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The food-water-energy nexus and green roofs in Sao Jose dos Campos, Brazil, and Johannesburg, South Africa

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Green roofs affect the urban food-water-energy nexus and have the potential to contribute to sustainability. Here we developed a generalizable methodology and framework for data-sparse cities to analyze the food-water-energy nexus of green roofs. Our framework integrates the environmental costs and benefits of green roofs with food-water-energy systems and makes it possible to trace energy-water-carbon footprints across city boundaries. Testing the framework in São José dos Campos (SJC), Brazil and Johannesburg, South Africa, we found that green roofs are essentially carbon neutral and net energy consumers from a life cycle perspective. SJC is a net water beneficiary while Johannesburg is a net water consumer. Rainwater utilization could save irrigated water, but requires 1.2 times more energy consumption. Our results show that SJC and Johannesburg could direct their green roof development from local food production and energy saving, respectively and highlight opportunities for green roof practices in cities.

INTRODUCTION

Urbanization processes are accelerators of global changes in biophysical processes[1]. Despite apparent economic growth, new risks emerge in urban areas, such as food security, flooding, water scarcity, and heat islands. Food, water, and energy (FWE) are indispensable lifeline resources for cities that are emphasized as pressing concerns in the Sustainable Development Goals (SDGs) of the United Nations[2]. The interactions between FWE systems, referred to as the FWE nexus, increasingly reshape the shocks that were previously contained within a geographic area or a sector but now are becoming globally interconnected[3]. Since local-scale actions impact regional and global development[1], the cities take on more responsibilities to seek powerful governance approaches for the wicked FWE nexus challenges[4].

Green roofs are an innovative strategy for urban vertical space utilization that could enhance the land use efficiency in high-density cities, and show clear links to all three components of the FWE nexus, which is revealed from the conceptual framework[5] of green and blue infrastructure and urban FWE nexus. Specifically, green roofs perform well in the aspects of food (rooftop farming), water (rainwater harvesting, waterlogging prevention, water purification), and energy (temperature modulation, thus energy saving), guarding against the challenges of FWE nexus[4–6]. Urban areas depend on extracting external and tele-connected resources[7], and the cities' demands for FWE consequently have far-reaching environmental impacts within and outside city boundaries[8,9]. In this context, edible green roofs produce local food[10] and will consequently reduce the food mileage during transportation[11]. Rainwater collection for use and energy saving effects of green roofs also decline water and energy demand and

further avoid the environmental footprints embedded in the upstream supply chains[12,13]. However, processing, construction, maintenance, decommission, and disposal of green roofs generate environmental impacts; the carbon emissions of green roofs account for 10 kg per square meter during 30 years of life cycle[14]. If green roofs are part of the efforts to build a sustainable urban future, their trade-offs should be evaluated to distribute the benefits and adverse impacts. With cities at the core of securing a sustainable planet[15], understanding the trade-offs from an urban perspective is the key to capturing the interplays between green roofs and urban FWE nexus.

Researchers have made some progress in quantifying the implications of green roofs. In general, most urban-scale investigations are restricted to a silo lens, mainly focusing on life cycle impacts and (or) FWE-related benefits. For example, Saha and Eckelman[16] estimated the food production potential from edible rooftops in Boston. Jahanfar et al.[17] evaluated the power generation and carbon emissions of photovoltaic panels on green roofs in the city of Toronto. Sanyé-Mengual et al.[18] compared the life cycle environmental impacts of the linear food system and rooftop greenhouse in Barcelona, and quantified the total reductions of carbon emissions and energy savings of rooftop greenhouse. Zhou et al.[19] investigated the ecological and economic impacts of city-wide adoption of green roofs in Corvallis (Oregon, USA), involving water yield and purification, carbon sequestration, costs and benefits. Regarding multiple trade-offs evaluations of green roofs, studies are frequently limited to small scales, which cannot reflect the cardinal role of green roofs in urban areas. For instance, Toboso-Chavero et al.[20] established a procedure to determine the implications (including the degree of

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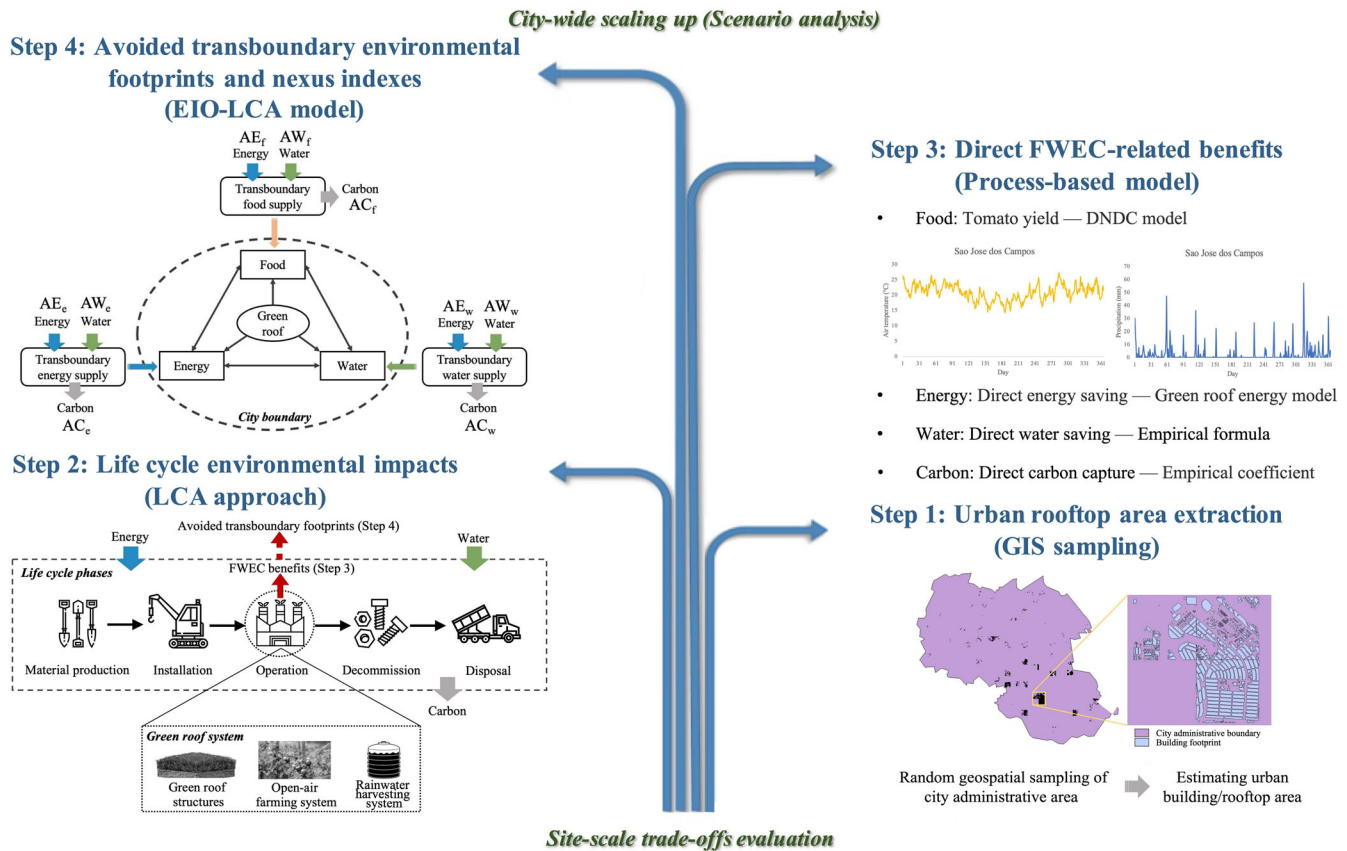✉email: fanxin.meng@bnu.edu.cn; zfyang@bnu.edu.cn

Fig. 1 A generalizable methodology and framework for urban FWE nexus of green roofs. It emphasizes the potential areas for urban green roof development by GIS sampling method (Step 1), green roofs' life cycle environmental impacts (Step 2), operational FWEC-related benefits by nested process-based model (Step 3), and consequently avoided transboundary environmental footprints by EIO-LCA model (Step 4). The city-wide scenario analyses were additionally conducted based on the site-scale trade-offs.

FWE self-sufficiency, life cycle environmental costs, and avoided CO_2 emissions) of different combinations of food and energy production, and rainwater harvesting strategies on neighborhood rooftops in Barcelona. Likewise, Salvador et al.[13] evaluated the self-sufficiency potential of rooftop gardens in a Brazilian technology park through food production, renewable generation, and rainwater harvesting. They further developed the Nexus Emission Index as a decision-making tool for roof planning to estimate the avoided CO_2 emissions by not using conventional systems (i.e., imported food, energy, and water networks).

Taken together, there is a lack of systemic focus on the impacts and benefits of green roofs in relation to FWE nexus at the city scale, and missing data is a vital stumbling block. To guide an embracing trade-offs assessment of urban-scale green roofs, we developed an integrated methodology and framework (Fig. 1) with geographic information system (GIS) and urban metabolism approaches, to capture the detailed flows between green roofs and urban FWE nexus. It includes the negative life cycle environmental burdens (energy consumption, water consumption, and carbon emissions), direct FWEC (food, water, energy, and carbon)-related benefits in the operational stage, and indirect avoided transboundary environmental footprints induced by the direct benefits. We applied the method to two representative data-sparse cities in different continents with distinct sizes and features to demonstrate the utility of the method, i.e., São José dos Campos (SJC) in Brazil and Johannesburg in South Africa (Supplementary Fig. 1). Our findings contribute to a systemic understanding of the dynamic links between green roofs and FWE nexus, and reveal the heterogeneity of SJC and Johannesburg for their decision-makings on urban green roof management.

The key results of this paper are outlined as follows: (1) trade-offs between life cycle environmental impacts, direct and indirect benefits of green roofs, (2) life cycle impacts of green roofs, (3) avoided transboundary environmental footprints induced by the direct benefits of green roofs and their drivers, (4) city-wide performance of green roofs based on the scenario analyses.

RESULTS

A generalizable methodology and framework

FWE-targeted prioritization of urban green roof initiatives can help decision-makers improve urban sustainability and the way in which green roofs deliver desired benefits and adverse impacts. In this study, a generalizable methodology and framework (Fig. 1) that integrates GIS (Step 1, Fig. 1) and urban metabolism methods (Steps 2–4, Fig. 1) is developed to clarify the dynamic links and trade-offs between green roofs and FWE nexus from an urban system perspective. The proposed methodology and framework quantify the green roofs' life cycle environmental impacts (Step 2, Fig. 1) and multiple FWEC-related benefits in the operational stage (Step 3, Fig. 1). More importantly, highlighting the in- and trans-city boundary interactions between green roofs and FWE nexus, the methodology and framework allow researchers to measure the avoided transboundary environmental footprints and identify the key drivers of indirect effects generated by green roofs (Step 4, Fig. 1). In addition, scenario-based evaluations of city-wide green roof implementations are conducted to direct the cities' local practices. Such methodology and framework can be replicated in any city especially for data-sparse cities to guide the urban and
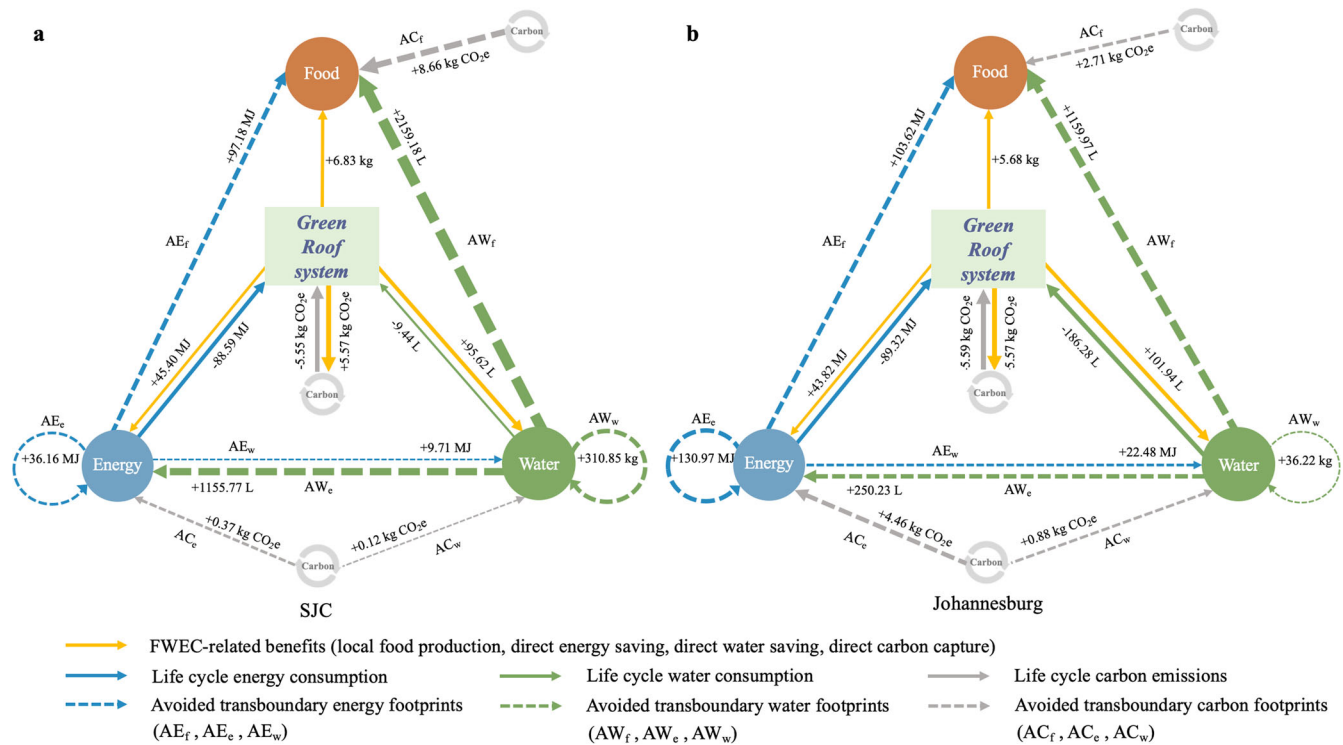
Fig. 2 Trade-offs of green roofs per square meter in relation to FWE nexus. The figure shows the life cycle environmental impacts, FWEC-related benefits, and avoided transboundary environmental footprints of green roofs. Panels (**a**) and (**b**) illustrate the detailed results of green roofs' trade-offs in SJC and Johannesburg, respectively. The center rectangle in each panel represents the entire green roof system in this study, including green roof structures, open-air farming system, and rainwater harvesting system. Three colored circles represent the food, energy, and water sectors and the corresponding resources. Positive values are the benefits of green roofs, in which the yellow arrows refer to the local direct FWEC-related benefits, and the dashed arrows refer to the avoided transboundary environmental footprints, including avoided energy footprints (AE_f, AE_e, AE_w), avoided water footprints (AW_f, AW_e, AW_w), and avoided carbon footprints (AC_f, AC_e, AC_w). As for the subscript letters, f, e, and w refer to the local food production, direct energy saving, and direct water saving, respectively; AE_f is the avoided transboundary energy footprints by local food production on green roofs, the same is true for the others (see Supplementary Table 1 for more abbreviations). Negative values represent the life cycle environmental burdens of green roofs, including energy consumption, carbon emissions, and water consumption over the green roofs' full life cycle.

regional development decisions such as greenery development, FWE governance initiatives, as well as coalitions among cities.

Trade-offs analysis

In previous studies, the trade-offs of green roofs on FWE nexus are hindered by a lack of systemic lenses and approaches. The presented method supports the systemic trade-offs analysis of green roofs through the quantifications of life cycle environmental impacts (Step 2, Fig.1), direct FWEC-related benefits in the operational stage (Step 3, Fig. 1), together with the avoided transboundary environmental footprints induced by the local direct benefits (Step 4, Fig. 1). Such an analysis for trade-offs encompasses multiple elements within and outside cities, stressing that an isolated lens of linkages between green roofs and FWE nexus would lead to the understanding bias by over- or underestimating the implications of green roofs.

The modeling results reflect that green roof implementation is a promising practice for localizing sustainable development goals. Specifically, green roofs generate direct operational benefits including local food (tomato) production (6.83 kg·m^{-2}, 5.68 kg·m^{-2}, Fig. 2, respectively for SJC and Johannesburg annually, the same goes hereafter. More calculation details can be found in Methods), direct water saving (95.62 L·m^{-2}, 101.94 L·m^{-2}), direct energy saving (45.40 MJ·m^{-2}, 43.82 MJ·m^{-2}), and direct carbon capture (5.57 kg·m^{-2}, 5.57 kg·m^{-2}). Green roofs therefore provide a solid impetus to SDG2 (food), SDG6 (water), SDG7 (energy), and SDG13 (climate). However,

green roofs come at the cost of materials, resources, and energy inputs from the life cycle perspective. The environmental impacts associated with these inputs are trade-offs for the benefits resulting from green roofs. To be concrete, the life cycle carbon emissions (5.55 kg·m^{-2}, 5.59 kg·m^{-2}, Fig. 2) of green roofs nearly offset their carbon capture. While the life cycle energy consumptions (88.59 MJ·m^{-2}, 89.32 MJ·m^{-2}) are 2 times their direct energy saving, the life cycle water consumptions (9.44 L·m^{-2}, 186.28 L·m^{-2}) are 0.1 and 2 times SJC's and Johannesburg's direct water saving, respectively. Thus, green roofs are regarded as basically carbon neutral and net energy consumers in SJC and Johannesburg, net water consumer in Johannesburg, but net water beneficiary in SJC from a life cycle perspective.

Certain land uses have far larger spillover impacts than their own small spatial extents[21]. The micro-scale green roofs within city boundaries can indirectly contribute to regional environmental footprint savings by enhancing urban self-sufficiency of resources and weakening the cities' import dependence. All of the avoided transboundary environmental footprints induced by green roofs' benefits in SJC and Johannesburg exceed their corresponding life cycle environmental impacts, enabling green roofs to benefit from the indirect effects beyond cities (Supplementary Discussion). To be specific, the avoided transboundary environmental footprints of green roofs in SJC and Johannesburg are respectively 1.6–384 and 1.4–7.8 times their life cycle impacts. It is noted that SJC's local food production contributes most to the transboundary energy (68%, Fig. 4), carbon (95%), and water (59%)
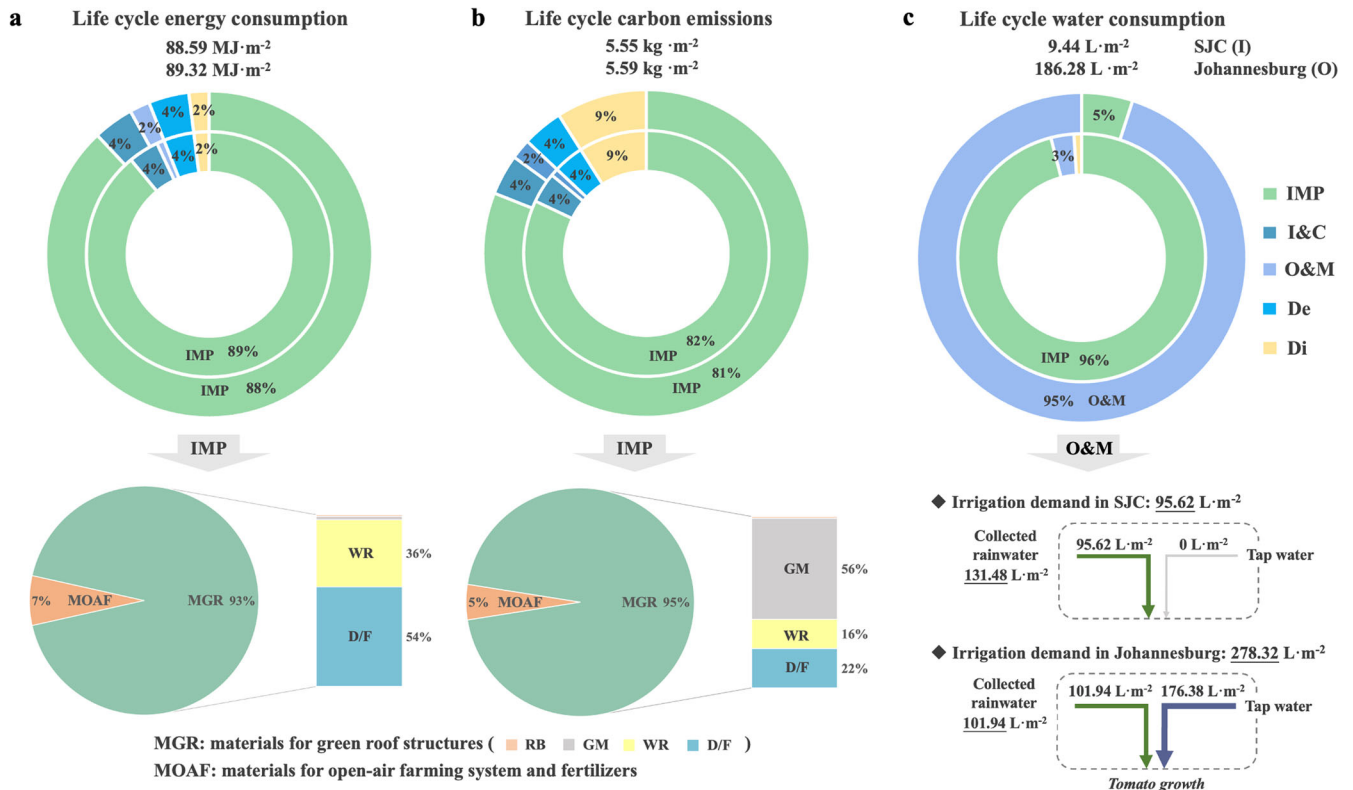
Fig. 3 Life cycle impacts of green roofs per square meter. Panels (**a**), (**b**), and (**c**) respectively show the life cycle energy consumption, carbon emissions, and water consumption of the green roof system from left to right. I inner circle, O outer circle, IMP infrastructure material production, I&C installation and construction, O&M operation and maintenance, De demolition, Di disposal, RB root barrier, GM growing medium, WR water retention, D/F drainage/filter.

footprints, and the local food production in Johannesburg is responsible for most of the upstream water footprints as well (80%). Whereas direct energy saving in Johannesburg is an especially important driver of both transboundary energy footprints (51%) and carbon footprints (55%). However, the avoided environmental footprints induced by the direct water saving benefits in SJC and Johannesburg are both relatively minor, with only 1–9% and 3–11% of the total avoided environmental footprints.

Compared with direct impacts, the indirect spillover effects of site-scale green roofs in cities are often less visible and less well understood. Nevertheless, managing these transboundary impacts of land use is often more important than direct impacts[21]. Distant interactions between green roofs and FWE nexus across jurisdictional boundaries reflect one's dependency and responsibilities on other geographic areas. Cities should make their governance arrangements (e.g., trade agreements, supply chain structures) at broader spatial scales based on green roofs' overall expected impacts to reinforce the urban land teleconnections and resource sustainability.

Life cycle environmental impacts

Step 2 (Fig. 1) in the methodology and framework investigated the life cycle performance of green roof system. Regarding life cycle energy consumption and carbon emissions, green roofs show a similar pattern in SJC and Johannesburg (Fig. 3a, b), 88–89% of energy consumption and 81–82% of carbon emissions are concerned in the infrastructure material production (IMP, see more abbreviations in Supplementary Table 1) phase. By analyzing the materials involved in this phase, i.e., materials for green roof structures (MGR), materials for open-air farming system and fertilizers (MOAF), it is found that MGR is the greatest impact

contributor with 93% of energy consumption and 95% of carbon emissions in the IMP phase. Taking a further step to investigate different MGR structures, the drainage/filter (D/F) layer and growing medium (GM) layer have dominant shares of the environmental costs, respectively in terms of energy (54%) and carbon (56%) (Fig. 3a, b). Thus, the application of MGR with lower energy and carbon budgets especially for the D/F layer and GM layer should be underscored. Additionally, the disposal (Di) phase is the second most important influential stage of life cycle carbon emissions owing to the waste treatment (Fig. 3b). The actions of material sorting and waste recovery respectively in the IMP and Di phases, hence, are both vital for improving the life cycle environmental friendliness of green roofs in the long run.

Regarding life cycle water consumption, there are heterogeneities between SJC and Johannesburg. Cities' local meteorology shapes different irrigation demands for tomatoes, and using rainwater to irrigate proves to be a solution that fosters a direct saving of irrigation water in the operation and maintenance (O&M) phase. The total rainwater harvesting capacity of green roofs in SJC (131.48 L·m^{-2}) can fully meet the irrigation demand for tomato production (95.62 L·m^{-2}). While in Johannesburg, the harvested rainwater of green roofs is 101.94 L·m^{-2} and meets around 37% of the tomato irrigation demand (278.32 L·m^{-2}), and Johannesburg consequently requires an additional tap water supply in the O&M phase. Therefore, there is a significant gap in the life cycle water consumption of green roofs between SJC (9.44 L·m^{-2}, Fig. 2a) and Johannesburg (186.28 L·m^{-2}, Fig. 2b). Specifically, 96% of life cycle water consumption in SJC is sourced from the IMP phase (Fig. 3c) and 95% of that is concentrated in the O&M stage of green roofs in Johannesburg (Fig. 3c).

What's mentioned that the rainwater harvesting system is more energy and carbon intensive compared with tap water irrigation (using tap water for tomato irrigation directly rather than
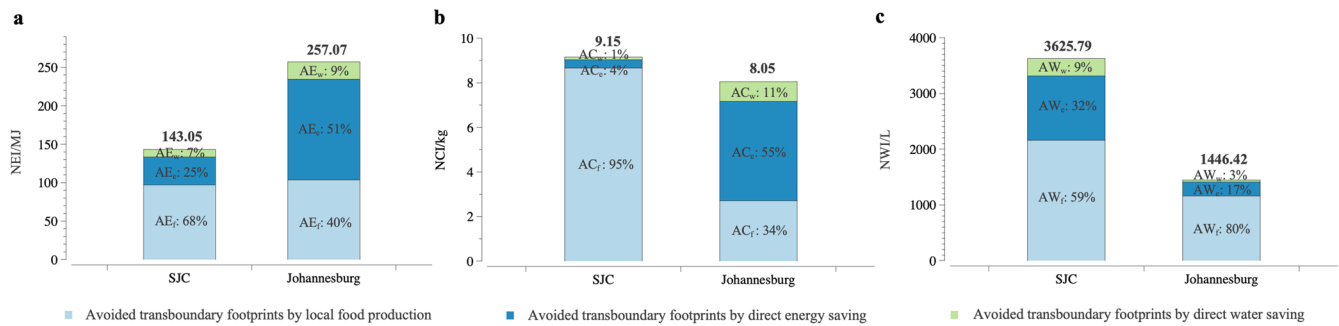
Fig. 4 Structural analysis for nexus index of green roofs per square meter. a Avoided transboundary energy footprints, the total value is defined as Nexus Energy Index (NEI) which is the sum of AE_f, AE_e, AE_w. **b** Avoided transboundary carbon footprints, the total value is defined as Nexus Carbon Index (NCI) which is the sum of AC_f, AC_e, AC_w. **c** Avoided transboundary water footprints, the total value is defined as Nexus water Index (NWI) which is the sum of AW_f, AW_e, AW_w. Bold numbers on top of each bar indicate the total value of the nexus index.

collecting rainwater to irrigate, and the life cycle impacts of this scheme are available in Supplementary Fig. 2) from a life cycle perspective. Results indicate that the life cycle energy consumption and carbon emissions of rainwater harvesting are respectively 1.2 and 1.5 times higher than tap water (Supplementary Table 2), and 84% and 91% of the life cycle energy consumption and carbon emissions come from the IMP phase of rainwater harvesting system (in which the rainwater harvesting tank contributes 86% to both energy and carbon in the IMP phase, Supplementary Fig. 3). Thus, the material selection of the rainwater harvesting system and especially for the tank might provide the chance to improve the life cycle performance of rainwater irrigation system.

Avoided transboundary environmental footprints and nexus indexes

Step 4 (Fig. 1) in the methodology and framework allows for identifying the key drivers of green roofs' transboundary effects. Results show that the driving forces to avoid the transboundary energy, water, and carbon footprints of green roofs diverge in SJC and Johannesburg, which can be interpreted as their trade structure heterogeneities in the upstream supply chains for urban FWE resources. The NEI (Nexus Energy Index, total value of avoided transboundary energy footprints induced by FWE-related benefits of green roofs) in SJC is only 56% of Johannesburg, while the NCI (Nexus Carbon Index, total value of avoided transboundary carbon footprints) in SJC turns to 1.2 times Johannesburg (Fig. 4a, b). It indicates that the upstream production and supply chains of SJC are carbon intensive, and the local food production constitutes the largest driving force to avoid the transboundary carbon footprints (i.e., AC_f, referring to the avoided carbon footprints by local food production) with 95%, and the AC_f exceeds the total NCI in Johannesburg. In consequence, the development of rooftop farming in SJC should be regarded as a key measure to reshape the regional carbon budgets.

Whereas the direct energy saving (AE_e and AC_e, respectively referring to the avoided energy and carbon footprints by direct energy saving) in Johannesburg drives the highest fractions of NEI and NCI with 51% and 55% respectively (Fig. 4a, b). The AE_e of green roofs in Johannesburg is 92% of the total NEI in SJC. Though green roofs in Johannesburg are net energy consumed from a life cycle perspective, the avoided energy footprints induced by direct energy saving (AE_e) are 5 times the net energy consumption (i.e., life cycle energy consumption minus direct energy saving) and could compensate for it based on the transboundary effects. Accordingly, capturing the potential of energy saving is the key to urban greenery implementation orienting FWE goals in Johannesburg.

Regarding the NWI (Nexus Water Index, total value of avoided transboundary carbon footprints) (Fig. 4c), SJC and Johannesburg

are structurally similar, that is, local food production (AW_f, avoided water footprints by local food production) by green roofs is the most critical contributor, with 59% and 80% respectively. In which the AW_f in SJC is 1.5 times the total NWI in Johannesburg, which can be explained by SJC's water-intensive food import process. Considering the leading promotion of food production in SJC on upstream carbon emission reductions, rooftop farming in SJC features apparently synergistic effects on transboundary carbon and water footprint savings in regions and would hopefully be the center of urban planning stage.

Scenario analysis
To evaluate the performance of city-wide green roof implementations, the geospatial analyses of the studied cities were carried out following Step 1 in the bespoke methodology and framework (Fig. 1), and a series of scenarios were proportionally conducted based on the simulation results of green roofs per square meter from Steps 2–4. On the premise that 30% of the urban building rooftops are available, if developing all the available rooftops into green roofs (Scenario B-S3), SJC showed full potential to satisfy its total urban vegetable demand (Fig. 5a), while the maximum food self-sufficiency rate of Johannesburg conservatively reaches 72.37% (Fig. 5b).

In addition, with the goal of 25% of water supplied from alternative sources in Johannesburg by 2050, the results indicate that the direct water savings (by using rainwater to substitute for irrigation water) of green roofs in Johannesburg in scenario B-S3 could contribute 5.3–7.1% to the city's goal. However, Johannesburg's highly irrigated characteristic of tomatoes leads to remarking issue of life cycle water consumption, which is 1.8 times green roofs' direct water savings (Fig. 2b). Even if the harvested rainwater is exclusively used for tomato irrigation, it could barely meet 37% of the tomato irrigation demand in Johannesburg. Thus, growing water-saving vegetables is of primary importance for Johannesburg to lessen the plentiful water consumption for irrigation. In terms of SJC, the harvested rainwater in SJC hopefully meets the entire tomato irrigation demand, and green roofs could further promote surprising upstream water footprint savings that are 1.2–2.4 times the city's water demands each year (Fig. 6b), demonstrating the ideal direct and indirect water saving effects when growing tomatoes on green roofs in SJC.

In scenario B-S3, from an energy perspective, green roofs in these two cities are net energy consumers within city boundaries. Both green roofs from SJC and Johannesburg draw indirect benefits by avoiding transboundary energy footprints that exhibit a trend to exceed 30% of city's energy demand (Fig. 6a, d). However, the life cycle energy consumption of green roofs in SJC will even achieve 45% of annual urban energy demand in the worst scenario. From a carbon perspective, green roofs in SJC and
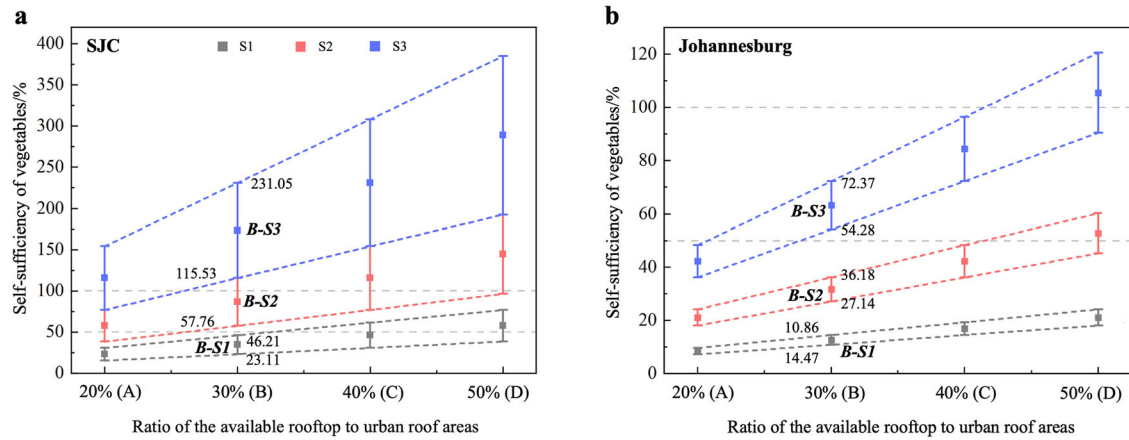
Fig. 5 Vegetable self-sufficiency of city-wide green roofs in different development scenarios. Panels (**a**) and (**b**) show the self-sufficiency of vegetables in SJC and Johannesburg, respectively. Taking Scenario B cluster in SJC (**a**), B-S1, B-S2, and B-S3 refer to 20%, 50%, and 100% of the city's available roofs converted into green roofs, with the premise that 30% of urban building rooftops are available. Before the settings of scenarios, we assumed the urban rooftop areas (building footprints) as 5–10% of urban administrative areas in SJC (more details are available in Methods), resulting in the range of self-sufficiency of vegetables under each sub-scenario in Cluster B.
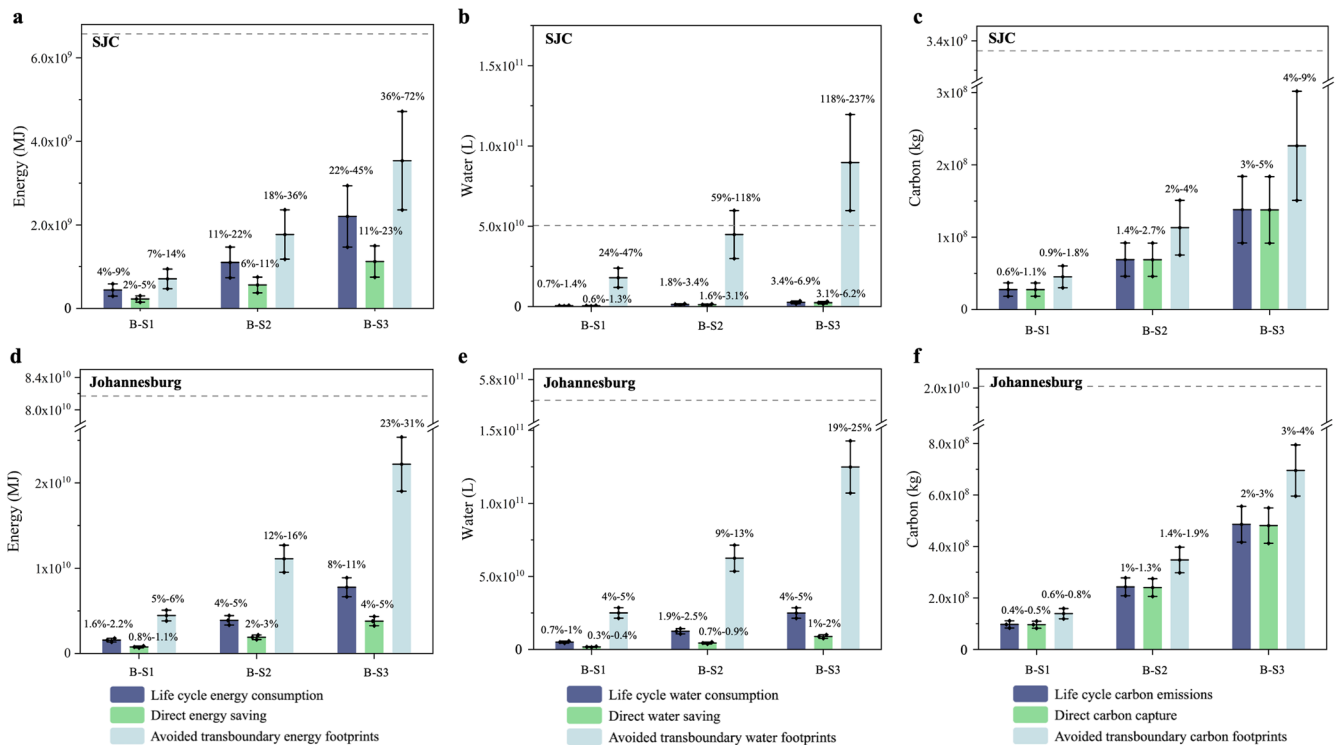

Fig. 6 Implications of city-wide green roofs in 30% of the available urban rooftop assumption. a–c The implications of green roof in SJC about energy, water, and carbon from left to right. **d–f** illustrate the implications of green roofs in Johannesburg about energy, water, and carbon from left to right. Taking panel (**a**) as an example, the three columns in different colors refer to the energy implications (i.e., life cycle energy consumption, direct energy saving, and avoided transboundary energy footprints) respectively in scenarios B-S1, B-S2, and B-S3 in SJC. The dotted line at the top presents the city's energy demand, which is used to compare with the life cycle energy consumption, direct energy saving, and avoided transboundary energy footprints of urban green roofs. The city-wide energy implications of green roofs vary because the urban roof area is a range. The percentages above the column that indicate the minimum and maximum values of the proportion of the energy implications to the urban energy demand, are accordingly in a range.

Johannesburg are carbon neutral within city boundaries. Seen from their environmental performance outside cities, the avoided transboundary carbon footprint of green roofs in SJC would contribute 0.04–0.07% to Brazil's 2030 carbon reduction target[22]. In Johannesburg, this figure would climb to 0.14–0.2% to South Africa's 2030 carbon reduction target[23] (see more in Supplementary Table 3). Despite the conservative performance on the national scale, it implies that green roofs make sense at least and

cities should realize the necessity for regional carbon reductions and climate adaptation by taking their green roof actions.

DISCUSSION

In this study, we designed an integrated methodology and framework (Fig. 1) for data-sparse cities that combines GIS and urban metabolism approaches to quantify the dynamic interplays

between up-scaling green roofs and FWE nexus at the urban scale, including life cycle environmental impacts, direct FWE-related benefits in the operational stage, and avoided transboundary environmental footprints induced by direct benefits. Recognizing that cities are influencing, and be influenced by, the external world via complex linkages and feedbacks[24], green roofs thus function for buffering the transboundary threats of cities by providing local FWE resources. Green roofs' implications beyond cities would make a headway into research and be a breakthrough for stakeholders to address the wicked urban and regional ecological challenges starting from green roof implementations. In particular, we established the Nexus Index series that considered the total potential of avoided transboundary environmental footprints in the long run as a way of providing subsidies for FWE-oriented prioritization.

The systemic understanding of the linkages between green roofs and FWE nexus within and beyond cities fosters a holistic measurement that improves upon current studies, which typically investigate the life cycle environmental impacts and (or) operational benefits of green roofs[25–29]. The progress can be achieved based on this generalizable methodology and framework where researchers can capture the delivery of life cycle environmental costs and operational FWE-related benefits of green roofs, together with visualizing the supply chain risks by tracking the embodied energy-water-carbon footprints beyond urban administrative boundaries. More importantly, the presented integrated methodology and framework can be applied in any city across the globe. It is typically urgent for cities with lower data availability to run complex models and important for Global South cities with not balanced existing knowledge and conflicts with limited resources[30,31]. The comparative information puts FWE resources on a level playing field with relevant impact domains and allows decision-makers to juxtapose the costs and effectiveness of green roof development scenarios, involving potential direct and indirect co-benefits and disservices at the city scale. By doing so, cities pose the potential to lower their barriers towards a more sustainable future by incorporating the value of green roofs into myriad FWE-oriented decision-making.

We highlighted that local food production took a key part in ensuring urban food security and decreasing the embodied impacts from upstream food supply chains. Specifically, SJC's local food production on green roofs could satisfy total urban self-sufficiency in prospect and drives 95% of the avoided transboundary carbon footprints. But note that extensive synergies and trade-offs exist between land use, water consumption, and energy consumption for food production[32]. In the case of water, it is the basis for all system transformations[33], if local food production purely aims at increase self-sufficiency but ignores the competing water resources between urban and agricultural sectors, it would be difficult to achieve the SDGs without water security[34]. The scheme of rainwater collection is regarded as a future solution to replenish the direct water resources for agricultural sustainability[35]. For instance, SJC's rainwater harvesting capacity is 1.4 times the tomato irrigation demand and fully covers the irrigated water, and the surplus of collected rainwater in SJC can be used to replace other urban water use types such as municipal, landscape, as well as toilet flushing, and thus decrease the urban direct water supply. Whereas the rainwater collection scheme is energy intensive, with 1.2 times and 1.5 times life cycle energy consumption and carbon emissions of tap water. In other words, using rainwater for irrigation may not be more sustainable than using tap water from the perspective of life cycle performance. However, to some extent, this may also represent that the amount of energy consumption and carbon emissions can be reduced by optimizing the design and operation of rainwater harvesting system, especially in the material selection of the rainwater collection tank, which generates 86% of the energy consumption

and carbon emissions in the IMP phase of the whole rainwater harvesting system.

On the other side, current rainwater management practices (e.g., sponge cities in China) are generally designed to intercept rainwater for flood control, and the potential for rainwater harvesting for reuse is less underappreciated. If the appropriate rainwater harvesting techniques are applied, 30–50% of rainwater in the driest areas could be used for crop irrigation[36]. Therefore, strengthened rainwater management measures for rainwater harvesting are recommended. There is also a need to encourage inter-municipal cooperation in designing and building coherent sponge facilities at the watershed level[37], to store as much rainwater as possible during water abundance periods and convey rainwater resources to cities with high water demand but lacking adequate rainwater. Urban challenges are often tackled in a separate way, an integrated assessment like FWE nexus is promoted for managing global resource issues and distributing the trade-offs of urban nature-based solutions (e.g., green roofs), since the negative externalities of every one of FWE systems in a silo lens compromise the long-term resilience and generate reinforced feedback loops of undesired resilience[38].

Given the differences in the trade-offs of green roofs on food-water-energy-land resources, heterogeneous considerations need to be made regarding the city's own characteristics (e.g., urban rooftop space potential, total food demand, rainwater endowment, and trade structure). It is possible for cities with limited rooftop areas and vegetable demand to achieve total vegetable self-sufficiency hopefully (e.g., SJC). However, for cities with high vegetable demand like Johannesburg, its vegetable self-sufficiency simply reaches a maximum of 72.37% under scenario B-S3, and it would be similarly difficult for Toronto[39] and Boston[16] to realize their entire vegetable self-sufficiency even in the scenario of 100% green roof conversion. Cities that have difficulty achieving their food self-sufficiency should consider improving food production efficiency (e.g., controlled-environment agriculture, growing more types of vegetables by full utilization of space per unit area) and exploiting other productive spaces in the cities (e.g., community gardens, school farms). In the meantime, the tree- and forest-based agriculture systems that could deliver nutritious food have been recommended to reshape and add resilience to food systems[40]. Transformations of various landscapes could be future paradigms for urban agriculture development and stimulate the pathway changes in land use as well[41]. Although achieving complete food self-sufficiency is not always promising, it is noteworthy that local agriculture is not a total solution to feed cities, but should be considered complementary to other sources of food supply[42] and an approach to reduce food mile emissions[43]. Especially for cities in the Global South and developing countries, local food production deserves further exploration for food security. To buffer the possible turbulence of local food provision in the context of urbanization[44], productive land shortage[45], extreme-weather events[46], and recent pandemic[47], the development of rooftop farming will be a step forward that makes vertical farming an emerging urban approach for compact cities.

Our results showed that rainwater substitution played a critical role in the irrigation water savings of crop growth, but the rainwater harvesting capacity was related to the local climatic conditions of cities. When considering tomato cultivation in cities with poor rainwater endowment but high irrigation demand like Johannesburg, some creative and practical methods are required for improving agricultural water use efficiency to release enough water for urban use, such as technological improvements (switching from less efficient diffuse irrigation to more efficient sprinkler or drip irrigation, reducing leakage of water infrastructure to fields) and crop screening (water-efficient crops, spatial allocation for planting)[48,49]. Here is also a reminder for stakeholders to systemically assess the trade-offs when adopting new

water-saving technologies[50–52]. Integrated analyses of the effects of potential solutions on reducing water scarcity, their financial and resource requirements, and the potential impacts on socio-economic development will provide opportunities for sustainable water use and additional emission reductions[53]. From a trans-boundary perspective, the local food production in SJC drives the highest proportion of avoided transboundary energy and carbon footprints, while Johannesburg's direct energy savings drive most transboundary energy and carbon footprints. Given that the benefits contributed by green roof planning differ in their role in regional environmental improvement, cities should determine their focus on local green roof development based on their own FWE goals and trade agreements, for example, SJC and Johannesburg can orient their green roof development from local food production and energy benefits (e.g., energy saving and energy generation), respectively.

Urban green roof is an innovative nature-based solution combating urban nexus challenges. Although we have made several advances in quantifying multiple interactions of green roofs on FWE nexus for SJC and Johannesburg in this study, there exist some limitations to achieving the embracing quantifications. To be specific, we made assumptions to select the rooftop area in the cities and did not identify the actually suitable areas since the local building attributes and spatial data were unavailable, and the scenario assumptions also increase the uncertainties of up-scaling results. Due to the lack of local life cycle parameters of green roofs, we adopted conventionally agreed factors from the leading database Gabi. Similarly, part of the empirical coefficients and proxy data were selected to run the nested process-based models. Furthermore, to aggregate the embodied transboundary environmental footprints, we used sectoral data to map the resource flows of products. Nonetheless, these limiting assumptions were necessary for data-sparse cities based on the urban scope of this study. The paper will therefore act as a stepping-stone to provide a methodology and framework that can be a strong foundation from which extensive future work can be born, particularly in cities from Global South. Even though the method requires a significant amount of data that many cities may not have, a future database of cities in the Global South can provide the parameters to be used in the methodology, in case the city does not have the data.

Establishing a credible local data system is an important basis for exploring the interlinkages between green roofs and FWE nexus. In this way, researchers can focus on the specific identification of the available rooftop areas and contribute to more accurate scenario development and analysis. In addition, it is also possible to enrich the assessment dimensions of green roofs in relation to FWE nexus and further quantify the connections between SDGs and FWE impacts by green roofs. For example, the educational significance and health benefits of rooftop agriculture can be assessed, and the rooftop agricultural systems can be prospectively evaluated and monitored to ensure the nutrient provisions based on the agrobiodiversity indices. In addition, the installation of photovoltaic panels on green roofs could actuate the synergistic energy benefits by generating renewables and saving energy. The functions of green roofs on waterlogging reduction and rainwater purification also provide insights for green roof evaluations.

Current research tends to rely on selective samples and the majority of urban settlements globally remain unknown. What is more, this imbalance is replicated geographically between north and south, and between cities with different sizes (population) and income levels (per capita GDP) located in the global regions[5]. Here we call for the explorations of the linkages of green roofs on FWE nexus based on urban heterogeneities. Further, another stream of research to be considered is the framework and assessment tool for wide kinds of FWE nexus implications from an urban lens, involving other green and blue infrastructures[54] such as street trees, urban wetlands, and green spaces.

METHODS

Following the integrated methodology and framework (Fig. 1), this study shaped the dynamic links and trade-offs between green roofs and FWE nexus. The method descriptions are as follows (see Supplementary Methods for more details), and the raw data and calculation processes are available in the Supplementary data[55].

Urban rooftop area extraction
The GIS sampling method (Step 1, Fig. 1) was applied to estimate the potential building footprints in the cities. For SJC and Johannesburg, this study respectively took 10% and 5% of their urban administrative area as the samples in the ArcGIS software to extract the potential building footprints (Supplementary Fig. 4). It was found that the building footprints in SJC covered 7.5% of the sampled area and those in Johannesburg occupied 14.7%. Based on the sampled results, it was assumed that 5–10% of the total area in SJC and 15–20% in Johannesburg could be regarded as building footprints, and the rooftop areas were the same as the building footprints.

Life cycle environmental impact assessment
A cradle-to-grave life cycle assessment (Step 2, Fig. 1) was conducted to account for the energy consumption (Primary Energy Demand, including renewable and non-renewable resources), water consumption (Blue water consumption, including hydropower), and carbon emissions (GHG, IPCC AR5 GWP100, except for biogenic carbon) of green roofs per square meter in one year (Supplementary Methods 1). In this study, the whole green roof system consists of the green roof structures, open-air farming system, and rainwater harvesting system (see Supplementary Fig. 5 for the system boundaries). Five stages were included in this life cycle assessment, that is, the stage of infrastructure material production, installation and construction, operation and maintenance, demolition, and disposal (see Supplementary Table 4 for the detailed scopes). The life cycle impacts can be mathematically represented as follows:

$$F_i = \sum_1^j AD_j \, BD_{i,j} \tag{1}$$

where F_i refers to the total output of environmental impact i embodied in each life cycle stage; i refers to the impact categories, such as energy consumption, water consumption, and carbon emissions; AD_j refers to the activity data of material j in each life cycle stage; $BD_{i,j}$ refers to material j's background data for the impact category i, which are calculated based on the Gabi database.

Direct FWEC-related benefits
During the whole life cycle stages of green roofs, the operation and maintenance stage could generate direct FWEC-related benefits, including local food production, direct energy saving, direct water saving, and direct carbon capture, the corresponding process-based modeling methods (Step 3, Fig. 1) are available as follows and Supplementary Methods.

Given that tomato is one of the most widely consumed and grown vegetable crops around the world, the tomato growing was regarded as representative of the open-air farming on green roofs. The process-based biogeochemical model DeNitrification-DeComposition (DNDC) model[56] was used to estimate the tomato yield on green roofs in SJC and Johannesburg. Three categories of parameters are fed into the DNDC model to simulate the tomato's daily incremental growth: (1) typical daily meteorological data, including temperature and precipitation (Supplementary Fig. 6); (2) soil data, including the land use type and top soil texture; (3)

cropping data, including the crop parameters, fertilization, and irrigation (see Supplementary data[55] for the parameters).

In this study, the green roof energy model developed by David Sailor and Brad Bass, was applied to determine the energy savings of green roofs. Within this model, input files were created for American cities by modifying the benchmark file for that city's climate zone with city-specific information, including site information, utility rate schedules, and annual precipitation profiles. This study selected two proxy American cities in the same climate zones as SJC and Johannesburg based on the ASHRAE climate zone (Supplementary Table 5). Based on the input values for building type, location, leaf area index of green roofs, growing media depth, and irrigation operations (see Supplementary Methods 2 and Supplementary data[55] for the details), the simulation results could be interpolated.

The study additionally considered a rainwater harvesting system to collect the rooftop rainwater for irrigation. The rainwater harvesting potential of green roofs was estimated by Eq. (2), which was essentially based on the average rainfall of each location and the runoff coefficient of green roofs:

$$RH = A \times P \times C \qquad (2)$$

Where RH is the amount of rainwater harvested, in L; A is the green roof area, in m^2, a unit area (i.e., one square meter) was applied to calculate first in this research; P is the actual local precipitation, in mm; C refers to the harvesting efficiency of green roofs, often indicated as the runoff coefficient. In the green roof system, rainwater first infiltrated the green roof vegetation and entered the ground rainwater collection tank through the rainwater collection pipe, a conservative value of 15% efficiency was considered for the catchment area to compensate for the effects of leaks, wind, and rainfall rates[57].

An index of direct water saving was further defined based on the rainwater harvesting potential and irrigation demand of green roofs. If the harvested rainwater was greater than the irrigation demand for tomatoes, the harvested rainwater could be fully used to irrigate tomatoes and offset their irrigation water consumption; in this case, the irrigation demand was regarded as direct water saving. Conversely, if the harvested rainwater was less than the irrigation demand for tomatoes, the irrigation demand could be partially satisfied by the harvested rainwater, then the harvested rainwater was defined as direct water saving. The formulas for direct water saving of green roofs are shown below:

$$DWS = \begin{cases} RH(RH \leq ID) \\ ID(RH > ID) \end{cases} \qquad (3)$$

$$ID = BW \times TP \qquad (4)$$

Where DWS is the direct water saving of green roofs, in L; ID is the total irrigation demand of tomatoes, in L; BW is the irrigation demand of tomato per kg, in L·kg^{-1}, which is sourced from Mekonnen and Hoeskstra;[58] TP is the tomato yield of green roofs per square meter, in kg·m^{-2}, which is calculated by the DNDC model.

During the growing period, the average daily carbon capture of tomatoes[59] was 18.56 g of CO_2·m^{-2}. This study assumed that the growing period for tomato crops on green roofs in the case cities was 150 days[60], and there could be two growth cycles each year. Thereby, the annual carbon capture per unit area of the studied green roofs could be estimated (see Supplementary data[55] for the details).

Avoided transboundary environmental footprints and nexus indexes

This study applied the EIO-LCA (Economic Input-Output based Life Cycle Assessment) model (Step 4, Fig. 1) to estimate the avoided transboundary environmental footprints induced by the direct

FWE-related benefits, i.e., local food production (f), direct energy saving (e), and direct water saving (w) of green roofs. Here it was assumed that the entire food, water, and energy resources of SJC and Johannesburg were provided from other regions within the national territory. Therefore, this study constructed Brazil- and South Africa-based EIO-LCA models based on the GTAP v10 database, and additionally used the current local prices of products (i.e., water, electricity, gas, and tomato) and consumer price index (CPI) to convert the physical products into economic values for each sector (i.e., food, water, and energy sectors) (see Supplementary Methods 3 and Supplementary data[55] for the details).

The Nexus Index (NI) series were additionally established to determine the structure of green roofs' avoided transboundary environmental footprints. The NI series include the Nexus Energy Index (NEI), Nexus Water Index (NWI), and Nexus Carbon Index (NCI), which respectively refer to the total avoided transboundary energy, water, and carbon footprints induced by the direct FWE-related benefits of green roofs. The Nexus Index series can be mathematically represented as follows:

$$NEI = \sum AE_i \qquad (5)$$

$$NWI = \sum AW_i \qquad (6)$$

$$NCI = \sum AC_i \qquad (7)$$

where AE_i, AW_i, AC_i represent the avoided transboundary energy, water, and carbon footprints induced by the specific benefit i (f, e, and w) of green roofs, in MJ, L, kg CO_2e. f, e, and w refer to local food production, direct energy saving, and direct water saving. Taking f as an example, AE_f, AW_f, AC_f respectively refer to the avoided transboundary energy, water, and carbon footprints by local food production on green roofs, the same is true for the others (see more abbreviations in Supplementary Table 1).

Scenario analysis

Extracting the available rooftop areas that can be converted into green roofs is the key to evaluating the performance of city-wide green roof implementations. The identification of available rooftop areas is related to the building types, rooftop structural resistance and slope, and rooftops shaded by neighboring buildings. Due to the data being unavailable, we make some assumptions to assess the available rooftop areas by setting A-D scenarios with the ratio of an available rooftop to the entire roof area in cities as 20% (A), 30% (B), 40% (C), and 50% (D). Further, three sub-scenarios were set within the A-D scenarios (Table 1), which respectively refer to 20% (S1), 50% (S2), and 100% (S3) of

Table 1. Scenario settings of urban green roof development.

Available rooftop ratio	Scenario	Description
20% (A)	A-S1	20% green roof conversion
	A-S2	50% green roof conversion
	A-S3	100% green roof conversion
30% (B)	B-S1	20% green roof conversion
	B-S2	50% green roof conversion
	B-S3	100% green roof conversion
40% (C)	C-S1	20% green roof conversion
	C-S2	50% green roof conversion
	C-S3	100% green roof conversion
50% (D)	D-S1	20% green roof conversion
	D-S2	50% green roof conversion
	D-S3	100% green roof conversion

the building roofs converted into green roofs. Scenario B (30%) was taken as an example to explain the performance of city-wide green roof implementations, including scenarios B-S1, B-S2, and B-S3. More details for the scenarios of 20% (A), 40% (C), and 50% (D) of available rooftop ratios can be found in Supplementary Figs. 7–9 and Supplementary Table 3. The results of differing rooftop availability assumptions were proportionally scaled up to the results per square meter reported from Steps 2–4.

Study areas

Globally, the population in urban areas is growing rapidly, and the mean annual growth rate of the population in the Global South cities is four times rate in the Global North[61]. In light of the unprecedented rate of urbanization and its negative implications for urban FWE resource management especially in Global South countries, we need a strategy for sustainable urban FWE resources within urban areas. To our knowledge, although cities in developing countries, particularly large countries, share socio-economic characteristics and vulnerabilities, their predominant solutions vary widely across the regions, which is related to demographic and development characteristics. On the basis of support of the IFWEN project (https://ifwen.org/), this study selected two Global South cities as the case cities, São José dos Campos (SJC) in Brazil and Johannesburg in South Africa, and these two cities provided an excellent basis for this study due to regional factors. SJC covers 1099 km^2 and represents the core municipality in the metropolitan region of the Paraíba River Valley in the southeast of São Paulo State, Brazil (Supplementary Fig. 1a). SJC is an important aircraft manufacturing city and scientific research center in Latin America, with a 2B climate type (Hot-Dry) in the ASHRAE climate zone. The city is also one of the most economically dynamic in the state between the two most active production and consumption areas in the country, i.e., the megalopolis of São Paulo and Rio de Janeiro, with about 713,943 urban residents in 2018. For São Paulo, resilience measures and nature-based solutions for climate change mitigation and adaptation are favored[22]. Johannesburg is the capital of Gauteng Province in the northeast of South Africa (Supplementary Fig. 1b) covering 1645 km^2 with a 3 A climate type (Warm-Humid) in the ASHRAE climate zone. In Johannesburg, the main industrial sectors are agriculture, tanning, and textiles. Johannesburg is the most developed and richest city in South Africa, and the urban population of Johannesburg was 5,674,824 in 2018. In particular, Johannesburg has clearly set its goals for a climate resilient city— by 2050, the city has 30% green cover (including green roofs)[23]. Based on the above, the exploration of the impacts of green roofs on FWE nexus will provide an innovative solution for SJC and Johannesburg to align their priorities for food, water, and energy sustainability.

DATA AVAILABILITY

The majority of the data have been included either directly in the main text or detailed in the Supplementary Information. All code and supporting data are available at https://doi.org/10.6084/m9.figshare.21785882.v3 under a CC-BY-4.0 license, which provides the primary data, data source, data processing, and computations to interpret, verify or extend this work.

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AUTHOR CONTRIBUTIONS

F.X.M., R.A.B., J.A.P.O., and K.C.S. initiated the idea for the paper and designed the research; F.X.M. and Q.L.Y. performed the research, ran the models and calculations, conducted the analysis, visualized the figures, and wrote the original draft; R.A.B. led the data collection, validated the models and calculations and revised the draft; Y.C.H. and R.J. assisted in the data collection, model simulation and revising the draft; G.Y.L. contributed ideas for the analyses and gave comments on the draft; J.A.P.O., Z.F.Y., and K.C.S. revised and provided critically important content, and supervised the research. All authors actively contributed to the draft review.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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