Supplementary Information

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

Fanxin Meng[1 *], Qiuling Yuan[1], Rodrigo A. Bellezoni[2,3], Jose A. Puppim de Oliveira[2,4,5], Yuanchao Hu[6], Rui Jing[7], Gengyuan Liu[1], Zhifeng Yang[1,8 *], Karen C. Seto[9]

[1]State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing, 100875, China

[2]São Paulo School of Management (FGV EAESP), Fundação Getúlio Vargas (FGV), Rua Itapeva, 474, sala 712, Bela Vista, São Paulo, 01332-000, Brazil

[3]Center for Territorial Inteligence (Centro de Inteligência Territorial – CIT), Av. Bias Fortes, 382, 11◦ andar, Lourdes, Belo Horizonte, MG, 30170-011, Brazil

[4]Brazilian School of Public and Business Administration (FGV EBAPE), Fundação Getúlio Vargas (FGV), Rua Jornalista Orlando Dantas 30, Rio de Janeiro, 12495, Brazil

[5]Institute for Global Public Policy, Fudan University, Shanghai, 200433, China

[6]School of Resource and Environmental Sciences, Wuhan University, 129 Luoyu Road, Wuhan, 430079, China

[7]College of Energy, Xiamen University, Xiamen, 361000, China

[8]Key Laboratory for City Cluster Environmental Safety and Green Development of the Ministry of Education, Institute of Environmental and Ecological Engineering, Guangdong University of Technology, Guangzhou, 510006, China

[9]Yale School of the Environment, Yale University, 380 Edwards St, New Haven, CT, 06511, USA

** Corresponding emails: fanxin.meng@bnu.edu.cn; zfyang@bnu.edu.cn*

Supplementary Methods 1: Life cycle assessment

This study considered three environmental impact categories (energy consumption, water consumption, and carbon emissions) of the whole green roof system, which consists of the green roof structures, open-air farming system, and rainwater harvesting system in this research. The background data were sourced from the corresponding primary energy demand (PED) including renewable and non-renewable resources, blue water consumption (BW) including hydropower, and greenhouse gases (GHG, IPCC AR5 GWP100, except for biogenic carbon) in Gabi database. Here five stages were involved 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). Given that vegetable growing often requires deeper mediums[1], a selection of intensive green roofs was regarded as representative of rooftop open-air farming. Specifically in the material production phase, the materials for green roof structures, open-air farming system, and fertilizers were considered. The rainwater harvesting system was included in the operation and maintenance phase, and this inclusion was based on our assumption that the harvested rainwater could be used for tomato irrigation in the operation and maintenance phase. Due to the limitations of local site data in SJC and Johannesburg, the general data were applied to account for the life cycle impacts of the whole green roof system.

Supplementary Methods 2: Direct energy saving simulation

Here the green roof energy model developed by David Sailor and Brad Bass was applied to evaluate the direct energy saving potential of green roofs, which was validated to be accurate in predicting both roof surface temperatures and the resulting energy consumption for heating and cooling of the buildings[2]. In this study, two proxy American cities in the same climate zones as San Jose dos Campos (2B, Hot-Dry) and Johannesburg (3A, Warm-Humid) were selected based on the ASHRAE climate zone (see Supplementary Table 5 for the climate conditions), which are Phoenix, Arizona and Memphis, Tennessee, respectively. Within this energy model, the roof area and growing media depth were set as 1 m^2 and 30 cm, and the irrigation operation was considered additionally. Given the uncertainty of the specific type of building where the green roof is located, we ran simulations for new office buildings, new residential buildings, old office buildings, and old residential buildings, and the weighted average of the four building types was taken as the energy saving benefits of green roofs (see Supplementary data[3] for the details).

Supplementary Methods 3: Avoided transboundary environmental footprints accounting

In this study, the avoided transboundary environmental footprints induced by direct FWE-related benefits were estimated based on the EIO-LCA model. We assumed that the entire food, water, and energy resources of SJC and Johannesburg were provided from other regions within the national territory. Then the national value-based input-output table from GTAP v10 database was applied to construct the Brazil- and South Africa-based EIO-LCA models in this research. Firstly, we matched the food, water, and energy products with the industrial sector within the Brazil- and South Africa-based EIO-LCA models. Secondly, we converted the physical food, water, and energy products (direct FWE-related benefits) into economic value for corresponding sectors based on the current local prices of products and the consumer price index (CPI). The economic parameters are investigated from local markets and governmental statistical yearbooks. The corresponding sectors in the EIO are "*Vegetable, fruit, nuts (food)*", "*Electricity (energy)*", "*Gas manufacture, distribution (energy)*", and "*Water (water)*" (see details in Supplementary data[3]).

Taking the avoided carbon footprints induced by the FWE-related benefits products of green roofs as an example, the carbon emission matrix B driven by the final demand for the avoided food, water, and energy imports products (equal to the direct FWE-related benefits products) can be established based on the EIO-LCA model, which is calculated as follows:

$$B=R(I-A)^{-1}Y \tag{1}$$

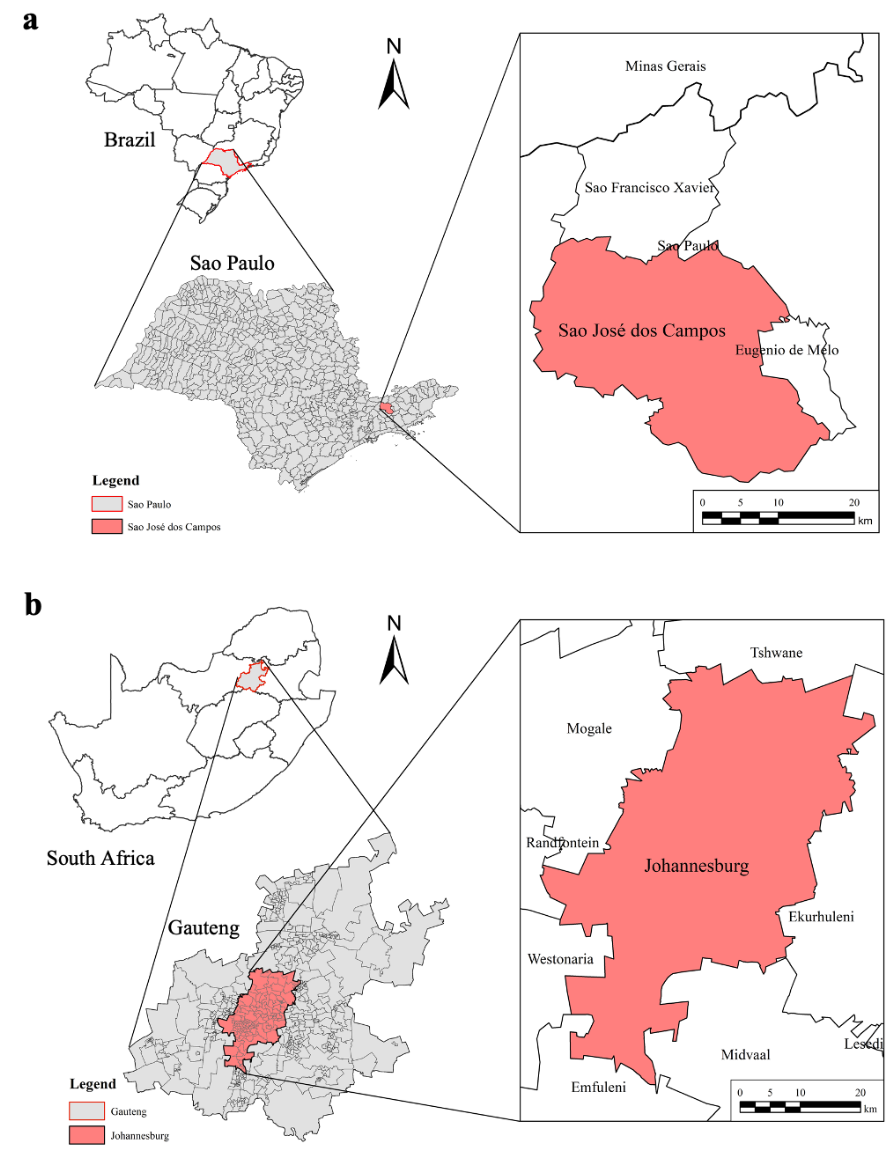
Where B is the carbon emission matrix driven by the final demand for the avoided food, water, and energy products imported; R is the carbon emission intensity matrix of each economic sector within this model, the elements in the diagonal of all sectors in each country or region are from the GTAP v10 database; I is the unit matrix; A is the direct consumption coefficient matrix, from GTAP v10 database; Y is the diagonal matrix with the diagonal element Y_j, indicating the final demand for the avoided food, water, and energy products imported in sector j, million Yuan, and in this model. To be mentioned, the value Y in this model referring to the economic value of the direct FWE-benefits products, should be matched into the corresponding FWE sectors, while the corresponding Y values for all other sectors are zero.

Supplementary Discussion: Trade-offs of green roofs

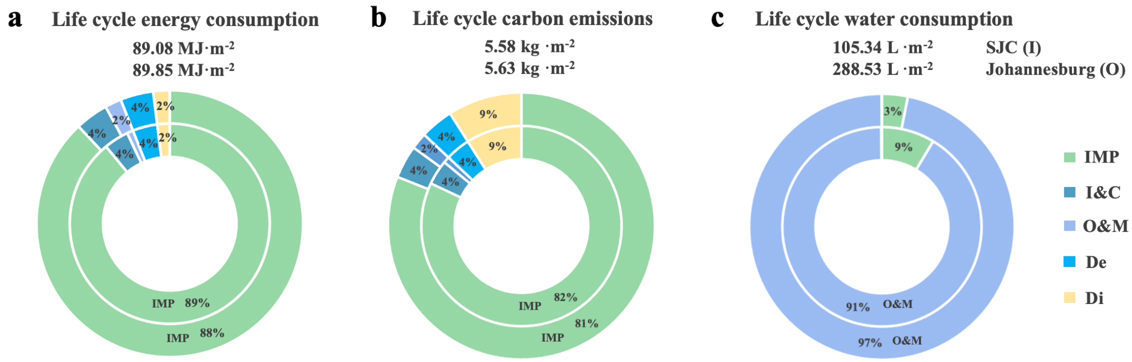
Local food production on green roofs in SJC and Johannesburg supplied 6.83 kg (Fig. 2a) and 5.68 kg (Fig. 2b) of tomato per square meter, respectively. From the energy perspective, due to the climate regulation effect, green roofs can modulate the ambient temperature and further reduce the energy consumption of buildings. In SJC, the direct energy saving from green roofs was 45.40 $MJ \cdot m^{-2}$, and the life cycle energy consumption was 88.59 $MJ \cdot m^{-2}$. Similar values were observed for Johannesburg's green roofs, i.e., 43.82 $MJ \cdot m^{-2}$ and 89.32 $MJ \cdot m^{-2}$. The direct energy saving benefits of green roofs in these two cities were 49%–51% of the total energy consumption in their entire life cycle, which agreed with the findings of Wang et al.[4] and indicated that green roofs are net energy consumers. From a carbon emission perspective, the direct carbon capture potential of green roofs in SJC and Johannesburg virtually offset their life cycle carbon emissions, making them nearly carbon neutral. Specifically, the direct carbon capture potentials of green roofs in SJC and Johannesburg were exactly the same, 5.57 $kg \cdot m^{-2}$, with life cycle carbon emissions also close at 5.55 $kg \cdot m^{-2}$ and 5.59 $kg \cdot m^{-2}$, respectively in SJC and Johannesburg.

Based on the direct benefits of local food production, energy saving, and water saving by green roof implementation, urban food, energy, and water imports from outside city boundaries can be reduced. These reductions lead to transboundary environmental footprint savings in the upstream production and supply chains, which can be considered as indirect benefits of green roofs. Our results revealed that the avoided energy footprints in SJC were 143.05 $MJ \cdot m^{-2}$ (i.e., AE_f: 97.18 $MJ \cdot m^{-2}$, AE_e: 36.16 $MJ \cdot m^{-2}$, AE_w: 9.71 $MJ \cdot m^{-2}$, referring to the avoided energy footprints by local food production, energy saving and water saving respectively, from Fig. 2), which were 1.6 times the life cycle energy consumption (i.e., 88.59 $MJ \cdot m^{-2}$). In Johannesburg, the avoided energy footprints were 2.9 times the life cycle energy consumption, with 257.07 $MJ \cdot m^{-2}$ of avoided energy footprints (i.e., AE_f: 103.62 $MJ \cdot m^{-2}$, AE_e: 130.97 $MJ \cdot m^{-2}$, AE_w: 22.48 $MJ \cdot m^{-2}$). In addition, the avoided transboundary carbon footprints in SJC were 9.15 $kg \cdot m^{-2}$ (i.e., AC_f: 8.66 $kg \cdot m^{-2}$, AC_e: 0.37 $kg \cdot m^{-2}$, AC_w: 0.12 $kg \cdot m^{-2}$), 1.6 times of the life cycle carbon emissions (i.e., 5.55 $kg \cdot m^{-2}$), and 8.05 $kg \cdot m^{-2}$ of the avoided carbon footprints (i.e., AC_f: 2.71 $kg \cdot m^{-2}$, AC_e: 4.46 $kg \cdot m^{-2}$, AC_w: 0.88 $kg \cdot m^{-2}$) were 1.4 times of the life cycle carbon emissions (i.e., 5.59 $kg \cdot m^{-2}$) in Johannesburg.

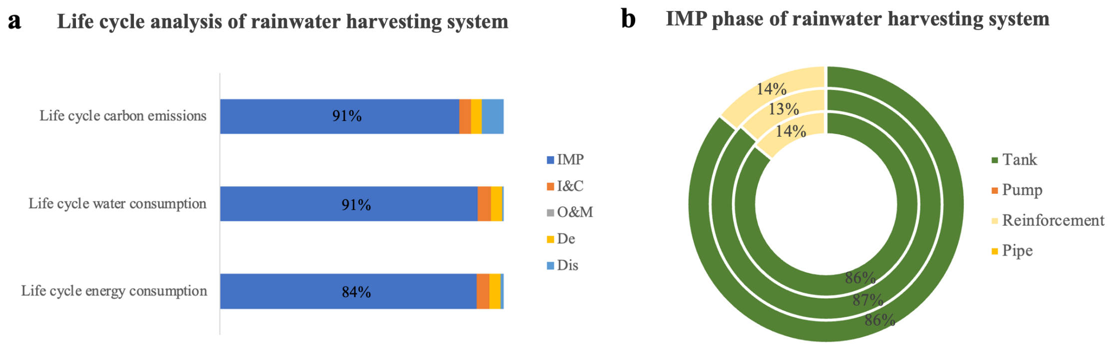
From the water perspective, the direct water saving potentials of green roofs were similar, namely, 95.62 $L \cdot m^{-2}$ and 101.94 $L \cdot m^{-2}$, respectively, for SJC and Johannesburg (Fig. 2). But there were disparities between SJC's and Johannesburg's life cycle water consumption of green roofs, the life cycle water consumption of green roofs in SJC was 5% of that in Johannesburg (186.28 $L \cdot m^{-2}$). Consequently, green roofs in SJC are net water beneficiaries while Johannesburg's green roofs are net water consumers within the city boundary. From a transboundary perspective, green roofs have considerable benefits on water footprint savings. Especially in SJC, the green roofs avoided 3,625.79 $L \cdot m^{-2}$ (i.e., AW_f: 2,159.18 $L \cdot m^{-2}$, AW_e: 1,155.77 $L \cdot m^{-2}$, AW_w: 310.85 $L \cdot m^{-2}$, Fig. 2a) of water footprints beyond urban boundaries, which represented an impressive 384 times the life cycle water consumption (i.e., 9.44 $L \cdot m^{-2}$). Modestly but still positive, 1,446.42 $L \cdot m^{-2}$ (i.e., AW_f: 1,159.97 $L \cdot m^{-2}$, AW_e: 250.23 $L \cdot m^{-2}$, AW_w: 36.22 $L \cdot m^{-2}$, Fig. 2b) of transboundary water footprints were reduced in Johannesburg, accounting for nearly 7.8 times the life cycle water consumption (i.e., 186.28 $L \cdot m^{-2}$).



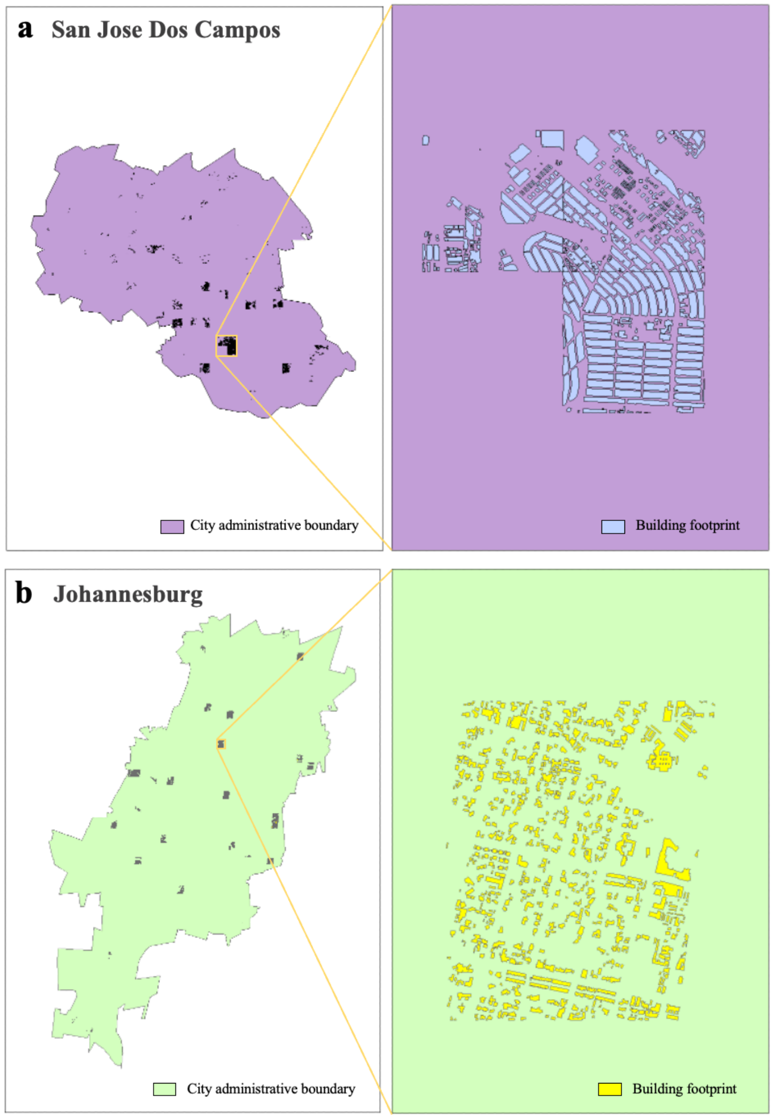
Supplementary Figure 1. Location of São José dos Campos (a) and Johannesburg (b).



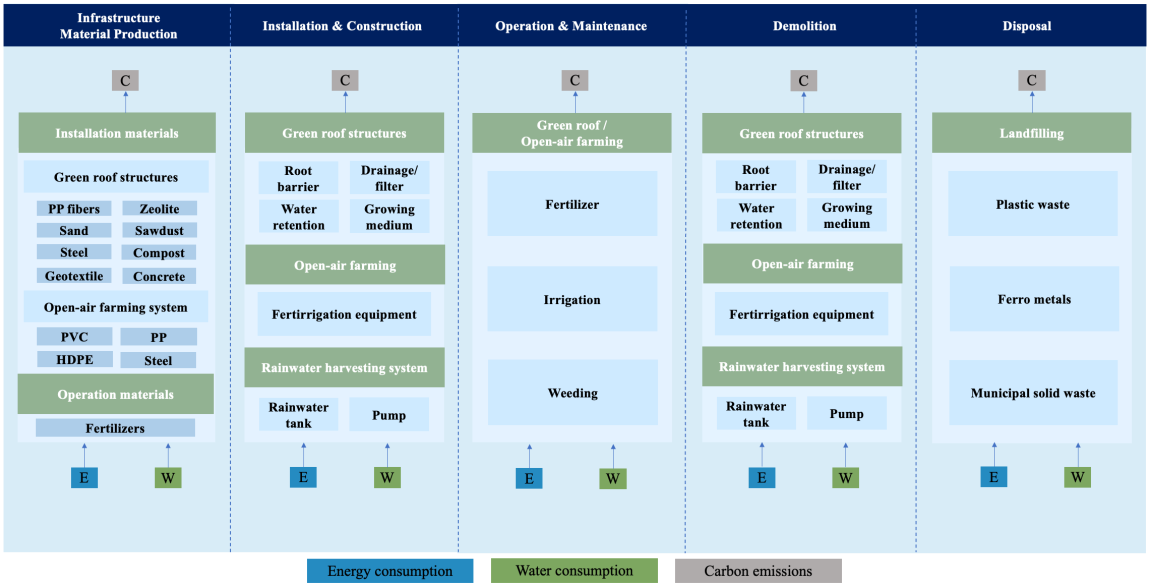
Supplementary Figure 2. Life cycle impacts of green roofs per square meter when using tap water for tomato irrigation. I: inner circle; O: outer circle; IMP: infrastructure material production; I&C: installation and construction; O&M: operation and maintenance; De: demolition; Di: disposal.



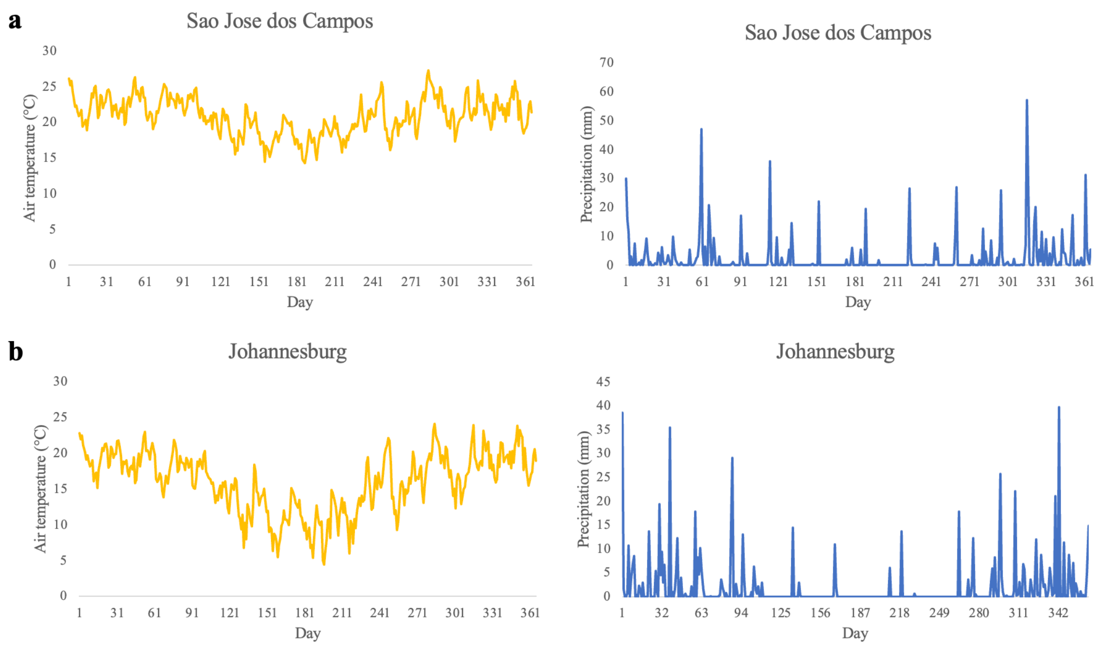
Supplementary Figure 3. Life cycle analysis of the rainwater harvesting system. (a) IMP: infrastructure material production, I&C: installation and construction, O&M: operation and maintenance, De: demolition, Di, disposal. (b) from the inner circle to the outer circle, life cycle energy consumption, water consumption, and carbon emissions are referred to in that order.



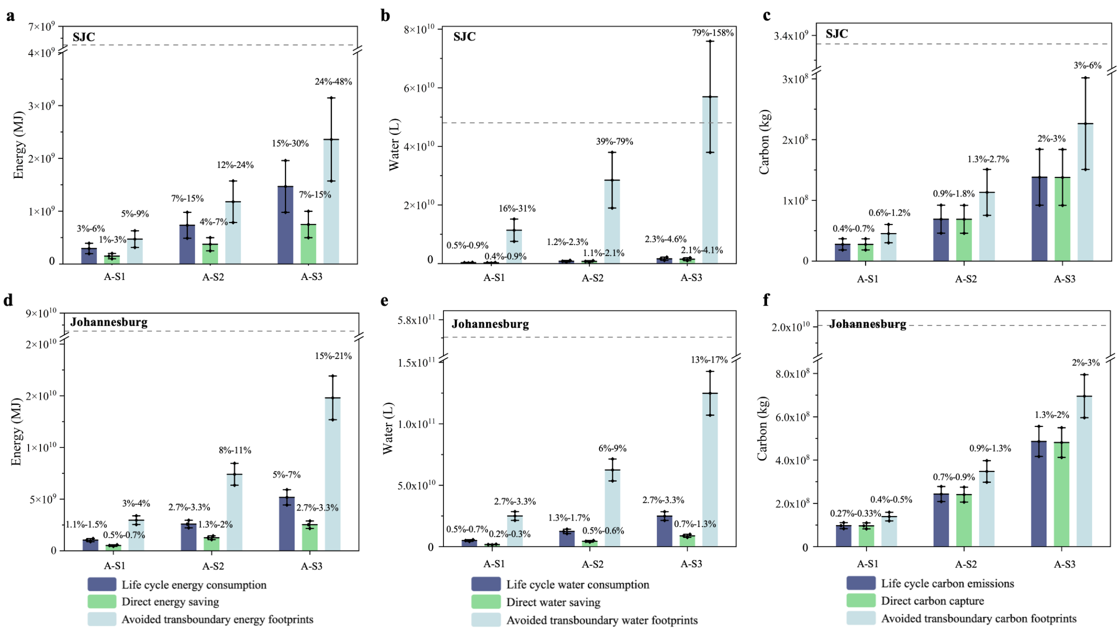
Supplementary Figure 4. GIS sampling of São José dos Campos (a) and Johannesburg (b), the building footprints on the right are examples of one of the samplings on the left.



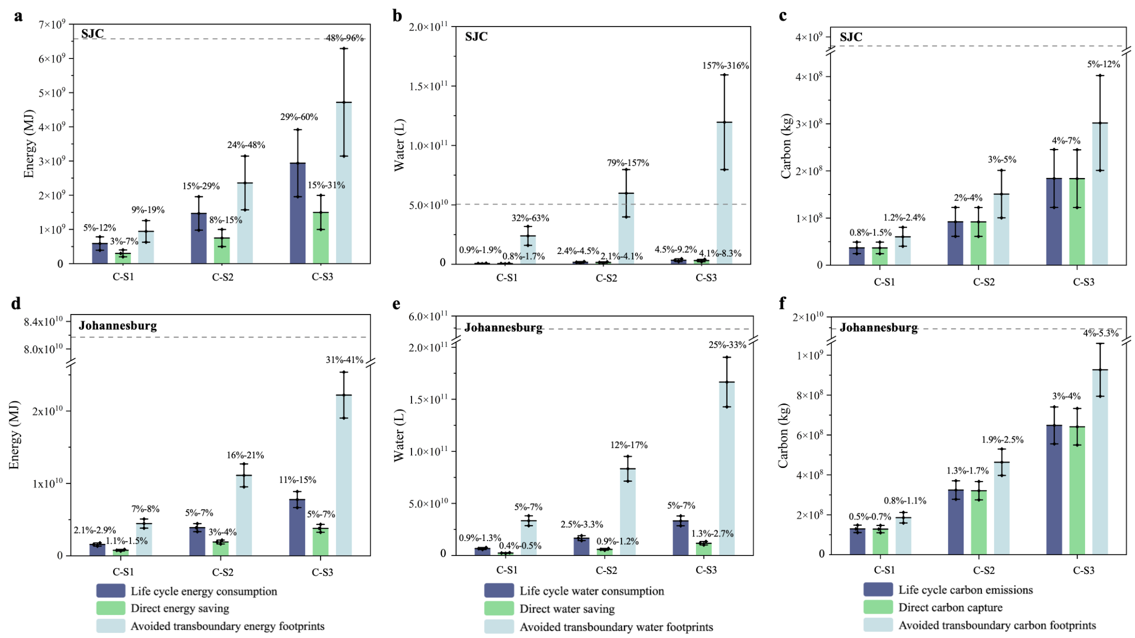
Supplementary Figure 5. Life cycle phases of the whole green roof system.



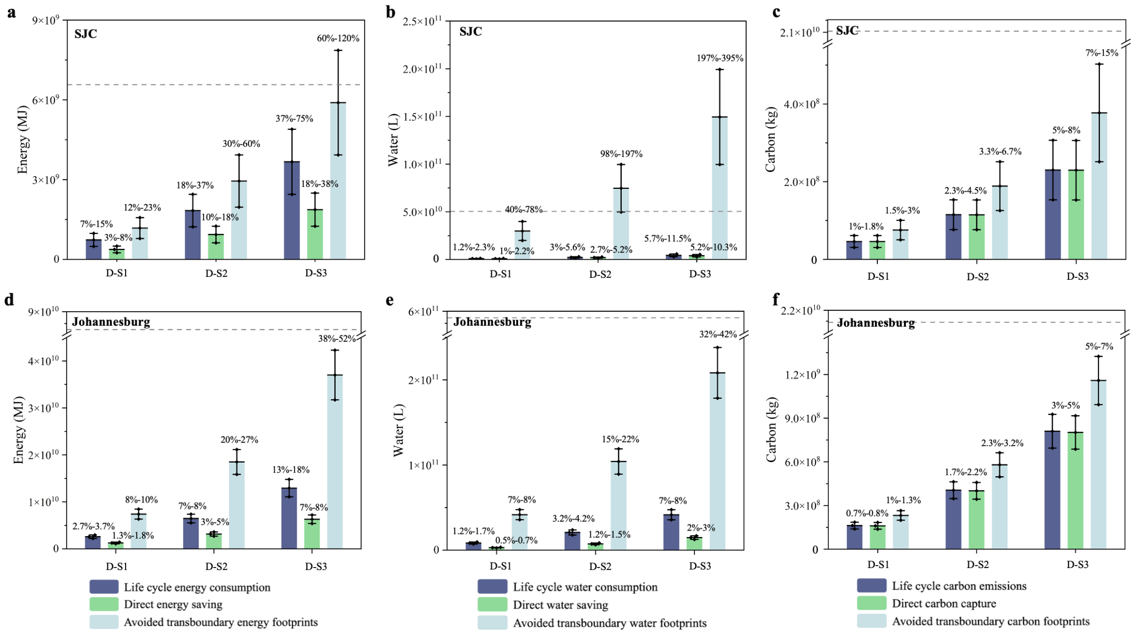
Supplementary Figure 6. Daily temperature and precipitation of São José dos Campos (a) and Johannesburg (b).



Supplementary Figure 7. Implications of city-wide green roofs in 20% of the available urban rooftop assumption.



Supplementary Figure 8. Implications of city-wide green roofs in 40% of the available urban rooftop assumption.



Supplementary Figure 9. Implications of city-wide green roofs in 50% of the available urban rooftop assumption.

Supplementary Table 1. Nomenclature.

Abbreviation	Description
GBI	Green and blue infrastructure
FWE	Food, water, and energy
FWEC	Food, water, energy, and carbon
LCA	Life cycle assessment
AE_f	Avoided transboundary energy footprints by local food production
AE_e	Avoided transboundary energy footprints by direct energy saving
AE_w	Avoided transboundary energy footprints by direct water saving
AC_f	Avoided transboundary carbon footprints by local food production
AC_e	Avoided transboundary carbon footprints by direct energy saving
AC_w	Avoided transboundary carbon footprints by direct water saving
AW_f	Avoided transboundary water footprints by local food production
AW_e	Avoided transboundary water footprints by direct energy saving
AW_w	Avoided transboundary water footprints by direct water saving
NI	Nexus Index
NEI	Nexus Energy Index
NCI	Nexus Carbon Index

NWI	Nexus Water Index
MGR	Materials for green roof structures
MOAF	Materials for open-air farming system and fertilizers
IMP	Infrastructure material production
I&C	Installation and construction
O&M	Operation and maintenance
De	Demolition
Di	Disposal
RB	Root barrier
GM	Growing medium
W/R	Water retention
D/F	Drainage/filter

Supplementary Table 2. Life cycle performance of rainwater and tap water.

Life cycle performance	Energy consumption (MJ)	Water consumption (L)	Carbon emissions (kg CO_2e)
Rainwater	6.06E-03	1.81E-03	4.89E-04
Tap water	5.18E-03	1.00296	3.30E-04

Supplementary Table 3. Contributions to the urban and national targets for different green roof development scenarios with various ratios of available urban rooftops.

Available rooftop ratio		20% (A)			30% (B)			40% (C)			50% (D)		
Scenario		A-S1	A-S2	A-S3	B-S1	B-S2	B-S3	C-S1	C-S2	C-S3	D-S1	D-S2	D-S3
Urban water target	Johannesburg	0.71%–0.94%	1.76%–2.35%	3.53%–4.70%	1.06%–1.41%	2.65%–3.53%	5.29%–7.06%	1.41%–1.88%	3.53%–4.70%	7.06%–9.41%	1.76%–2.35%	4.41%–5.88%	8.82%–11.76%
National carbon target	Johannesburg	0.005%–0.009%	0.01%–0.02%	0.03%–0.05%	0.008%–0.014%	0.02%–0.04%	0.04%–0.07%	0.01%–0.02%	0.03%–0.05%	0.05%–0.09%	0.01%–0.02%	0.03%–0.06%	0.07%–0.12%
	SJC	0.02%–0.03%	0.05%–0.07%	0.09%–0.13%	0.03%–0.04%	0.07%–0.04%	0.14%–0.20%	0.04%–0.05%	0.09%–0.13%	0.13%–0.27%	0.05%–0.07%	0.12%–0.17%	0.23%–0.33%

Supplementary Table 4. Scope and boundary of the energy and water consumption, and carbon emissions over the life cycle of the whole green roof system.

Life cycle phase	Description
1 Infrastructure material production	This phase refers to the process of all the material production and was divided into three parts: 1) the materials used for the installation and construction of the regular green roof structures. 2) and materials for the fertirrigation of open-air farming. 3) and all the fertilizers used in the operation and maintenance phase. And all the materials transported to the building site are considered separately for each phase.
2 Installation & Construction	This phase includes two parts: 1) the labor and equipment inputs for the installation and construction, such as lift, and labor used in the construction process. We assume that the energy and CO_2 value are 5% of the materials in the phase of infrastructure material production[5]. Water consumption is regarded as zero here. 2) and the transportation for the materials used in this phase are considered here.
3 Operation & Maintenance	This phase includes three parts:

1) irrigation water for vegetable cultivation in this phase, including tap water used for irrigation, and rainwater collected in the harvesting system for irrigation.

In this study, we assume that all the tomatoes are planted on the intensive green roofs, and the harvested rainwater can be used for the vegetable cultivation in this phase (the life cycle energy consumption, water consumption, and carbon emissions of rainwater harvesting system are included in this phase).

We account for the blue water demand for tomato growth based on the climate conditions and geographical locations, and evaluated the utilizable green water for irrigation from the rainwater collection on the basis of local precipitation. Then the required tap water for irrigation can be calculated by deducting the rainwater collection from blue water demand.

2) direct labor for weeding and irrigation activities, which is evaluated as 5% of the embodied energy and CO_2 of the materials used in this phase[4].

3) and the transportation for the materials used in this phase are considered here.

Direct FWEC-related benefits are accounted for separately in this phase.

4 Demolition	This phase includes the equipment and labor inputs in demolition work, which is evaluated as 90% of the embodied environmental effects in the installation and construction phase.
5 Disposal	In this phase, we assume that all the building wastes from the decommissioning phase are transported to the municipal landfill sites, which including two processes: 1) transportation of all the construction waste to the landfill site, the transportation distance is assumed as 25 km. 2) the landfill processes for different materials are considered.

Supplementary Table 5. Climate conditions of São José dos Campos and Johannesburg.

Case city	São José dos Campos	Johannesburg
ASHARE Climate Zone	2B (Hot-Dry)	3A (Warm-Humid)
Köppen climate classification		Subtropical highland climate (Cwb)
Corresponding US city	Las Vegas, or Phoenix, Arizona	Memphis, Tennessee
Annual HDD Base 18 °C/65 F #	264.4 °C/475.52 F	924.2 °C/1695.56 F
Annual CDD Base 10 °C/50 F #	4140.5 °C/7484.9 F	2770.9 °C/5019.62 F

Supplementary References

1. Walters, S. A., & Stoelzle Midden, K. Sustainability of urban agriculture: Vegetable production on green roofs. *Agriculture* **8,** 168 (2018).
2. https://sustainability-innovation.asu.edu/urban-climate/green-roof-calculator/.
3. Meng, F. et al. Supplementary data for the food-water-energy nexus and green roofs in Sao Jose dos Campos, Brazil, and Johannesburg, South Africa. figshare. Dataset. https://doi.org/10.6084/m9.figshare.21785882.v3 (2023).
4. Wang, Y. et al. Environmental performances and energy efficiencies of various urban green infrastructures: A life-cycle assessment. *J. Clean. Prod.* **248,** 119244 (2020).
5. Meng, F. et al. Energy efficiency of urban transportation system in Xiamen, China. An integrated approach. *Appl. Energy* **186,** 234–248 (2017).