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Bottom-up model for the sustainability assessment of rooftop-farming technologies potential in schools in Quito, Ecuador

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ABSTRACT

Rooftop-farming technologies can transform unexploited roofs into agricultural areas; and though studies have quantified the sustainability of diverse rooftop-farm systems, researchers lack a direct comparison between these farms using a unified sustainability index. Therefore the proposed bottom-up model aims to quantify the sustainability of rooftop-farm technologies application in school building stocks, thus permitting an objective comparison and ultimately selection of the best-fitted farm system. This model handles large building samples by combining Statistical Mining Techniques with the Integrated Value Model for Sustainability Assessment. It uses data on the economic, environmental and social aspects of the farms, and relates them to the technical limitations and functionality found in the host buildings. The model has three consecutive stages: 1) in the *City Stage* reference buildings are identified from the stock, 2) the *Building Information Stage* determines the logistics and infrastructure requirements; and, 3) the *Farm Technology Stage* quantifies the farms' sustainability. This model was used to assess the potential implementation of three rooftop-farms (edible-green roofs, rooftop greenhouses and integrated rooftop greenhouses) in the primary school stock in Quito, Ecuador. Two reference buildings represented the primary school stock of the city; and, in both typologies, edible-green roofs obtained the highest sustainability values of 0.62 and 0.65. The environmental pillar was the most discriminant in which green-roofs achieved twice the sustainability values for the rooftop-greenhouses due to their larger rainwater harvesting capacity, thermal resistance and contribution to the increment of urban greenspaces.

1. Introduction

Urban rooftop farming (URF) can transform unexploited roofs into agricultural areas thus increasing the city food self-sufficiency (Buehler and Junge, 2016), reducing its environmental footprint (Viljoen and Bohn, 2014), and enhancing its social cohesion (Thomaier et al., 2014). Though some studies have begun comparing the sustainability of rooftop-farms to their ground counterparts, no special attention has been given to the comparison between URF technologies (Kim et al., 2018). Some studies have quantified aspects on the economic –lifecycle costs (Eaves and Eaves, 2018)-, environmental –lifecycle assessment (Goldstein et al., 2016)- and food-security potential –production yields (Benis et al., 2017)- of urban agriculture (UA), relegating other significant aspects like education and social acceptance. What is more, quantitative data are lacking regarding the viability of rooftop-farming in large-scale applications (Haberman et al., 2014). Though some studies have assessed the urban potential of a specific URF –rooftop-greenhouses (RTGs) in industrial parks (Sanyé-Mengual et al., 2015a) and low-income neighbourhoods (Nadal et al., 2019)- no consideration was given to the viability of other farms. Recent studies have compared the city-wide potential of high and low-intensity rooftop-farming using indicators such as food-yield (Saha and Eckelman, 2017), and energy and water use (Benis et al., 2017). However, these studies do not include quantifiable indicators on the educational or social aspects nor provide a framework for deriving a global sustainability value.

As the literature suggests (Artmann and Sartison, 2018), a

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bottom-up urban-modelling strategy is adequate for large-scale UA purposes. Bottom-up modelling analyses individual buildings and then extrapolates their results to a city-scale using statistical techniques (Li et al., 2018). One of these techniques is the use of mining tools to identify reference buildings that act as accurate representatives of the building stock. In this line, the objectives of this article are first to provide decision-makers with a new holistic sustainability framework for evaluating rooftop-farming; and then, to apply this model to compare the potential implementation of three URFs in the primary school stock in Quito, Ecuador. To the best of the authors' knowledge, this model is the first to combine statistical mining with the Integrated Value Model for Sustainability Assessment (*MIVES*) -a validated multi-criteria decision-making tool (Viñolas et al., 2009). This article has five sections: a) the introduction and a brief state of the art on sustainability assessment of URF, b) the description of the new evaluation framework and case study, c) the results, d) the discussion of the model strengths and uncertainties, and e) the conclusions and future work.

1.1. A brief state of the art

Though many studies have identified the potentials and setbacks of UA and specifically for urban rooftop farming –Barcelona, Spain (Sanyé-Mengual et al., 2016) and Berlin, Germany (Specht et al., 2016)-, the comparison between high-tech controlled-environment agriculture and open-air farms is a nascent field. A cost-benefit analysis of edible-green roofs (eGR), RTGs and climate-controlled RTGs showed a non-viability for greenhouses due to high investments costs (Benis et al., 2018). A comparison of the profitability of RTGs and vertical farms using simulation-based models identified the inability of economically quantifying the co-benefits of the farms (Eaves and Eaves, 2018). In another study, two building-based farms -eGR and RTG- and four ground-farms in the USA were assessed using lifecycle analysis *(LCA)* (Goldstein et al., 2016). That study showed that low-tech technologies have a better performance due to lower energy demand; however, the different crops and harvesting seasons complicated the comparison. Another study assessed the environmental impacts of three URF growing systems in Bologna, Italy using LCA and lifecycle costings *(LCC)* on prototype crops (Sanyé-Mengual et al., 2015c). The results highlighted the negative influence of water pumps in hydroponic crops; although, the limitations of those prototypes could have biased the correct allocation of resources in the lifecycle inventories.

The sustainability of URF has also been assessed using participatory methods to define sets of indicators, either to evaluate their level of social acceptance (Sanyé-Mengual et al., 2018) or the adequacy of governance policies (Landert et al., 2017). A simulation-based tool compared the city-wide potential and sustainability of three building-based farms using three indicators –water use, energy use, and food yield (Benis et al., 2017); however, qualitative and social aspects were not considered. Another study combined interviews with LCA and LCC to compare two types of green roofs (Kim et al., 2018). The interviews showed a preference for the edible-green roofs despite them having twice the lifecycle costs of the standard green roofs. However, this preference was not included in the sustainability quantification. An evaluation scheme was formulated to assess the suitability of farm systems by defining the farm's purpose, then assessing its implementation efficiency, and finally analysing its three-folded sustainability (Artmann and Sartison, 2018). This scheme, to the best of the authors' knowledge, has not been applied to a real sample. Table 1 exclusively depicts recent studies that compare or propose frameworks to compare the sustainability of URF technologies.

2. Methods

The new sustainability model for evaluating the potential implementation of rooftop-farming in a building stock is presented in Fig. 1 and includes three stages: a) City, b) Building Information, and c) Farming Technology. This model is built upon the conceptual evaluation scheme found in the literature (Artmann and Sartison, 2018). Various techniques and methods are used in each stage to move a step forward compared to previous models. In the City stage, statistical mining techniques serve to identify reference buildings from the building stock. The second stage combines fieldwork, simulation and literature review to analyse the technical feasibility of the roofs to host farms. Lastly, the Farming Technology stage defines a sustainability valuation tool using the validated Integrated Value Model for Sustainability Assessment (MIVES).

2.1. City Stage: Identification of reference buildings

A bottom-up urban-modelling strategy was used to permit the up-scaling of results at the city level. The school building stock was classified into architectural typologies as to obtain an in-depth knowledge of the current state of these buildings, and to identify the city-scale deficiencies, rooftop farming potential and food self-sufficiency capacity. The methodology for the European project TABULA was used (Ballarini et al., 2014). It divides the edifices into categories defined by the construction period and gross floor area of the buildings; and then, identifies *reference buildings (*RBs*)* for each representative category (above 4%) using statistical *clustering K-mean method*. The subdivisions for the classification are steps of 1000 m^2 for gross floor area; and, milestones for economic or political relevant events and changes in construction codes for the construction period (Crespo and Ortiz, 1999).

Clustering is a data mining technique for finding subgroups with higher intra-cohesion than that of the entire sample. K-means method creates "k" non-overlapping clusters represented by their centroids. As mining techniques are exploratory, the results are highly dependent on the data variables selected. A study found that a combination of six data variables provides the best cohesion results when using the k-mean method for building classification (Arambula Lara et al., 2014). Based on the classification of Italian schools (Arambula Lara et al., 2015) and Serbian schools (University of Belgrade, 2018), the independent variables chosen were: compactness (S/V), ground floor area (Agf), external wall area (Aw), U-value of walls (Uw), U-value of roofs (Ur) and, number of storeys (F). The clustering algorithm was run in R software using libraries "cclust", "cluster" and "vegan". First, the data variables were normalised to Z-scores due to the different measuring units; next, the presence of multivariate outliers –considered anomalous observations- was checked using the cumulative probability in a chi-square distribution of the Mahalanobis distance. Probabilities below 0.005 were considered outliers and discarded from the sample. The highest Calinski-Harabasz index served to identify the best number of "k" clusters. This index was calculated for $k = 2$, $k = 3$, $k = 4$ and $k = 5$. Once the number of "k" was defined, the k-mean algorithm was iterated until results converged. The clusters centroids are the mean values of the data variables for each subgroup. Their statistical significance was verified using the ANOVA test in IBM SPSS Statistics. Finally, the edifices with the least squared Euclidean distance to their cluster's centroid were selected as reference buildings.

The initial school dataset (Ministerio de Educación del Ecuador, 2018) was crosschecked with official building register information to remove duplicate entries due to schools sharing infrastructures. The final database includes 123 entries and depicts information on each school's ID, number of students, construction year, gross floor

Table 1
Studies comparing or defining frameworks to compare the sustainability of URF.

Ref.	Location	Sus. Pillar	Indicators	Method	Global Index	Farm Techs
Benis et al. (2018)	Lisbon, Portugal	E	NPV, IRR, Payback period	Cost-benefit analysis	–	eGR, RTG, RTG(c)
Eaves and Eaves (2018)	Quebec, Canada	E	Gross profit	Cost analysis	–	RTG, VF
Goldstein et al. (2016)	Boston & NYC, USA	N	GWP Freshwater Ecotoxicity Marine eutrophication Water depletion Land use Resource depletion	LCA	–	RTG, eGR
Benis et al. (2017)	Lisbon, Portugal	N	Food yield Water use Energy use	Simulation	No	RTG, VF, iVF
Sanyé-Mengual et al. (2015c)	Bologna, Italy	E N	GWP, Water depletion CED, Human toxicity Total cost	LCA LCC	No	NFT, floating, soil beds
Landert et al. (2017)	Basel, Switzerland	S	97 indicators	Interviews	Yes	–
Sanye-Mengual et al. (2017)	Various	E N S	Food self-sufficiency GWP Cost	Interviews/GIS/LCA/LCC	No	–
Kim et al. (2018)	Seoul, Korea	E N S	Cumulative cost Environmental indicators	LCA/LCC/Interviews	No	eGR, GR
Artmann and Sartison (2018)	Theoretical	E N S	Production Regulatory services Cultural services	3 step scheme: Purpose – Implementation efficiency – Impact efficiency	Yes	–
Fargue-Lelièvre and Clérino (2018)	France	E N S	7 objectives 30 indicators	4-step tool: Objectives - Indicators- Interpretation - Auto-evaluation	No	–

Economic (E), Environmental (N), Social (S), net present value (NPV), internal return rate (IRR), global warming potential (GWP), cumulative energy demand (CED), lifecycle assessment (LCA), lifecycle costs (LCC), edible-green roof (eGR), rooftop greenhouse (RTG), climate-controlled rooftop greenhouse (RTG(c)), vertical farm (VF), indoor vertical farm (iVF), nutrient film technique (NFT), green roof (GR), communal rooftop garden (cRG), private rooftop garden (pRG).

area, degradation state of the infrastructure, historical listings and construction system. The technical characteristics for each school were collected in individual datasheets (see the model in Appendix B) using available geographic information system (GIS) data (Secretaría de Territorio Habitat y Vivienda, 2019), technical drawings, photographs and site visits. The thermal properties for materials were taken from the Energy Efficiency Code for Residential Buildings (Ministerio de Desarrollo Urbano y Vivienda, 2018); and, the thermal transmittance for building elements (U-value) was calculated according to ISO-13370 for ground floors (ISO, 2017b) and ISO-6946 for all remaining building elements (ISO, 2017a).

2.2. Building Information Stage: Implementation feasibility

The reference buildings are then analysed on account of their technical feasibility for hosting rooftop-farms. Researchers constructed a set of parameters based on the criteria used for the implementation of RTGs in educational buildings in Barcelona, Spain (Nadal et al., 2018); and, new parameters and values were defined as follows. Table 2 presents these criteria, the compliance of which was verified during field visits to the reference buildings.

2.3. Farming Technology stage: sustainability assessment

The sustainability evaluation uses the Integrated Value Model for Sustainable Assessment (MIVES), a multi-criteria decision-making method based on the multi-attribute utility theory (Viñolas et al., 2009). MIVES main advantages are its adaptability, specificity, and the inclusion of multiple data inputs. The crucial points contained in this method are the definition of a weighted requirements tree and the use of value functions to compare indicators with different measurement units.

The requirements tree is a hierarchical structure encompassing all aspects to be considered in the decision-making process. It is composed of requirements (R_i) subdivided into criteria (C_j) and these into indicators (I_k); however, only the most significant indicators are included as to permit an efficient application of the model (Viñolas et al., 2009). Ten stakeholders from the municipality and construction, engineering and UA fields defined this tree during two seminars held in June 2018 (see Fig. 2) relying on proper knowledge and available literature on RTG's implementation in schools (Nadal et al., 2018) and sets of criteria for the assessment of UA (Landert et al., 2017). The tree has sixteen indicators corresponding to the economic, environmental and social dimensions for sustainability and includes one additional indicator named technical. During the seminars, the stakeholders decided to include this fourth requirement as the farm's management is to be carried out by children and teachers without the support of qualified personnel; and as such, simpler technologies are preferable. The MIVES configuration was particularised for this case study to include this additional requirement, as previously done in fomer studies (Fuente et al., 2016). Since the final goal of the sustainability framework is to evaluate the URF potential in building stocks, the tree includes indicators that closely relate to the rooftop characteristics -e.g. I_1) Reconstruction cost and I_7) Thermal insulation. Several indicators were discarded for not being discriminatory -organic waste or inclusion of the product in school menus- or for being outside the scope -neighbourhood acceptance, product quality. The stakeholders' preferences were also disregarded as not to induce a bias in the results.

The tree weights result from comparing the aspects inside each

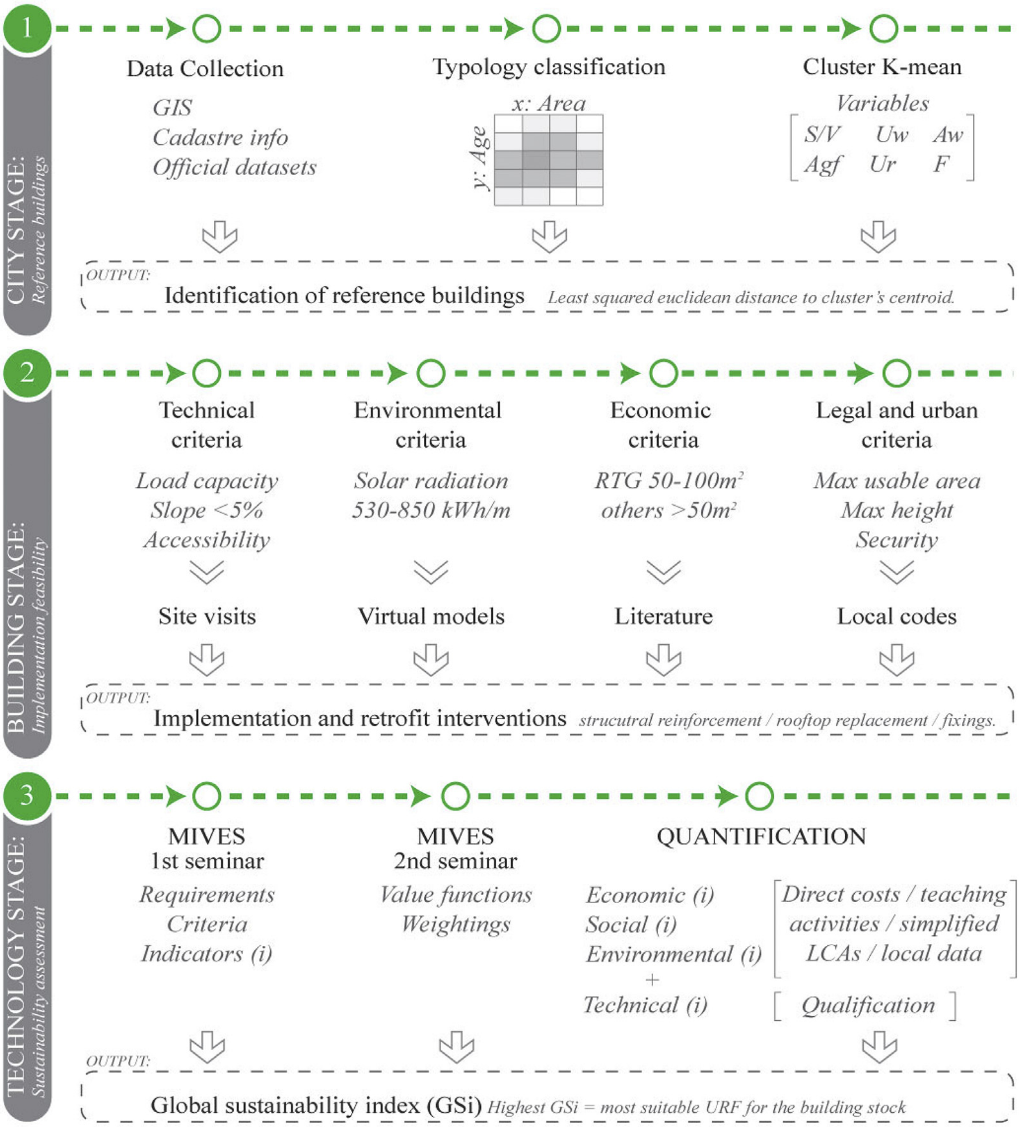


Fig. 1. Framework for the proposed sustainability assessment. Compactness (S/V), ground floor area (Agf), external wall area (Aw), U-value for walls (Uw), U-value for roofs (Ur), number of storeys (F), rooftop greenhouse (RTG).

ramification and grading them based on their importance to the decision-making process. An Analytic Hierarchy Process (AHP) (Saaty, 1990) was used during the seminars to allocate the final weights. The social requirement was granted the highest importance due to its educational potential -possibility of using the URF as experimental workshops on sustainability- and to the complexity of compliance with urban legislation as replicable less-demanding alternatives are preferable. The economic requirement was the next most significant requirement, favouring low-cost strategies due to limitations in investment funds. The importance of environmental indicators is more closely related to the geographical context. For the case study of Quito, Ecuador, due to the high precipitation rate, the capacity of a roof to harvest rainwater was considered the most critical environmental indicator, giving the global warming potential and energy efficiency indicators similar lesser importance. A detailed description of the indicators can be found in Appendix D.

The tree is valued sequentially starting from the direct quantification for the indicators and the application of the value functions (see Fig. 2). As previously said, value functions serve to compare indicators with different measurement units based on a 0 to 1 satisfaction scale. Value functions are calculated using five parameters: indicator direct quantification's maximum value (X_{max}), indicator direct quantification's minimum value (X_{min}), inflexion point of the direct quantification (F_i), the non-dimensional value in the inflexion point (K_i), and the shape factor (P_i). The shape factor defines the function type and it was assigned as follows: costs are linear functions ($P_i = 1$), indicators with acceptable ranges are concave ($P_i < 1$), and indicators with minimum mandatory requirements are convex ($P_i > 1$). The minimum direct value for all indicators was zero, and the maximum was the highest of the alternatives. The value function equations and the parameters used for each indicator are found in Appendix C. The global sustainability index (GSi) is calculated by adding the non-dimensional values of the requirements, criteria and indicators scaled according to their weights (see Fig. 2).

The direct quantification for the indicators follows different methods: construction costs are calculated based on inventories

Table 2
Criteria used to analyse the implementation feasibility of rooftop farms.

Criteria	Parameters description
Economic	Minimum area of 50 m^2 for all URF Maximum area of 100 m^2 for RTGs[a] The economic feasibility of adapting the rooftops is analysed in the sustainability valuation
Environmental	Minimum solar radiation of 530–830 kWh/m^2/y[a] The irradiance was calculated on georeferenced urban 3D models of the reference buildings using *Insight-360*[b]
Legal and urban	Compliance with local planning, construction and urban codes For RTGs in Quito, Ecuador: Maximum useable roof area of 30%[c] 5 m setbacks[c] Maximum building height[c] Inclusion of fire detection systems[c]
Technical	Minimum overload capacity 200 kg/m^2[a] Overload capacity for green-roofs 490 kg/m^2[d] Acceptable slope 2–5%[c] Accessible through staircases[c] Free of all mechanical fixings[a]

[a] (Nadal et al., 2018).
[b] Insight 360 is a energy and solar analysis simulation software (Autodesk, 2019).
[c] (Municipio del Distrito Metropolitano de Quito, 2011).
[d] (Ministerio de Desarrollo Urbano y Vivienda, 2014).

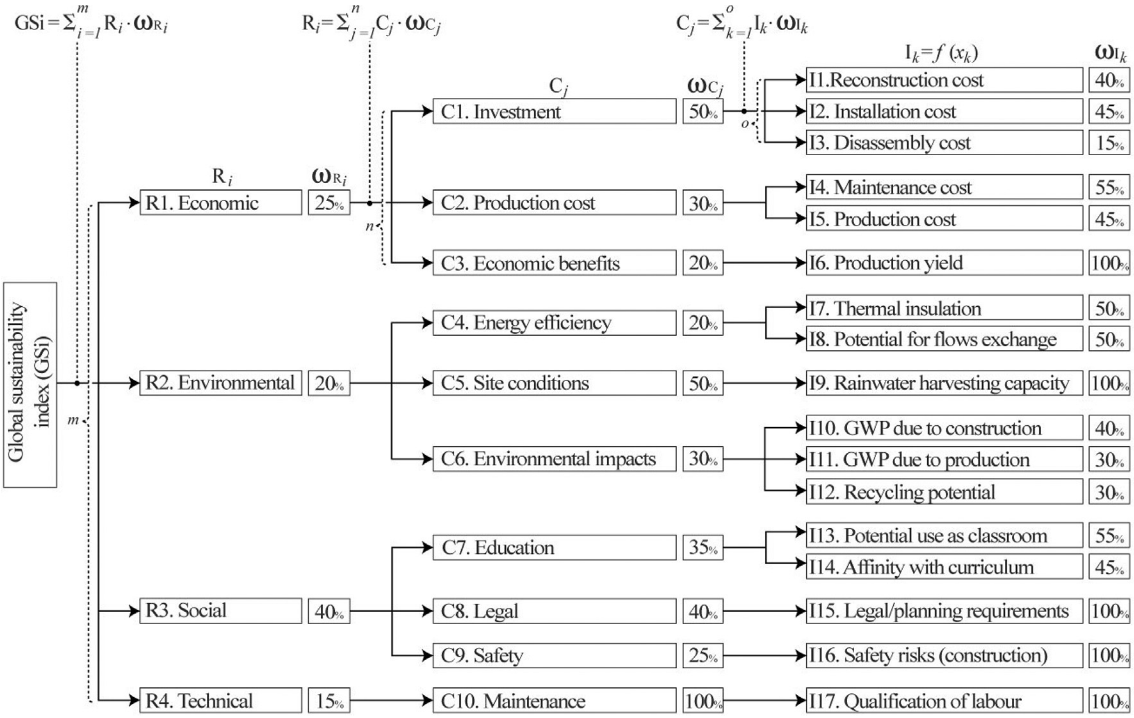


Fig. 2. Requirements tree for the assessment of URF potential in the school building stock in the study case. Global warming potential (GWP), indicators non-dimensional value (I), criteria non-dimensional value (C), requirements non-dimensional value (R), indicators' weights (ω_I), criteria' weights (ω_C), requirements' weights (ω_R), global sustainability index (GSi), direct quantification of the indicators (x).

and published local prices; reference costs (maintenance – production) are taken from literature and extrapolated to local context using the Power Purchasing Parity and Inflation rates (see Appendix D). Production yields were taken from local literature on traditional or small-scale production practices as to better reflect the expected yields in schools (see section 2.4.1.). Thermal insulation values were taken from scientific publications (Delor, 2011). The social and technical indicators were valued using point scales, where the indicators were subdivided into components based on the literature and local standard practices –e.g. For I_{14}) Affinity with curriculum, a list of all the experimental activities –retrieved from the Ecuadorian Ministry of Education- was used, and a point was given for each activity that could be developed or aided by the presence of the URF. Rainwater harvesting capacity and quantity of recycled materials are calculated based on local technical codes and recycling practices. The global warming potential (GWP) indicators were calculated based on the methodology for a Simplified LCA using the "IPCC GWP 100 years lifecycle impact assessment". Simplified LCAs follow the LCA framework (ISO, 2006) but allow the use of generic and global available data (Guinée and Lindeijer, 2002). The GWP was calculated for two independent objects: the infrastructure of the farm and the food production, as suggested in literature (Sanyé-Mengual et al., 2015b). The infrastructure is analysed using a cradle-to-grave approach which includes the extraction, transportation, construction, maintenance and end-of-life stages, and a functional unit of 1 m^2/y and lifespan of 50 years as suggested for green-roofs (Bianchini and Hewage, 2012) and rooftop greenhouses (Sanjuan-Delmás et al., 2018). Food production was analysed using a cradle-to-gate approach including the infrastructure, production and waste stages for a functional unit of 1 kg/y of lettuce. A cut-off perspective was used for life cycle inventories (LCIs) (Ekvall and Tillman, 1997). The environmental impact quantification was done on SimaPro 8.2 using the Ecoinvent 3 database. Detailed information on the procedure, inventories, data sources and all necessary data for the calculation of each indicator can be found in Appendix D.

2.4. Case study

Quito, the capital of Ecuador, has an equatorial highland climate with an average temperature of 16 °C and a thermal amplitude of 11.3 °C (Instituto Nacional de Meteorología e Hidrología, 2013), which permits year-round open-air farming. Quito is one of the first cities in South America to support UA and has one of the most active programs in the region (FAO, 2014). However, land planning policies do not consider UA in their regulatory frameworks; and as such, there are no guidelines on its implementation nor its suitability. Due to the educational and social benefits of rooftop farms, schools are prime locations for URF implementation (Nadal et al., 2018). The Ecuadorian Ministry of Education supports the creation of urban-farms in its schools, and in 2017 launched the "TiNi initiative" to provide half square meter of farmland for each student (Ministerio de Educación del Ecuador, 2016). Regrettably, ground space availability limited the creation of farms to peri-urban and rural schools.

School buildings in the city are mostly uninsulated concrete frame structures with single-layer envelopes made of medium-weight concrete blocks or bricks; the roofs are ribbed slabs or metal claddings (Escuela Politécnica Nacional, 1995). The unfinished building's envelope causes faster degradation and water infiltration. Most open spaces are cement courtyards, which is why less than a third of schools have green areas. Refurbishing the roofs to include rooftop-farms could address these deficiencies due to the co-benefits of URF -increased thermal insulation, waterproofing, and larger lifespans. Additionally, URF could provide the required farm-space for the implementation of the TiNi initiative in urban schools.

2.4.1. Selection of rooftop farm technologies

In 2010, a New York City public school constructed the first fully-equipped outdoor classroom on a green roof (Greenwich Village School, 2012). More recently, the Fifth-Street-Farm project created modular edible-green roofs (eGRs) for use in NYC schools (Fifth Street Farm Project, 2008); sprouting similar initiatives across the USA and Canada (Fickes, 2014). Rooftop greenhouses (*RTG*) have also been created in educational buildings. In 2011, the New York Sun Works installed a RTG on the Manhattan School for Children (New York Sun Works, 2010). Following its success, the NYC Department of Education installed 67 RTGs as part of its "Greenhouse Project" (Nordgrén, 2017), and Detroit installed RTGs in over a third of its public schools (Detroit Public Schools Community District, 2012). In line with the existent projects, the URF technologies assessed in this article are described below (see Fig. 3). Appendix E provides the construction details for these technologies.

Edible green roofs (eGR): agriculture is a relatively new application for green roofs, adding vegetable production to their known benefits of rainwater runoff reduction, energy conservation and mitigation of the heat island effect (Walters and Stoelzle Midden, 2018). Extensive green roofs (<15 cm depth) are adequate for shallow-root crops with low-yields; however, thicker substrates can achieve yields comparable to those of ground agriculture (Whittinghill et al., 2013). This study uses a semi-intensive roof with 20 cm substrate composed of expanded clay (60%), slag (10%), brick shards (10%), peat (10%) and organic compost (10%) as suggested in the literature (Vacek et al., 2017).

Rooftop greenhouse (RTG): The greenhouse is an unconditioned asymmetric-tropical vault model, with structural bolted frame and tensioners of galvanised steel, low-density polyethene (LDPE) enclosure and a polyester climate screen. This model is the most common in the country (González, 2018). The hydroponic system is a modified Nutrient Film Technique (mNFT) in 4 inch PVC pipes (Ministerio de Agricultura y Ganadería, 2018). The plants are grown in small baskets placed in the PVC channels where an electrical pump continuously recirculates the nutrient solution.

Integrated rooftop greenhouse (iRTG): this greenhouse exchanges metabolic flows -heat, CO_2 and water-with its host building as to reduce their aggregated environmental impact (Sanjuan-Delmás et al., 2018). It includes features such as waste heat capture, rainwater harvesting, evaporative cooling and some form of renewable energy (Gould and Caplow, 2012). In this study, the iRTG uses the same model as the RTG and includes rainwater harvesting and a mechanical ventilation system; the analysis considers all construction interventions required.

Year-round lettuce production served for accounting the resource consumption and yields achieved by each URF technology (see Table 3). People consume large quantities of lettuce in Ecuador (Instituto Nacional de Estadística y Censos, 2011), and it is suitable for production in the three technologies. Lettuce yield in hydroponic greenhouses is three to four times larger than in soil crops due to steadier climate conditions resulting in higher growth rates and to the multilevel cultivation of the mNFT technique which increases the crop density (Ministerio de Agricultura y Ganadería, 2018). Since there is no available local data on iRTGs yield, it was set to the maximum yield in hydroponic greenhouses in the country considering that heat and CO_2 integration will increase the crop yields as suggested in the literature (Nadal et al., 2017). Resource consumption —including water, fertilisers and substrate-are detailed in Appendix D, subsection 11. As greenhouses are unconditioned in the country, the electricity modelled accounts exclusively for the circulation pumps and centrifugal fans using standard power consumptions for the equipment.

3. Results

These results are the first application for the proposed framework to a specific building typology in a city. The feasibility and sustainability of three rooftop-farming technologies to address the most significant deficiencies of existing schools in Quito —namely roof degradation, lack of green areas, and space inadequacy for implementing environmental projects- were quantified and compared. This section presents the results following the stages of the proposed method.

3.1. City stage: schools' reference buildings

There are no previous studies on architectural typologies in the country; and as such, the first step was to create the typological classification. This classification resulted in a 4x5 matrix of which only eight categories were significant (see Fig. 4a) -above the specified threshold of 4%- as schools built before 1945 and after 2006 are scarce. Each significant category is represented by one reference building unless the clustering shows that two or more subgroups are equally distributed. From here on, the results are

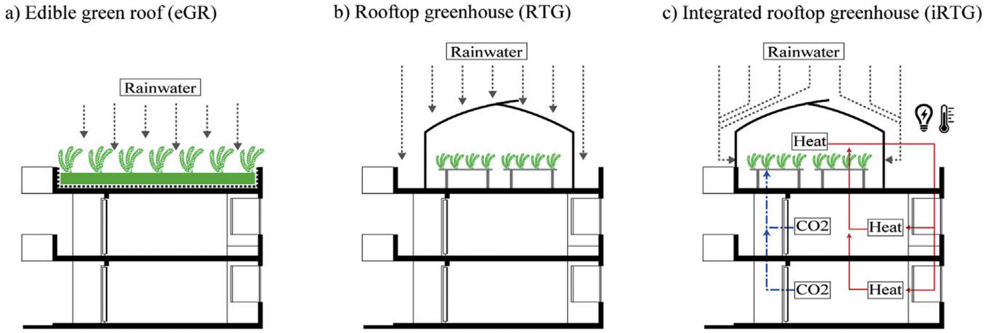


Fig. 3. Rooftop farming technologies considered in the feasibility and sustainability assessment.

Table 3
Yields and resource consumption for lettuce production in the selected URF technologies.

	Unit	eGR	RTG	iRTG
Crop yield	kg/m^2	3.60[a]	9.75[b]	11.71[b]
Water consumption	L/d/m^2	4.04[c]	1.03[b]	1.03[b]
Crop density	plants/m^2	12[a]	24[b]	24[b]
Crop cycle	d	80–90[a]	31–52[b]	31–52[b]
Number of crops	crop/y	4[a]	9[b]	9[b]

Edible-green roof (eGR), rooftop greenhouse (RTG), integrated rooftop greenhouse (iRTG).

[a] (Instituto Nacional Autónomo de Investigación Agropecuaria, 2008).

[b] (Mafla, 2015).

[c] (Francisco Medina, 2017).

described for the most representative category in the schools' stock. The descriptive data for the building sample is in Appendix F.

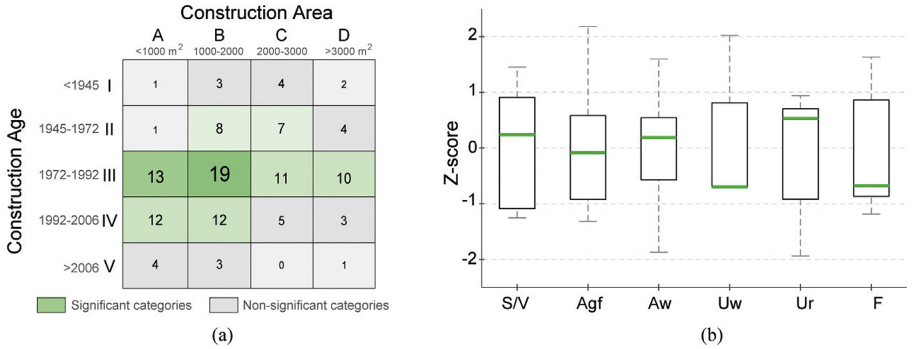
As specified in Section 2.1, the variables used for clustering were: compactness, ground floor area, external wall area, U-value of external walls, U-value of the roof, and the number of storeys. There is little variability in the sample regarding the thermal properties due to the widespread use of single-leaf envelopes (see Fig. 4b). There were no multivariate outliers as all cumulative probabilities were above 0.09 for the chi-square distribution with six degrees of freedom —corresponding to the number of variables used. Two clusters obtained the highest Calinski-Harabasz index with a value of 16.97 (see Fig. 5a). Using k = 2 in the K-mean algorithm resulted in 57% of the schools assigned to Cluster A and 43% to Cluster B, for the most significant typology category. The ANOVA test showed significant variances ($\rho \leq 0.05$) for compactness, ground floor area, roof's U-value, and the number of storeys. The two remaining parameters did not present significant differences and were the least influential in the cluster formation (see Fig. 5b).

The resulting school typologies are A) Disperse, one-storey buildings with pitch asbestos-cement roofs; and, B) Compact, two-storey buildings with flat concrete slabs. As both types are significant to the sample, two reference buildings were assigned and selected as the ones closest to their cluster centroids. The application of the clustering to the eight significant typology categories showed good agreement with the two identified school typologies, signalling little variability in construction practices since 1945. The review of the entire stock showed that 63.4% and 28.4% of the schools share similar characteristics as those of Cluster A and Cluster B, respectively. These results are in line with a 1995 study on construction systems in Quito's schools (Escuela Politécnica Nacional, 1995) which identified two types of schools —modules and compact- based on field surveys.

3.2. Building information stage: feasibility to implement rooftop farms in the reference buildings

The resulting reference schools are shown in Fig. 6. Based on the criteria defined in Section 2.2, the buildings were checked for their technical capacity and constraints to host rooftop farms. As authors expect the URF would be installed on the main buildings, the parameters described hereafter correspond to these. Table 4 shows the feasibility evaluation and required interventions in each school according to the farm type.

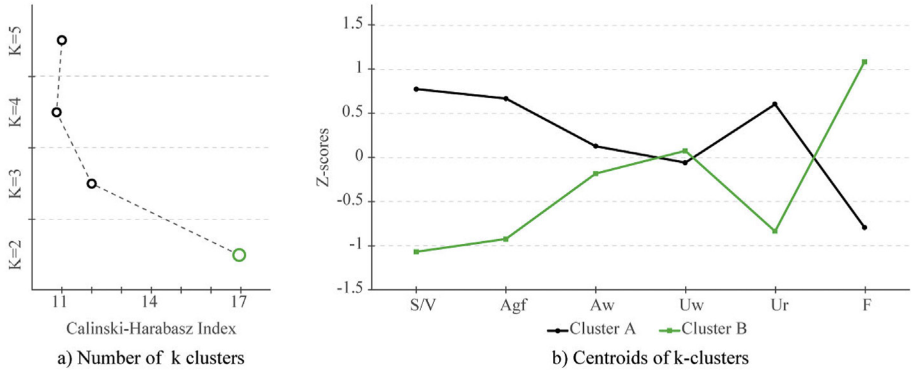
Reference school A has several one-storey buildings of which the predominant ones are two independent cross-shaped buildings interconnected by a lightweight metallic roof. The retrofitting is limited to one of these buildings to decrease the reconstruction impacts. The roof is composed of five independent sheds; the



Construction Age	A <1000 m^2	B 1000-2000	C 2000-3000	D >3000 m^2
<1945 I	1	3	4	2
1945-1972 II	1	8	7	4
1972-1992 III	13	19	11	10
1992-2006 IV	12	12	5	3
>2006 V	4	3	0	1

🟩 Significant categories ⬜ Non-significant categories

Fig. 4. (a) Typological classification of school buildings in Quito, and (b) Descriptive data of the sample. Compactness (S/V), ground floor area (Agf), external wall area (Aw), U-value for walls (Uw), U-value for roofs (Ur), number of storeys (F).



a) Number of k clusters b) Centroids of k-clusters

Fig. 5. Selection of "k" number of clusters using Calinski Index and cluster centroids characterisation using Z-scores.

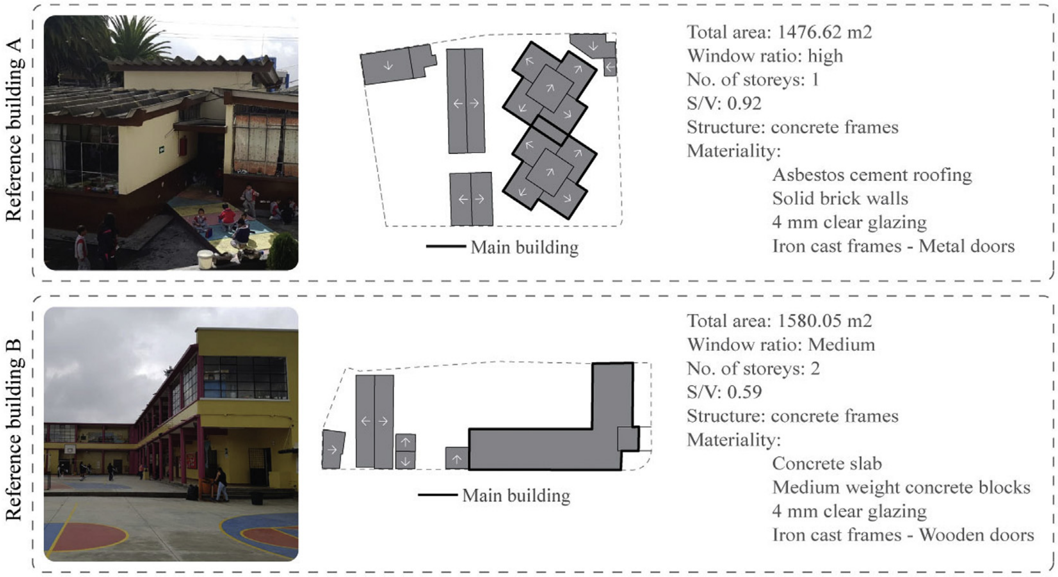


Fig. 6. School reference buildings, site plans of the school premises, and main characteristics. Compactness (S/V).

Table 4
Feasibility criteria and needed reconstruction interventions for the reference buildings to host rooftop-farms.

Criteria	Parameter	Reference school A			Reference school B			Source
		eGR	RTG	iRTG	eGR	RTG	iRTG	
Feasibility criteria								
Economic	Roof maximum available area (m^2)	231	231	231	517	517	517	Field visits
	Roof farm size (m^2)	231	50	50	517	100	100	OD
Environment	Solar radiation ($kWh/m^2/y$)	1326	1326	1326	1388	1388	1388	OD
Legal	Area restriction	No	Yes	Yes	No	Yes	Yes	IRM
	Height restriction	No	Yes	Yes	No	Yes	Yes	IRM
Technical	Load capacity of the buildings (kg/m^2)	75	75	75	200	200	200	NEC 1977
	Roof slope (percentage)	8	8	8	0	0	0	GIS STHV
	Accessibility	No	No	No	No	No	No	Field visits
Reconstruction interventions								
	Roof replacement	Yes	Yes	Yes	No	No	No	
	Structural reinforcement	Yes	Yes	Yes	Yes	No	No	
	Access type	Ext	Ext	Ext	Int	Int	Int	
	Mechanical fixings	No	No	Yes	No	No	Yes	
	Parapets	Yes	Yes	Yes	Yes	Yes	Yes	
	Construction permits	High	High	High	High	Low	Med	
	Construction risks	High	High	High	High	Med	Med	

Edible-green roof (eGR), rooftop greenhouse (RTG), rooftop greenhouse (iRTG), own data (OD), Ecuadorian construction code (NEC), Secretary of Territory, Habitat and Dwelling (STHV), Metropolitan regulation report (IRM).

central roof is 1 m above the others and thus is not included in the intervention. Due to their slope and structural capacity, these roofs will be dismantled and replaced by flat concrete slabs, precisely 12 cm composite steel deck with a minimum concrete compressive strength of 21 MPa and IPE metallic beams. The replacement of only one shed-roof is necessary for the installation of the rooftop greenhouse due to its area constraint (50–100 m^2). For the edible-green roof, the replacement of the four perimeter shed-roofs is considered. Additional interventions include the construction of an external staircase and parapets.

The main building in Reference School B is a 2-storey L-shaped building with a 20 cm unfinished concrete roof. The roof is currently inaccessible, and as such, the construction of a new flight of indoor staircases is needed. Parapets will be built on the inner façades complementing the existent ones. The roof overload capacity is not compliant with current regulations for green roofs; as such, reinforcement of the beams is necessary only for the installation of the eGR. The green roof will occupy the entire available area. As for compliance with urban policies, the RTG will be located facing the indoor courtyard. Site plans of the interventions and solar radiation models are found in Appendix G.

3.3. *Farming technology stage: s**ustainability** of three rooftop farms*

The sustainability evaluation was done for six scenarios resulting from the three URFs technologies application in the two reference schools. The values for the indicators in the six scenarios are shown in Table 5. The calculation procedures for each indicator are detailed in Appendix D. The most discriminant indicators between reference schools were the reconstruction cost, global warming potential and safety risks; all of which are related to the retrofit interventions defined previously. Reference school A has the highest values in these indicators due to the dismantling and construction of the new roofs. In the legal/planning indicator, School B has more urban limitations due to its lack of construction setbacks and maximum construction height. The remaining indicators are more discriminatory between farming technologies than between the host reference buildings.

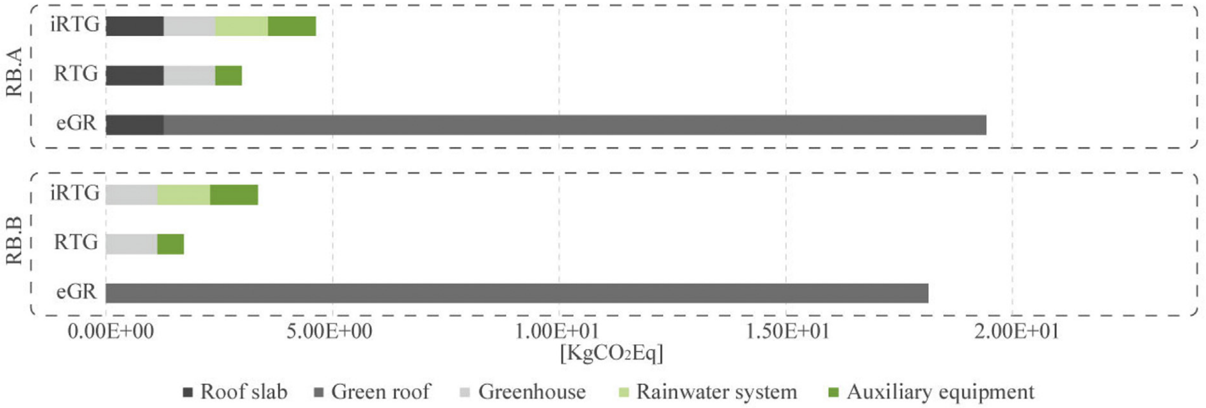
Considering there was no local data on the global warming potential (GWP) of URF technologies, the quantified impacts will be described in more detail than other indicators. The climate change impacts of the farm systems and lettuce production for the six scenarios are shown in Fig. 7. Green roofs have an impact of 18.15 kgCO$_2$eq/m^2; ten times the RTG and six times the iRTG values. However, the auxiliary equipment needed for the iRTG integration does not significantly increase the GWP, signalling the potential to use exhaust airflows from the building in the greenhouse. These results are in line with values found in literature like 17.34 kgCO$_2$eq/m^2 for extensive green roofs (Lamnatou and Chemisana, 2015) or 2.42 kgCO$_2$eq/m^2 for rooftop greenhouses (Sanyé-Mengual et al., 2015b). Lettuce production in the eGR has the highest GWP due to its infrastructure; however, its cultivation method (soil) is the lowest of the three farms with a value of 0.05 kgCO$_2$eq per kg of lettuce. In contrast, the mNFT used in the greenhouses has an impact of up to 1.76 kgCO$_2$eq per kg of lettuce. These results suggest that hydroponic systems can be a liability if not managed correctly.

The global sustainability index (GSi) for the six scenarios is shown in Fig. 8, the requirements and criteria indexes are in Appendix H. The edible-green roofs obtained the highest GSi with medium values of 0.62 and 0.65 for reference schools A and B, respectively. The other scenarios had even lower GSis raging from 0.45 to 0.5. In general, URFs in school B have better indexes due to the lesser reconstruction interventions. The economic requirement is the most discriminant between reference schools, with differences of up to 0.18. However, and since the social dimension was prioritised in the MIVES requirements tree −40% weight- the economic burden of replacing the rooftop does not become a conditioning parameter for the implementation of rooftop-farms. The economic dimension favours rooftop greenhouses because of its higher production yields; but, in the environmental, social and technical dimensions, edible-green roofs are ranked higher. These results are in line with the widespread use of green roofs on residential and commercial buildings in the city. As for both school typologies, edible-green roofs obtained the highest sustainability indexes; their up-scaling renders a potential farming area of 36,113 m^2 and a lettuce yield of 130,000 kg/y. This yield would supply an estimated of 128,839 persons in the city −using a per-capita consumption of 0.56 kg/person/y. In (Nadal et al., 2019), the authors determined that the potential installation of RTGs in a low-income neighbourhood of Quito would fulfill an annual lettuce yield at less than half the value that could be obtained by installing RTGs in the schools of the city (72,150 kg/y).

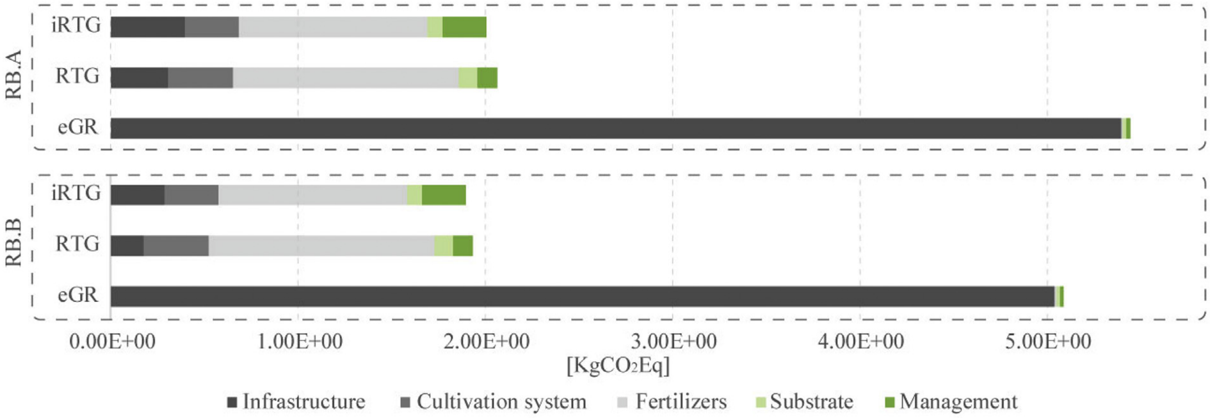
Table 5
Quantification of the indicators for the six assessed scenarios.

Req.	Indicator	Unit	Reference school A			Reference school B			Calculation
			eGR	RTG	iRTG	eGR	RTG	iRTG	
E	I1. Reconstruction cost	\$/m^2	254.5	316.3	331.4	60.0	28.6	38.7	See Appendix D.1
E	I2. Installation cost	\$/m^2	47.3	71.7	131.0	47.3	64.7	101.7	See Appendix D.2
E	I3. Disassembly cost	\$/m^2	13.4	15.0	17.3	13.4	15.0	17.3	See Appendix D.3
E	I4. Maintenance cost	\$/m^2	9.8	13.5	21.1	9.8	13.4	21.1	See Appendix D.4
E	I5. Production cost	\$/m^2	0.2	0.3	0.3	0.2	0.3	0.3	See Appendix D.5
E	I6. Production yield	kg/m^2/y	3.6	9.8	11.7	3.6	9.8	11.7	See Appendix D.6
N	I7. Thermal insulation	W/m^{2}K	1.7	3.6	3.6	1.7	3.6	3.6	See Appendix D.7
N	I8. Potential for flows exchange	Points	4.0	2.0	9.0	4.0	2.0	9.0	See Appendix D.8
N	I9. Rainwater harvesting capacity	Percentage	46.6	0.0	20.3	48.7	0.0	18.8	See Appendix D.9
N	I10. GWP due to construction	kgCO$_2$eq	19.4	3.0	4.6	18.2	1.7	3.4	See Appendix D.10
N	I11. GWP due to production	kgCO$_2$eq	5.5	2.1	2.0	5.1	1.9	1.9	See Appendix D.11
N	I12. Recycling potential	kg/m^2	0.8	0.9	1.0	0.8	0.9	1.0	See Appendix D.12
S	I13. Potential use as classroom	Points	2.0	3.0	3.0	2.0	3.0	3.0	See Appendix D.13
S	I14. Affinity with curriculum	Points	7.0	12.0	12.0	7.0	12.0	12.0	See Appendix D.14
S	I15. Legal/planning requirements	Points	3.0	5.0	5.0	3.0	6.0	6.0	See Appendix D.15
S	I16. Safety risk during construction	Points	12.0	10.0	10.0	11.0	8.0	8.0	See Appendix D.16
T	I17. Qualification of labour	Points	8.0	10.0	11.0	8.0	10.0	11.0	See Appendix D.17

Requirements: Economic (E), Environmental (N), Social (S), Technical (T).



a) Global warming potential of the rooftop-farm technologies installation in the reference schools



b) Global warming potential of lettuce production in the rooftop-farms and reference schools

Fig. 7. Global warming potential indicators for the six assessed scenarios: three URF technologies and two reference schools.

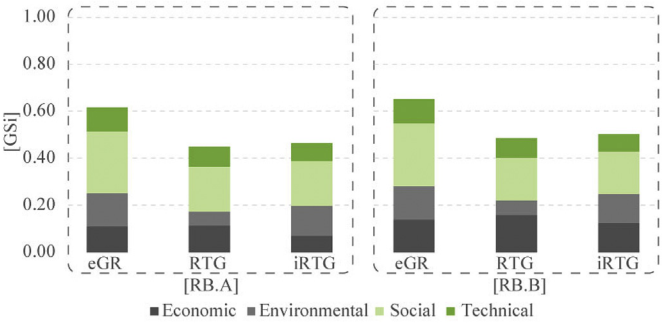


Fig. 8. Sustainability index of URF with the requirements contribution to the final index results.

4. Discussion

The proposed model is a new approach to the sustainability of large-scale applications of rooftop-farming by using statistically derived architecture typologies. The detailed analysis of these typologies —both in technical and planning terms — permitted the formulation of viable implementation strategies and the inclusion of the buildings retrofit impacts in the sustainability evaluation. This model differs from those found in literature on urban-scale applications for URF in which the feasibility criteria serves only for pre-screening short-term viability for rooftops farms (Saha and Eckelman, 2017). This model also differs from prior urban-scale studies that have not included the environmental and economic impacts for reconstructing or adapting the rooftops to host rooftop-farming (Sanyé-Mengual et al., 2015a). Though the structure of the sustainability valuation would be valid for similar assessments, the definition of the indicators and weighings are context-specific, and their extrapolation would require review by a panel of experts.

This model was applied successfully for the primary school stock of Quito. In this research project, schools served as a pilot due to governmental support and existing farmland cultivation projects; however, particular issues like continuous operation during holiday periods needs further consideration (Leibniz Centre for Agricultural Landscape Research, 2015). The proposed framework could be replicated to other building stocks and geographic contexts; mainly because the bottom-up modelling technique used —clustering- is adaptable to any architecture typology such as housing (Li et al., 2018) or commercial buildings (Gao and Malkawi, 2014). The proposed typological classification was intended to eliminate the significant influence of the age and area of the buildings during the clustering. However, the results for Quito showed little variability in the sample. This result signalled the possibility of removing the typological classification in building stocks where construction practices have not changed significantly as opposed to other models found in the literature (University of Belgrade, 2018).

4.1. Sustainability model and definition of indicators

As analysed in depth in Section 1.1, previous quantitative sustainability evaluations for URF rely on individual indicators or analyse only one of the sustainability pillars, apart from seldom interdisciplinary discussions (Sanye-Mengual et al., 2017). This new MIVES-based valuation tool assesses all dimensions for sustainability simultaneously. By incorporating only discriminating indicators, it permits unbiased agile evaluations in terms of data collection and calculations, compared to previous holistic sustainability assessments for UA which use large sets of indicators (Landert et al., 2017).

This reduced number of indicators resulted from prioritising certain aspects of the decision-making process to reflect the specificity in the case-study (see Section 2.3). In this sense, this model prioritises the social impact URF has similarly as related studies conducted in different contexts (Sanyé-Mengual et al., 2018). The indicators included in this article relate to the use of URFs as teaching spaces and their incorporation to the learning curricula in these schools; without disregard to other social indicators -like improved access to food, community building, nutrition, among others- that may prove more relevant in different context conditions (Nadal et al., 2018). As expected, the results of applying this assessment model to Quito favours open-air farming despite the additional economic expenses for its construction. Thus the results differ from the aforementioned former studies on the economic viability for URF.

4.2. Sensitivity and interpretation of the global sustainability index

As the global sustainability index quantification depends directly on the weighting of the requirements tree, its consistency in different weighing scenarios proved its relative objectivity. However, the inclusion of techniques like Delphi and BIAS reduction could further improve this. The GSi index was recalculated in four scenarios: economic, environmental, social and technical. In each of these scenarios, a weight of 70% was given to its namesake requirement and 10% weights to those remaining, e.g. economic scenario (Economic 70%, Environmental 10%, Social 10%, Technical 10%). The results confirm the predominance of the edible-green roof over the RTG and iRTG models, and the stability of the GSi value under different scenarios with variations of less than 0.08 (see Fig. 9).

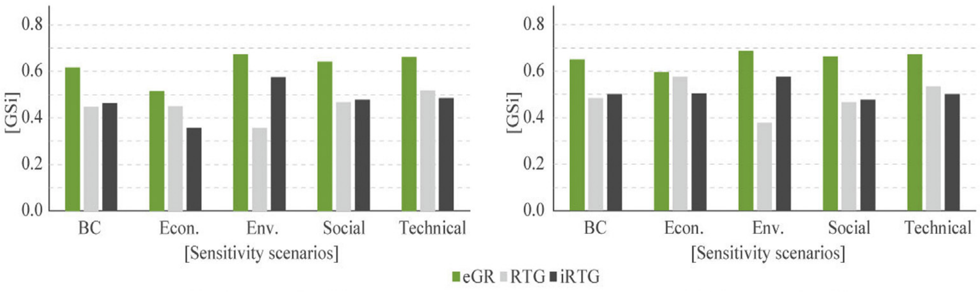
Edible-green rooftop farms are best suited for the assessed stock; however, it is noteworthy that none of the evaluated technologies achieved high indexes. This occurred due to contrasting values in the indicators, e.g. eGRs need lower economic investments but also have the lowest yields. In this way, the proposed framework not only grades URFs' sustainability but provides valuable information on crucial improvement points. Open-air farming -such as eGRs- is favoured for educational purposes (Buehler and Junge, 2016), and so it was expected that this farming system ranked higher than RTGs. However, green-roofs' high environmental impacts and low production yields are their main setbacks compared to RTGs. Lower yields occur because of the low percentage of organic matter in the substrate as to limit weight overloads (Walters and Stoelzle Midden, 2018), thus requiring a proper fertilisation program to guarantee productivity, and hence, incrementing its overall environmental impact.

On the other hand, greenhouses require higher economic investments, although this could be offset by the profits in large-scale commercial initiatives (Benis et al., 2018). Nevertheless, in social uptakes, where the focus is on education or self-supply, the greenhouse structure is a liability. This is especially true when the maximum area for a RTG is limited, and thus the co-benefits —like thermal insulation- are partial. A revision of the planning policies should address these deficiencies as to allow greenhouses to occupy the entire roof area.

Rainwater harvesting is crucial for URFs, being positive from an environmental point-of-view (Specht et al., 2014), but increasing the economic investment and requiring further planning and legal permits as technical equipment is required for these greenhouses (Specht et al., 2016). Therefore, in the case-study rainwater harvesting was an essential discriminative indicator that improved the environmental performance for eGRs and iRTGs, but compromised the economical impacts of the latter. However, in different geographic contexts with low precipitation rates, eGRs could be a liability if irrigated by rainwater (Walters and Stoelzle Midden, 2018). Building-integrated agriculture —of which iRTGs are an example- can significantly reduce fossil fuel consumption for thermally conditioning both the building and greenhouse (Nadal et al., 2017). But, if as in the case study, the host buildings are unconditioned, iRTGs benefits are reduced to a slight increase in production yield. Higher food yields in greenhouses are obtained using hydroponic systems. However, these systems imply significant environmental impacts during production due to their use of fertilisers and electricity (Sanyé-Mengual et al., 2015c). In this sense, future applications of the present model more focused on commercial outcomes could assess other cultivation systems as well as other relevant crops and generate strategies for the diversification of crops.

5. Conclusions and future work

This article describes in detail the new bottom-up model for evaluating the potential implementation of rooftop farming technologies in building stocks. To the authors' best knowledge, the main novelties and strengths in this model are the use of reference



a) Reference school A b) Reference school B

Fig. 9. Global sustainability index of URF technologies in different weighting scenarios. BC (base case).

buildings as accurate representatives of the stock, and the agile quantification of a unified sustainability index based on customisable discriminating indicators from a holistic sustainability approach. To achieve these novelties, this model relied on a bottom-up modelling strategy for dealing with large building samples; and, on seminars with experts for the selection of the indicators -which also gave objectivity to the sustainability assessment. This model was first applied to assess the sustainability for the hypothetical implementation of three rooftop-farm technologies in the school stock in Quito, Ecuador.

Two reference buildings represented the primary school stock of the city. In both schools, edible-green roofs obtained the highest sustainability index with values of 0.62 and 0.65, up to 37% above the other options. This result was due to their larger rainwater harvesting capacity, thermal resistance and lower economic investment. The application of eGRs in the schools would result in annual production yields of 130 t -almost twice the production of RTGs- and could supply the entire self-demand for the school population. The building-integrated agriculture alternatives had unexpected low indexes due to the city's particular climate conditions. However, and since all technologies had sustainability values below 0.70, significant improvements are needed for all rooftop-farms.

This bottom-up model is a promising tool to conduct sustainability assessments in building typologies and city-wide applications. As this is the first study on building typologies in the country, this method can serve as the starting point for additional research projects on building inventories, classification and energy benchmarking, or assessment of degradation states, among others. This framework is a flexible tool that could be used by stakeholders and local governments to assess different UA systems. This tool also has the potential to expand to other decision-making processes -like rehabilitation or energy efficiency- by adapting the indicators to best reflect the assessed topic. In this sense, future studies will deal with the adaptation and application of this model to other geographic contexts and building typologies, and the inclusion of other URF alternatives and different crops and cultivation systems. Additionally, rooftop-farming will be assessed as a potential passive energy rehabilitation strategy and compared to standard rehabilitation practices on school typologies.

CRediT authorship contribution statement

Gabriela Ledesma: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft. **Jelena Nikolic:** Conceptualization, Supervision, Writing - review & editing. **Oriol Pons-Valladares:** Conceptualization, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.122993.

References

Arambula Lara, R., Cappelletti, F., Romagnoni, P., Gasparella, A., 2014. Selection of representative buildings through preliminary cluster Analysis. In: International High Performance Buildings Conference.

Arambula Lara, R., Pernigotto, G., Cappelletti, F., Romagnoni, P., Gasparella, A., 2015. Energy audit of schools by means of cluster analysis. Energy Build. 95, 160–171. https://doi.org/10.1016/j.enbuild.2015.03.036.

Artmann, M., Sartison, K., 2018. The role of urban agriculture as a nature-based solution: a review for developing a systemic assessment framework. Sustainability 10. https://doi.org/10.3390/su10061937.

Autodesk, 2019. Insight - high performance and sustainable building design analysis [WWW Document]. URL. https://insight360.autodesk.com/oneenergy. accessed 5.8.20.

Ballarini, I., Corgnati, S.P., Corrado, V., 2014. Use of reference buildings to assess the energy saving potentials of the residential building stock: the experience of TABULA project. Energy Pol. 68, 273–284. https://doi.org/10.1016/j.enpol.2014.01.027.

Benis, K., Reinhart, C., Ferrão, P., 2017. Development of a simulation-based decision support workflow for the implementation of Building-Integrated Agriculture (BIA) in urban contexts. J. Clean. Prod. 147, 589–602. https://doi.org/10.1016/j.jclepro.2017.01.130.

Benis, K., Turan, I., Reinhart, C., Ferrão, P., 2018. Putting rooftops to use – a cost-benefit analysis of food production vs. energy generation under mediterranean climates. Cities 78, 166–179. https://doi.org/10.1016/j.cities.2018.02.011.

Bianchini, F., Hewage, K., 2012. How "green" are the green roofs? Lifecycle analysis of green roof materials. Build. Environ. 48, 57–65. https://doi.org/10.1016/j.buildenv.2011.08.019.

Buehler, D., Junge, R., 2016. Global trends and current status of commercial urban rooftop farming. Sustainability 8, 1–16. https://doi.org/10.3390/su8111108.

Crespo, P., Ortiz, C., 1999. Aportes para una historia de la educación municipal en Quito. Procesos Rev. Ecuat. Hist. I. 13, 57–72.

Delor, M., 2011. Building-Integrated Agriculture. Current state, potential energy benefits and comparison with green roofs. Sheffield, UK.

Detroit Public Schools Community District, 2012. Farm and garden: DPSCD farm-to-school [WWW Document]. URL. https://www.detroitk12.org/Page/7168. accessed 5.10.19.

Eaves, J., Eaves, S., 2018. Comparing the profitability of a greenhouse to a vertical farm in quebec. Can. J. Agric. Econ. 66, 43–54. https://doi.org/10.1111/cjag.12161.

Ekvall, T., Tillman, A.M., 1997. Open-loop recycling: criteria for allocation procedures. Int. J. Life Cycle Assess. 2, 155–162. https://doi.org/10.1007/BF02978810.

Escuela Politécnica Nacional, 1995. Proyecto de seguridad sísmica para las construcciones escolares. Invirtiendo en el futuro de Quito. Stanford: GeoHazards Internation, Quito, Ecuador.

FAO, 2014. Ciudades más verdes en América Latina y El Caribe. Un informe de la FAO sobre la agricultura urbana y periurbana en la región. FAO, Roma, Italy.

Fargue-Lelièvre, A., Clérino, P., 2018. Developing a tool to evaluate the sustainability of intra-urban farms. In: Sustainable Agriculture. From Common Principles to Common Practices. Proceedings from the International Forum on Assessing Sustainability in Agriculture. Chania, pp. 1–10.

Fickes, M., 2014. School roofs aren't what they used to Be [WWW Document]. March 1. URL. https://webspm.com/Articles/2014/03/01/School-Roofs.aspx. accessed 5.10.19.

Fifth Street Farm Project, 2008. Fifth Street farm. A NYC public school green roof project [WWW Document]. 2011. URL. http://www.5thstreetfarm.org/. accessed 3.11.19.

Fuente, A. De, Pons, O., Josa, A., Aguado, A., 2016. Multi-Criteria Decision Making in the sustainability assessment of sewerage pipe systems. J. Clean. Prod. 112, 4762–4770. https://doi.org/10.1016/j.jclepro.2015.07.002.

Gao, X., Malkawi, A., 2014. A new methodology for building energy performance benchmarking: an approach based on intelligent clustering algorithm. Energy and Buildings 84, 607–616. https://doi.org/10.1016/j.enbuild.2014.08.030.

Goldstein, B., Hauschild, M., Fernández, J., Birkved, M., 2016. Testing the environmental performance of urban agriculture as a food supply in northern climates. J. Clean. Prod. 135, 984–994. https://doi.org/10.1016/j.jclepro.2016.07.004.

González, E., 2018. Invernaderos, materiales e insumos en Ecuador. Quito, Ecuador.

Gould, D., Caplow, T., 2012. Building-integrated agriculture: a new approach to food production. In: Metropolitan Sustainability: Understanding and Improving the Urban Environment, pp. 147–170. https://doi.org/10.1533/9780857096463.2.147.

Greenwich Village School, 2012. Greenroof environmental literacy laboratory [WWW Document]. 2012. URL. https://www.ps41.org/m/pages/index.jsp?uREC_ID=357954&type=dtal-literacy-laboratory-gell/. accessed 3.11.19.

Guinée, J.B., Lindeijer, E., 2002. Scientific background, in: Springer Science & Business Media. In: Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Kluwer Academic Publishers, Dordrecht, p. 692.

Haberman, D., Gillies, L., Canter, A., Rinner, V., Pancrazi, L., Martellozzo, F., 2014. The potential of urban agriculture in montréal: a quantitative assessment. ISPRS Int. J. Geo-Inf. 3, 1101–1117. https://doi.org/10.3390/ijgi3031101.

Instituto Nacional Autónomo de Investigación Agropecuaria, 2008. Guía técnica de Cultivos. In: Manual No. 73, 2008th ed. INIAP, Quito, Ecuador.

Instituto Nacional de Estadística y Censos, 2011. Encuesta Nacional de Ingresos y Gastos de los Hogares Urbanos y Rurales [WWW Document]. 2012. URL. https://www.ecuadorencifras.gob.ec/institucional/home/. accessed 1.7.20.

Instituto Nacional de Meteorología e Hidrología, 2013. Anuarios Meteorológicos, 2017. Quito, Ecuador.

ISO, 2006. ISO 14040:2006 Environmental Management — Life Cycle Assessment — Principles and Framework, second ed.

ISO, 2017a. ISO 6946:2017 Building Components and Building Elements - Thermal Resistance and Thermal Transmittance - Calculation Methods, third ed.

ISO, 2017b. ISO 13370:2017 Thermal Performance of Buildings - Heat Transfer via the Ground - Calculation Methods, third ed.

Kim, E., Jung, J., Hapsari, G., Kang, S., Kim, K., Yoon, S., Lee, M., Han, M., Choi, Y., Choe, J.K., 2018. Economic and environmental sustainability and public perceptions of rooftop farm versus extensive garden. Build. Environ. 146, 206–215. https://doi.org/10.1016/j.buildenv.2018.09.046.

Lamnatou, C., Chemisana, D., 2015. Evaluation of photovoltaic-green and other roofing systems by means of ReCiPe and multiple life cycle-based environmental indicators. Build. Environ. 93, 376–384. https://doi.org/10.1016/j.buildenv.2015.06.031.

Landert, J., Schader, C., Moschitz, H., Stolze, M., 2017. A holistic sustainability assessment method for Urban food system governance. Sustainability 9, 1–21. https://doi.org/10.3390/su9040490.

Leibniz Centre for Agricultural Landscape Research, 2015. There's Something Growing on the Roof (Berlin).

Li, X., Yao, R., Liu, M., Costanzo, V., Yu, W., Wang, W., Short, A., Li, B., 2018. Developing urban residential reference buildings using clustering analysis of satellite images. Energy Build. 169, 417–429. https://doi.org/10.1016/j.enbuild.2018.03.064.

Mafla, E., 2015. Respuesta de tres variedades de lechuga (Lactuca sativa L.). In: con tres niveles de fertilización en producción hidropónica en la zona de Ibarra, Provincia de Imbabura. Univ. Técnica Babahoyo. Universidad Técnica de Babahoyo.

Medina, Francisco, 2017. Necesidades nutricionales y de riego de la lechuga. Granja. Rev. Agropecu. 22, 104–111.

Ministerio de Agricultura y Ganadería, 2018. Lechuga se produce de forma hidropónica [WWW Document]. Agosto 16. URL. https://www.agricultura.gob.ec/lechuga-se-produce-de-forma-hidroponica/. accessed 5.13.19.

Ministerio de Desarrollo Urbano y Vivienda, 2014. Norma ecuatoriana de la Construcción. Cargas (No sísmicas). MIDUVI, Registro Oficial, Año II, Nro. 319, p. 44. Ecuador.

Ministerio de Desarrollo Urbano y Vivienda, 2018. Eficiencia Energética en Edificaciones Residenciales. MIDUVI, Registro Oficial, Año I, Edición Especial No. 358, Ecuador.

Ministerio de Educación del Ecuador, 2016. In: Quito, Ecuador (Ed.), Guía introductoria a la metodología TINI. Tierra de niñas, niños y jóvenes para el buen vivir, Asociación.

Ministerio de Educación del Ecuador, 2018. AMIE (Estadísticas educativas a partir de 2009-2010) [WWW Document]. 2009. URL. https://educacion.gob.ec/amie/. accessed 11.13.18.

Municipio del Distrito Metropolitano de Quito, 2011. Régimen Administrativo del Suelo. Municipio del Distrito Metropolitano de Quito, Ecuador.

Nadal, A., Llorach-Massana, P., Cuerva, E., López-Capel, E., Montero, J.I., Josa, A., Rieradevall, J., Royapoor, M., 2017. Building-integrated rooftop greenhouses: an energy and environmental assessment in the mediterranean context. Appl. Energy 187, 338–351. https://doi.org/10.1016/j.apenergy.2016.11.051.

Nadal, A., Pons, O., Cuerva, E., Rieradevall, J., Josa, A., 2018. Rooftop greenhouses in educational centers: a sustainability assessment of urban agriculture in compact cities. Sci. Total Environ. 626, 1319–1331. https://doi.org/10.1016/j.scitotenv.2018.01.191.

Nadal, A., Rodríguez-Cadena, D., Pons, O., Cuerva, E., Josa, A., Rieradevall, J., 2019. Feasibility assessment of rooftop greenhouses in Latin America. The case study of a social neighborhood in Quito, Ecuador. Urban For. Urban Green. 44, 126389. https://doi.org/10.1016/j.ufug.2019.126389.

New York Sun Works, 2010. The greenhouse project [WWW Document]. 2010. URL. https://nysunworks.org/. accessed 5.10.19.

Nordgrén, M., 2017. Growing trend: sustainable science in New York city schools [WWW Document]. Novemb. 2. URL. https://greenhomenyc.org/blog/growing-trend-sustainable-science-in-new-york-city-schools/. accessed 5.10.19.

Saaty, T.L., 1990. How to make a decision: the analytic hierarchy process. Eur. J. Oper. Res. 48, 9–26. https://doi.org/10.1016/0377-2217(90)90057-I.

Saha, M., Eckelman, M.J., 2017. Growing fresh fruits and vegetables in an urban landscape: a geospatial assessment of ground level and rooftop urban agriculture potential in Boston, USA. Landsc. Urban Plann. 165, 130–141. https://doi.org/10.1016/j.landurbplan.2017.04.015.

Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Ercilla-Montserrat, M., Muñoz, P., Montero, J.I., Josa, A., Gabarrell, X., Rieradevall, J., 2018. Environmental assessment of an integrated rooftop greenhouse for food production in cities. J. Clean. Prod. 177, 326–337. https://doi.org/10.1016/j.jclepro.2017.12.147.

Sanyé-Mengual, E., Cerón-Palma, I., Rieradevall, J., Montero, J.I., Oliver-Solà, J., 2015a. Integrating horticulture into cities: a guide for assessing the implementation potential of rooftop greenhouses (RTGs) in industrial and logistics parks. J. Urban Technol. 22, 87–111. https://doi.org/10.1080/10630732.2014.942095.

Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2015b. An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. Int. J. Life Cycle Assess. 20, 350–366. https://doi.org/10.1007/s11367-014-0836-9.

Sanyé-Mengual, E., Orsini, F., Oliver-Solà, J., Rieradevall, J., Montero, J.I., Gianquinto, G., 2015c. Techniques and crops for efficient rooftop gardens in Bologna. Italy. Agron. Sustain. Dev. 35, 1477–1488. https://doi.org/10.1007/s13593-015-0331-0.

Sanyé-Mengual, E., Anguelovski, I., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2016. Resolving differing stakeholder perceptions of urban rooftop farming in Mediterranean cities: promoting food production as a driver for innovative forms of urban agriculture. Agric. Hum. Val. 33, 101–120. https://doi.org/10.1007/s10460-015-9594-y.

Sanye-Mengual, E., Oliver-Sola, J., Ignacio Montero, J., Rieradevall, J., 2017. The role of interdisciplinarity in evaluating the sustainability of urban rooftop agriculture. Futur. Food-Journal Food Agric. Soc. 5, 46–58.

Sanyé-Mengual, E., Orsini, F., Gianquinto, G., 2018. Revisiting the sustainability concept of Urban Food Production from a stakeholders' perspective. Sustainability 10. https://doi.org/10.3390/su10072175.

Secretaría de Territorio Habitat y Vivienda, 2019. Visor geográfico del Plan de Uso y Ocupación del Suelo [WWW Document]. STHV - DMPPS. URL. https://territorio.maps.arcgis.com/apps/webappviewer/index.html?id=47ccc16154584d458d7e657dba576855. accessed 1.7.20.

Specht, K., Siebert, R., Hartmann, I., Freisinger, U.B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., Dierich, A., 2014. Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agric. Hum. Val. 31, 33–51. https://doi.org/10.1007/s10460-013-9448-4.

Specht, K., Siebert, R., Thomaier, S., 2016. Perception and acceptance of agricultural production in and on urban buildings (ZFarming): a qualitative study from Berlin, Germany. Agric. Hum. Val. 33, 753–769. https://doi.org/10.1007/s10460-015-9658-z.

Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U.B., Sawicka, M., 2014. Farming in and on urban buildings: present practice and specific novelties of zero-acreage farming (ZFarming). Renew. Agric. Food Syst. 30, 43–54. https://doi.org/10.1017/S1742170514000143.

University of Belgrade, 2018. School and Kindergarten Buildings - A Methodological Framework for the Formation of Typology and the Improvement of Energy Efficiency, Deutsche Gesellschaft Fur Internationale Zusammenarbeit (GIZ). Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ), Belgrade. https://doi.org/10.1017/CBO9781107415324.004.

Vacek, P., Struhala, K., Matějka, L., 2017. Life-cycle study on semi intensive green roofs. J. Clean. Prod. 154, 203–213. https://doi.org/10.1016/j.jclepro.2017.03.188.

Viljoen, A., Bohn, K., 2014. Second Nature Urban Agriculture: Designing Productive Cities, first ed. Taylor & Francis, London, UK. https://doi.org/10.4324/9781315771144.

Viñolas, B., Cortés, F., Marques, A., Josa, A., Aguado, A., 2009. MIVES: modelo integrado de valor para evaluaciones de sostenibilidad. In: Centro Internacional de Métodos Numéricos en Ingeniería (CIMNE). II Congrés Internacional de Mesura i Modelització de La Sostenibilitat. Barcelona, Spain, pp. 1–24.

Walters, S., Stoelzle Midden, K., 2018. Sustainability of urban agriculture: vegetable production on green roofs. Agriculture 8, 168. https://doi.org/10.3390/agriculture8110168.

Whittinghill, L., Rowe, D., Cregg, B., 2013. Evaluation of vegetable production on extensive green roofs. Agroecol. Sustain. Food Syst. 37, 465–484. https://doi.org/10.1080/21683565.2012.756847.