areas of the United States. Environ. Pollut. 2013, 178, 229–236.

49. Nowak, D.J.; Crane, D.E.; Stevens, J.C.; Hoehn, R.E.; Walton, J.T.; Bond, J. A Ground-Based Method of Assessing Urban Forest Structure and Ecosystem Services. Aboricult. Urban For. 2008, 34, 347–358.

50. Nowak, D.J.; Crane, D.E. Carbon Storage and Sequestration by Urban Trees in the USA. Environ. Pollut. 2002, 116, 381–389.

51. Chen, W.Y. The Role of Urban Green Infrastructure in Offsetting Carbon Emissions in 35 Major Chinese Cities: A Nationwide Estimate. Cities 2015, 44, 112–120.

52. Gratani, L.; Varone, L.; Bonito, A. Carbon Sequestration of Four Urban Parks in Rome. Urban For. Urban Green. 2016, 19, 184–193.

53. George, A.; Palmyra, V. The Potential Carbon Offset Represented by a Green Roof. Ph.D. Thesis, University of Virginia, Charlottesville, VA, USA, 2012.

54. Heusinger, J.; Weber, S. Extensive Green Roof CO2 Exchange and Its Seasonal Variation Quantified by Eddy Covariance Measurements. Sci. Total Environ. 2017, 607–608, 623–632.
55. Luo, H.; Liu, X.; Anderson, B.C.; Zhang, K.; Li, X.; Huang, B.; Li, M.; Mo, Y.; Fan, L.; Shen, Q.; et al. Carbon Sequestration Potential of Green Roofs Using Mixed-Sewage-Sludge Substrate in Chengdu World Modern Garden City. Ecol. Indic. 2015, 49, 247–259.
56. Kong, L.; Shi, Z.; Chu, L.M. Carbon Emission and Sequestration of Urban Turfgrass Systems in Hong Kong. Sci. Total Environ. 2014, 473–474, 132–138.
57. Grossi, F.; Ge, H.; Zmeureanu, R.; Baba, F. Feasibility of Planting Trees around Buildings as a Nature-Based Solution of Carbon Sequestration—An LCA Approach Using Two Case Studies. Buildings 2022, 13, 41.
58. Shafique, M.; Xue, X.; Luo, X. An Overview of Carbon Sequestration of Green Roofs in Urban Areas. Urban For. Urban Green. 2020, 47, 126515.
59. Kazemi, F.; Mohorko, R. Review on the Roles and Effects of Growing Media on Plant Performance in Green Roofs in World Climates. Urban For. Urban Green. 2017, 23, 13–26.
60. Marchi, M.; Pulselli, R.M.; Marchettini, N.; Pulselli, F.M.; Bastianoni, S. Carbon Dioxide Sequestration Model of a Vertical Greenery System. Ecol. Model. 2015, 306, 46–56.
61. Zaid, S.M.; Perisamy, E.; Hussein, H.; Myeda, N.E.; Zainon, N. Vertical Greenery System in Urban Tropical Climate and Its Carbon Sequestration Potential: A Review. Ecol. Indic. 2018, 91, 57–70.
62. Othman, R.; Kasim, S.Z.A. Assessment of Plant Materials Carbon Sequestration Rate for Horizontal and Vertical Landscape Design. Int. J. Environ. Sci. Dev. 2016, 7, 410–414.
63. Weissert, L.F.; Salmond, J.A.; Schwendenmann, L. A Review of the Current Progress in Quantifying the Potential of Urban Forests to Mitigate Urban CO2 Emissions. Urban Clim. 2014, 8, 100–125.
64. Lin, J.; Kroll, C.N.; Nowak, D.J. An Uncertainty Framework for I-Tree Eco: A Comparative Study of 15 Cities across the United States. Urban For. Urban Green. 2021, 60, 127062.