Future of Food: Journal on Food, Agriculture and Society
5 (1) Summer 2017

The role of interdisciplinarity in evaluating the sustainability of urban rooftop agriculture

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Data of the article

First received : 23 December 2016 | Last revision received : 14 May 2017
Accepted : 18 May 2017 | Published online : 20 June 2017
URN:nbn:de:hebis:34-2017042652446

Key words

Urban agriculture, Life cycle assessment, Qualitative research, Geographic information systems, Integrated assessment

Abstract

Recently, urban agriculture (UA) has expanded throughout cities of the developed world as a response to social injustices and environmental gaps of the globalized food system (including food security, economic opportunities and community building). Due to the limiting factors of the urban environment (e.g., land availability), UA often occupies the roofs of buildings as vacant space to further develop local food production through so-called urban rooftop agriculture (URA). This paper presents an interdisciplinary scheme employed to evaluate the sustainability of URA as a complex system while investigating the potential of URA in quantitative and qualitative terms as well as the environmental and economic impact of different types of URA. The implementation of URA, as a specific form of UA, in a Mediterranean context was assessed using Barcelona, Spain and Bologna, Italy as case studies. Interdisciplinary methods from four disciplines were combined: (a) qualitative research to identify the potential of URA by evaluating the perceptions of different stakeholders; (b) geographic information systems (GIS), to quantify the potential area for implementing URA; (c) life cycle assessment (LCA), to quantify the environmental impacts of URA forms; and (d) life cycle costing (LCC), to quantify the economic costs of URA forms. According to the results, a combined GIS-LCA tool is useful in evaluating the implementation of URA and the consequent environmental benefits at the city scale. Stakeholders highlighted the contribution of URA to the three dimensions of sustainability, as well as the potential risks tied to its complexity and novelty. Comparing different urban spaces, the implementation of URA is more feasible in the short-term on the roofs of retail parks than industrial ones. At the system scale, soil cultivation with compost in open-air rooftop gardens resulted in the most eco-efficient cultivation option. Open-air rooftop gardens had lower environmental impacts and economic costs than rooftop greenhouses. LCA and LCC results outlined the relevance of decisions in the design phase regarding cultivation technique, crop choice and management.

Introduction

Urban agriculture (UA) is spreading throughout cities worldwide in order to increase local food production (Mok et al., 2013; Orsini, Kahane, Nono-Womdim, & Gianquinto, 2013). In the Global North, UA encompasses multifunctional projects implemented to address environmental, economic and social gaps (Carney, 2011), such as the occurrence of "food deserts" (McClintock, 2011; Wrigley, Warm, Margetts, & Lowe, 2004). In particular, UA initiatives promoted by civil society improve community empowerment, social inclusion and communi-

Citation (APA):
Sanyé-Mengual, E., Oliver-Solà, J., Montero, J. I., Rieradevall, J. (2017). The role of interdisciplinariety in the evaluation of the sustainability of urban rooftop agricultureEncouraging private sector participation in climate finance. *Future of Food: Journal on Food, Agriculture and Society*, *5*(1), 46-58.

Table 1: The four main typologies of urban rooftop agriculture can be identified according to the type of production and the main goal (based on Sanyé-Mengual, 2015).

		Main goal	
		Social	Commercial
Type of production	Protected cultivation	Socially-oriented rooftop greenhouse featuring social initiatives for education and health *e.g., Manhattan School for Children (New York, United States)*	Business-oriented projects that employ protected culture *e.g., Gotham Greens (New York, United States)*
	Open-air cultivation	Socially-oriented rooftop garden encompassing community or individual initiatives *e.g., community rooftop garden in Via Gandusio's social housing (Bologna, Italy) (Orsini et al., 2014)*	Commercial initiatives which use open-air cultivation, also known as rooftop farms. *e.g., Eagle Street Rooftop Farm (New York, United States)*

ty-building processes (Armstrong, 2000; Block, Chávez, Allen, & Ramirez, 2012; Carney, 2011; Guitart, Pickering, & Byrne, 2012; Howe & Wheeler, 1999; Lawson, 2005; Lyson, 2004; Teig et al., 2009). In addition, the local nature of UA is linked to enhancing urban sustainability and resilience as well as to green and alternative economies (Arosemena, 2012; Guitart et al., 2012; Howe & Wheeler, 1999; McClintock, 2010; Sanyé-Mengual et al., 2013; Smith, Greene, & Silbernagel, 2013).

Notwithstanding the expansion of UA, the constrained land availability in cities (Badami & Ramankutty, 2015; Martellozzo et al., 2014) and soil contamination risk mainly due to former land uses (Antisari et al., 2015; McClintock, 2015, 2012) have motivated the occupation and employment of built areas for food production. Among the building-based UA forms, urban rooftop agriculture (URA) is becoming popular (Specht et al., 2014; Thomaier et al., 2015). URA is defined as "the development of agricultural activities on the top of buildings by taking advantage of the available spaces on roofs or terraces, which can be developed through open-air and protected technologies and used for multiple purposes" (Sanyé-Mengual, 2015, p.16). Since URA faces specific environmental constraints for growing plants (e.g., soil moisture and water access), cultivation techniques and management practices are key for overcoming limitations, such as the employment of Sedum on green roofs for improving water retention (Ahmed et al., 2017; Butler & Orians, 2011). Aside from these limitations, URA can support the local urban ecology by enhancing storm-water retention and habitat as well as improving the energy metabolism of buildings, particularly for designs similar to green roofs (Carter & Butler, 2008). URA encompasses four main typologies of projects, as reported in **Table 1** with examples.

Research on urban rooftop agriculture

URA has been the focus of a small number of studies, limiting the scientific support for decision-making processes at the policy and practice levels. Current research pays attention to three main aspects: context and acceptance of URA, potential contribution to food security, and sustainability aspects.

Context and acceptance of urban rooftop agriculture

The potential barriers and opportunities for implementing URA have been evaluated in the literature. In one such study, the limitations and strengths of implementing rooftop greenhouses (RTGs) in Barcelona were evaluated by focus groups composed of experts (Cerón-Palma et al., 2012). Another investigation compiled the benefits and challenges identified by several scientific studies in a literature review (Specht et al., 2014). Both studies outlined the potential contribution of URA to the three dimensions of sustainability: environment, economy and society. Regarding practice, a recent compilation of on-going URA initiatives reported the most common types and techniques employed (Thomaier et al., 2015). Finally, the social acceptance of UA was evaluated in Berlin with questionnaires, where the typologies of URA and multiple cultivation techniques were assessed (Specht et al., 2016). Beyond the available literature, URA is a complex system with the participation of diverse stakeholders (e.g., policymakers, practitioners, consumers, and citizens) and there is a need to deepen the understanding (i.e., knowledge, concepts, definitions, and perceived opportunities and risks) of these different stakeholders to better understand the implementation processes associated to URA.

Contribution to food security

The potential implementation of URA and its contribution to urban food security has also been assessed in the literature. Rooftop gardens could satisfy up to 75% of the demand for vegetables by the citizens of Bologna, according to the rooftop area identified as suitable for this purpose (Orsini et al., 2014). In New York City, rooftops were categorized according to their suitability for implementing URA in a study by Columbia University (Berger, 2013). Towards the goal of achieving food self-sufficiency in Cleveland, the use of 62% of the roofs of commercial and industrial buildings could increase urban self-sufficiency by 1.5 times (Grewal & Grewal, 2012). In general, food systems have traditionally been excluded from urban planning (Pothukuchi & Kaufman, 2000). Although UA has recently been included in some planning tools, such as in Chicago (Chicago Metropolitan Agency for Planning, 2010), the lack of specific tools and data prevents establishment of a systematic means for evaluating the incorporation of food systems into urban planning (Pothukuchi & Kaufman, 2000). In this regard, there is a lack of quantitative tools for accounting for the potential implementation of URA, which could support planning decisions. Such tools could be used in large-scale planning to identify optimal spaces by comparing different urban emplacements and quantifying the potential area for implementing URA.

Sustainability aspects

Although several sustainability benefits are expected from URA (Cerón-Palma et al., 2012; Specht et al., 2014), studies have mostly focused on assessing agronomic and biodiversity aspects (Freisinger et al., 2015; Francesco Orsini et al., 2014; Whittinghill, Rowe, & Cregg, 2013). Regarding environmental aspects, Goldstein et al. (2016) evaluated different typologies of UA in temperate regions by accounting for their environmental impact through Life Cycle Assessment (LCA). Considering a circular economy approach, the employment of urban waste as a substrate for plant growth was demonstrated in a rooftop garden in Paris (Grard et al., 2015). Although the socio-cultural ecosystem services of UA were evaluated for Barcelona (Camps-Calvet et al., 2016), URA was excluded from the assessment. Therefore, an evaluation of the social and economic aspects of URA is still missing in the literature, especially with regard to quantitative methods.

Objectives

There are notable research gaps related to this topic that need to be addressed in order to support the development and implementation process of URA in developed countries: limited knowledge of the stakeholders' perceptions as well as a lack of both specific quantitative tools for planning and quantitative studies regarding the environmental, economic and social sustainability of URA. However, to approach such a complex system, multiple tools need to be combined, leading to an interdisciplinary scheme. This paper describes an interdisciplinary assessment performed to evaluate the sustainability of URA implementation and provides further information on URA in the Mediterranean context.

The interdisciplinary assessment scheme: an overview

Due to the complexity of URA, interdisciplinary research, i.e. research featuring "two or more distinct scientific disciplines", was employed for the sustainability assessment (Aboelela et al., 2007, p. 341). Furthermore, Aboelela et al. (2007) describe the resulting scheme as:

> '"…based upon a conceptual model that links or integrates theoretical frameworks from those disciplines, uses study design and methodology that is not limited to any one field, and requires the use of perspectives and skills of the involved disciplines throughout multiple phases of the

Table 2 : Description of the interdisciplinary assessment scheme: method, research question, scale and application

	Social sciences	Geography	Environmental sciences	Economy
Method	Semi-structured interviews	Geographic information systems	Life cycle assessment	Life cycle costing
Research question	WHY and HOW should urban rooftop agriculture be IMPLEMENTED?	HOW MUCH and WHERE can urban rooftop agriculture be IMPLEMENTED?	WHAT are the ENVIRONMENTAL impacts of urban rooftop agriculture types?	WHAT are the COSTS of urban rooftop agriculture types?
Scale	City	City	System – Product	System – Product
Application	Barcelona region	Industrial parks Retail parks (Barcelona area)	URA cases, cultivation techniques, and crops in Barcelona and Bellaterra, Spain and Bologna, Italy	

ISSN-Internet 2197-411x OLCL 862804632

research process. (p. 341)"

The interdisciplinary assessment scheme combines tools from four disciplines, which are compiled in **Table 2**. The four methods aimed to answer specific research questions at two main scales (i.e., city scale and system-product scale) and were applied to different regions and case studies. In the following sections, each method and its application are detailed.

Why and how should urban rooftop agriculture be implemented?

Social science methods were selected to evaluate the qualitative potential of URA. This approach aims to interact with the different stakeholders that take part in the development and implementation of URA. Evaluating the different discourses and perspectives supports the assessment of the qualitative potential, which aims to determine why and how URA should be implemented. Semi-structured interviews were used as qualitative tools to integrate multiple perspectives and descriptions of processes (Weiss, 1995).

Case study: stakeholders involved in the implementation of URA in Barcelona

Semi-structured interviews were performed in Barcelona to evaluate the potential implementation of URA systems in the city. 25 stakeholders with different roles were interviewed in the spring of 2013. Stakeholders were selected according to their knowledge of the implementation process of UA in Barcelona. Initial stakeholders were identified and snowball sampling was performed during the interviews. The 25 stakeholders represented key actors in the design (e.g., architects), implementation (e.g., administrators, planners), production (e.g., farmers, practitioners) and consumption (e.g., NGOs, food co-ops, citizens) of URA systems. The interviews lasted an average of 45 minutes and consisted of open questions on the following topics: the concepts of UA, their involvement in UA development in Barcelona, the potential for implementation of URA in Barcelona, the positive and negative aspects tied to URA, and the necessary actions in the short-term to implement URA. Interviews were transcribed and coded based on grounded theory techniques (Kuckartz, 2012), thereby obtaining bottom-up categories for the codes that composed the main discourses.

Evaluation of the qualitative potential

The discourses of the different stakeholders unveiled the current situation of UA and the potential integration of URA in Barcelona (Sanyé-Mengual et al., 2016). Several environmental, social and economic opportunities were associated with URA, particularly in the context of sustainable cities. However, some stakeholders showed a lack of support and acceptance of this new form of UA, which could become a limiting factor in the short-term development of URA in Barcelona.

We can differentiate three main groups according to how stakeholders defined UA:

1. The "real farmers" defined UA as "false agriculture": this first group of stakeholders denied that UA was agriculture itself, since these activities are not developed on agricultural land and there are no professional farmers running them. These stakeholders were involved in peri-urban and professional agriculture.
2. The "social gardeners" limited the definition of UA to a socially-oriented activity: this second group identified UA as a "real agriculture" but highlighted that UA must be exclusively for social purposes, thereby excluding commercial initiatives. This group included NGOs, urban gardeners, local administration and users of food co-ops.
3. The "wide-range gardeners" conceptualized an inclusive UA: this third group accepted the multiple goals of UA initiatives, although they highlighted the necessity to prioritize the productive function. This group encompassed new actors in UA, such as architects, regional government and individual actors.

We observed that this strong dichotomy between social UA and productive UA was strictly associated with the origin of UA in Barcelona. In the 80s, UA was initiated in Barcelona by the local government in the form of urban gardens for the elderly and it was therefore conceptualized as leisure-oriented UA, contrary to other regions of the world where UA was initiated as a way to ensure food security during war and economic crises (e.g., in North America, the United Kingdom and Cuba) (Altieri et al., 1999; Mok et al., 2014).

This variety of definitions and strong divergences among conceptualizations of UA is a barrier for establishing a framework where stakeholders can discuss and work towards the development of global UA policies and projects. The acceptance of URA as a new form of UA is based upon these conceptions. For those stakeholders that exclusively value the social aspects of UA, soil-based UA was therefore more interesting than URA since fewer resources are required.

The stakeholders also outlined the positive outcomes and the motivations for implementing URA initiatives associated with environmental, social and economic contributions to urban sustainability. Most of the stakeholders based their support on the environmentally-friendly discourses tied to local food production and urban

greening. Although the stakeholders perceived multiple barriers and challenges associated with the implementation of URA in Barcelona, these were mostly related to acceptance issues, economic costs and legal barriers. The identified opportunities and barriers were similar to those perceived by Berlin stakeholders (Specht, Siebert, & Thomaier, 2016) as well as those cited in other literature (Cerón-Palma et al., 2012; Specht et al., 2014).
The assessment of the multiple discourses of the stakeholders provided the basis for a successful implementation pathway for URA in Barcelona. Further research and figures about the benefits of URA are required to provide society with information on this form of UA. Dissemination of information and demonstration activities were identified as necessary actions to encourage the progressive acceptance and implementation of URA in Barcelona.

How much and where can urban rooftop agriculture be implemented?

The consideration of a planning lens is essential for evaluating the potential implementation of an urban strategy. To do so, multiple scales can be valued simultaneously by employing geographic information systems (GIS) for this type of assessment. GIS was used to quantify the potential by determining where and how much URA could be implemented. Quantifying the potential included identification of optimal spaces for developing URA, which is a key preliminary step for defining programs, urban strategies and planning actions.

An integrated GIS-LCA tool

A GIS-LCA tool was designed by the research team for evaluating the quantitative potential of URA. On the one hand, GIS was used for accessing spatial data (e.g., roof availability, area, sunlight) by consulting available maps, creating specific spatial data at the planning scale (e.g., retail parks) by digitizing spatial elements, and generating new data by creating databases (e.g., rooftop type, material). On the other hand, LCA was employed to assess the potential from an environmental perspective. Based on Sanyé-Mengual et al. (2013), the environmental benefits of providing local food that replaces the conventional supply-chain were accounted for (i.e., including greenhouse structures, crop production, distribution and waste management). The most restrictive typology of URA from a technical point of view was chosen for the assessment: RTGs require large spaces and their weight can limit the implementation of URA.

The integrated GIS-LCA tool (Sanyé-Mengual et al., 2015) consisted of three steps:

1. Definition of requirements: Different experts associated with URA (e.g., agronomists, engineers, architects) were interviewed to define the characteristics that a roof must comply with for an economically and technically feasible implementation of RTGs in the short-term (i.e., without re-structuring the roof). Seven requirements resulted from this step: available space, minimum area of 500m2, sunlight, allowed according to planning guidelines, adaptation to the technical building code, flat and resistant.
2. Quantification of the potential: Data to check these requirements were compiled in a rooftop database created in GIS with the aim of quantifying the potential area for short-term implementation of RTGs.
3. Evaluation of indicators: Finally, based on the quantified potential area of implementation, the potential food production and environmental benefits were quantified regarding possible food self-sufficiency (i.e., in relation to the population and consumption patterns) and the possible environmental savings related to food transportation, respectively. Environmental impact factors based on the LCA were obtained from the literature (Sanyé-Mengual et al., 2013).

Case study: the metropolitan area of Barcelona

In this study, the metropolitan area of Barcelona was used as a case study for the quantitative valuation of the potential implementation of URA. Two different urban spaces where RTGs could be implemented were evaluated: the industrial park of Zona Franca and the retail parks of Montigalà and Sant Boi del Llobregat (**Figure 1**). In both urban spaces, public (e.g., administrative offices) and private buildings (e.g., companies) were present.

Quantitative potential of RTG implementation in Barcelona

Table 3 reports the results of applying the GIS-tool to the three case studies in Barcelona. According to the results, retail parks had a greater relative short-term potential for implementing technically and economically feasible RTGs (53-74%) compared to industrial parks (8%) because of the architectural differences. Retail buildings are designed with more resistant structures and materials due to the public access to these spaces. In contrast, industrial parks are dominated by sheet metal buildings to minimize cost and be more suitable for the activity. However, industrial parks had the largest absolute potential (13 ha) since they are bigger structures than retail parks. Therefore, industrial parks could be optimal for the planning and implementation of large-scale URA projects (**Figure 1**). In general, both industrial and retail parks house food-related businesses (e.g., food distribu-

ISSN-Internet 2197-411x OLCL 862804632
UniKassel & VDW, Germany- June 2017

Figure 1: Location of the case studies for the quantitative assessment of the potential implementation of RTGs in the metropolitan area of Barcelona: industrial park Zona Franca, retail park Montigalà and retail park Sant Boi del Llobregat (based on Google Maps image).

Table 3 : Short-term potential for implementation of RTGs in Barcelona: relative potential, absolute potential, tomato production, self-supply level and GHG emissions savings, by case study

	Zona Franca park	Montigalà park	Sant Boi park
Relative potential (%)	8	53.2	73.7
Absolute potential (ha)	13.1	5.2	5.6
Tomato production (t·year^{-1})	1,959.7	860.6	921.2
Self-supply (% of inhabitants with satisfied annual tomato consumption)	8.1	3.5	3.8
GHG emissions savings (t CO2 eq·year^{-1})	852.5	373.2	399.4

tion centres and supermarkets) and could provide URA with distribution spaces for local food production.

In this study, implementation requirements were set for RTGs since they are the most restrictive type of URA. Thus, implementing open-air rooftop gardens, which can use cultivation techniques that are more adaptable to various spaces (e.g., plots, raised beds, pallet containers), could reach higher levels of potential implementation. A similar 2016 study by Orsini et al. evaluated the implementation of open-air rooftop gardens on terraces in the city of Bologna, Italy; however, they also considered irregularly-shaped terraces and small areas. They found that if the entire rooftop potential of the city was utilized, it would provide vegetables to satisfy the demand of 75% of Bologna's population.

What are the environmental impacts and economic costs of different types of urban rooftop agriculture?

The environmental impacts and economic costs of different types of URA were evaluated from a life cycle perspective, thereby considering all of the life cycle stages related to food production. Therefore, the life cycle assessment (LCA) (ISO, 2006a, 2006b) and the life cycle costing (LCC) (ISO, 2008) methods were followed. The quantification of the impacts related to the environmental and economic dimensions are crucial for evaluating a sustainable strategy such as URA. The quantitative results provide data to assess and compare different types of URA, cultivation techniques and crops in order to inform stakeholders and planners in decision-making processes.

Table 4 : LCA and LCC specifications considered in this study, by stage.

Stage	LCA	LCC
Goal and scope definition	Functional unit: 1 kg of food product. System boundaries: cradle-to-farm gate (i.e. harvest). This includes the life cycle of materials employed in the infrastructure and the auxiliary equipment (i.e., materials extraction, manufacturing, transportation and end of life management), the crop inputs (i.e., manufacturing and transportation) and the waste management (i.e., transport and treatment of resulting waste).	
Inventory	Experimental trials were used for compiling foreground inventory data (water consumption, design, etc.) while the ecoinvent (Swiss Center for Life Cycle Inventories, 2014) and the LCA Food (Nielsen et al., 2003) databases were used for background data (e.g. electricity production, materials processing).	A cost-benefit approach including both the costs and revenues of the systems was employed. Data from projects and producers were compiled for the inventory.
Impact assessment	The impact assessment included the following indicators: global warming (IPCC, 2007) and water depletion from the ReCiPe method (Goedkoop et al., 2009). The simapro software (PRé Consultants, 2013) was used for the calculations.	The indicator of total cost (€) was implemented using an excel sheet for calculations.
Interpretation	Comparison among URA types, cultivation techniques and crops. Comparison with conventional industrial production using data from the literature.	

LCA and LCC specifications

LCA is a standardized method described by the International Organization for Standardization's (ISO) method 14040-44 (ISO, 2006a, 2006b). On the other hand, LCC is a partially standardized method described by ISO 15686-5 (ISO, 2008) for the construction sector. Both methods establish a four-stage scheme: goal and scope definition, life cycle inventory, life cycle impact assessment (i.e., costs aggregation for LCC) and interpretation. **Table 4** summarizes the specifications of LCA and LCC for this study.

Case studies

Three case studies were chosen for the evaluation of the environmental impacts and economic costs of different typologies of URA. The three cases provided experimental data on the agronomic performance (crop yield, resource consumption, crop management, and crop design).

1. Rooftop greenhouse (RTG): The RTG-Lab is located in Bellaterra, Spain and is a RTG implemented by a research institution. Soil-less cultivation with perlite is employed for the production of tomatoes. The RTG-Lab is a pilot-scale project to test the feasibility of integrating the metabolic flows between buildings and RTGs.
2. Community rooftop garden (CRG): The CRG of Via Gandusio was initiated on the roof of a social housing in Bologna, Italy. The design includes three cultivation techniques (soil production with compost, floating hydroponic and the nutrient film technique) and six crops (tomato, pepper, melon, watermelon, eggplant, and lettuce).
3. Private rooftop garden (PRG): The PRG of Gran Via is on the terrace of a private home in the centre of Barcelona (Spain). It also employs soil-less production with perlite for diversified cultivation (tomato, chard, beet, lettuce, and cabbage)

Environmental impacts and economic costs of different forms of URA

The results from the LCA and LCC can be employed in planning and decision-making to prioritize URA forms, cultivation techniques and crops depending on the function and goal of the specific project or plan. Results were collected from completed studies of an RTG (Sanyé-Mengual et al., 2015), a CRG (Sanyé-Mengual et al., 2015) and a PRG (Sanyé-Mengual, 2015).

ISSN-Internet 2197-411x OLCL 862804632

Table 3 : Global warming potential (GWP) (kg CO2 eq.·kg-1) and economic cost (€·kg-1) of tomato and lettuce in the rooftop greenhouse (RTG), the community rooftop garden (CRG) the private rooftop garden (PRG), and industrial production. These values were calculated according to the cradle-to-farm gate approach.

	Crop	URA typology			Commercial Industrial production(*)
		Pilot commercial	Social	Social	
		RTG	CRG	PRG	
Global warming potential (*kg CO_2 eq.·kg^{-1}*)	Tomato	0.22	0.07	0.18	0.22-1.86(*)
	Lettuce	0.49	0.32	0.25	0.025-0.21(+)
Economic cost (*€·kg^{-1}*)		0.86	0.16-0.18	-	1.47(^)

(*)(Cellura et al., 2012; Page et al., 2012; Payen et al., 2015; Torrellas et al., 2012); (+)(Romero-Gámez et al., 2014); (^) Ministerio de Agricultura, Alimentación y Medio Ambiente, 2014)

Prioritizing URA forms

Table 5 details the environmental impact (i.e., global warming potential) of tomato and lettuce production and the economic cost of tomato production in different URA forms (i.e., RTG, CRG and PRG) as well as the value of the food products from industrial production (based on literature and market data).

The evaluation of the three case studies from Barcelona and Bologna highlighted that the products from open-air URA (i.e., CRG and PRG) had a lower global warming potential than the products from the RTG case. Specifically, the impact of the products from the CRG of Via Gandusio (Bologna) was 34% to 67% lower, while the impact of products from PRG (Barcelona) was 18% to 50% lower, depending on the product. The difference was mainly due to the large environmental impact associated to the materials employed in the greenhouse structure of the RTG. Furthermore, the users of the CRG can consume tomatoes five times more cheaply than the potential consumers from the RTG in Barcelona.

In addition to the factors considered in these figures, the prioritisation of the different forms of URA might also consider the goal of the system. Therefore, a business-oriented project may prefer the RTG technology in order to have a more controlled environment for crop management. In contrast, social projects or private gardens for self-sufficiency may prefer simpler cultivation techniques that can be managed with a lower level of knowledge and may enjoy the performance of an outdoor activity.

Compared to industrial vegetables, lettuce had a more negative environmental impact when produced by with URA (Romero-Gámez et al., 2014). However, this lettuce was produced in a polyculture garden alongside other crops. This design negatively affected the results since the irrigation parameters were uniform in the design, resulting in over-irrigation of the lettuce, thereby increasing the burdens related to water and energy consumption for irrigation. In the case of tomatoes, URA production had a lower GWP value than industrial production (Cellura et al., 2012; Page et al., 2012; Payen et al., 2015; Torrellas et al., 2012) and was more competitive in the market (MAGRAMA, 2014).

Prioritising cultivation techniques

Four different cultivation techniques and multiple crops, including both fruit and leafy vegetables, were evaluated in the three case studies (as reported in Section 5.2). The results from the LCA and LCC assessments provide quantitative data to inform garden design. The eco-efficiency of these systems was calculated comparing the global warming potential and the water depletion to the economic cost (**Figure 2**).

The cultivation of fruit in soil with organic fertilizer (i.e., compost) in the CRG resulted in the most eco-efficient option for both the GWP eco-efficiency and the water eco-efficiency (values highlighted in **Figure 2**). In contrast, the soil-based production of lettuce showed lower eco-efficiency, particularly for water depletion since lettuce was over-irrigated in this garden, leading to a seemingly high irrigation demand for this product. Although the crop yield in a RTG (25 kg·m-2) was greater than in

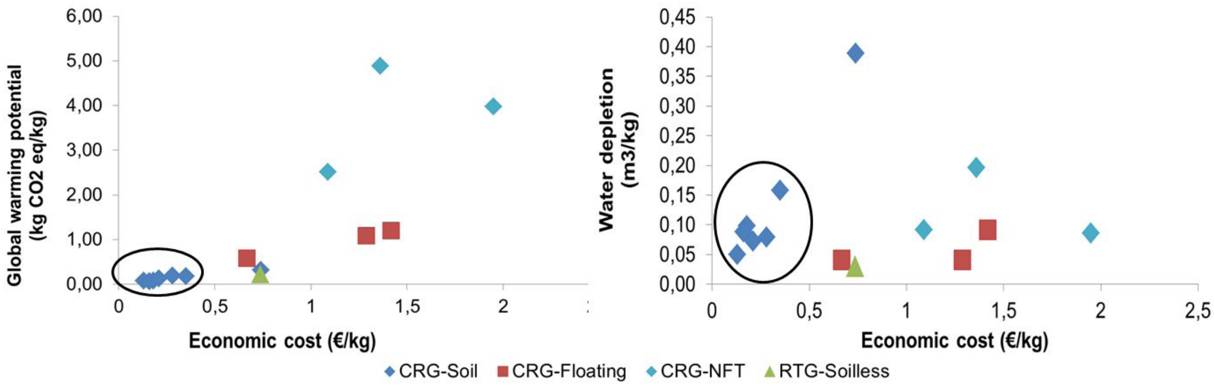

Figure 2: GWP eco-efficiency and water eco-efficiency of crop production in rooftop greenhouses (RTG) and community rooftop gardens (CRG). Edited from Sanyé-Mengual et al. (2015).

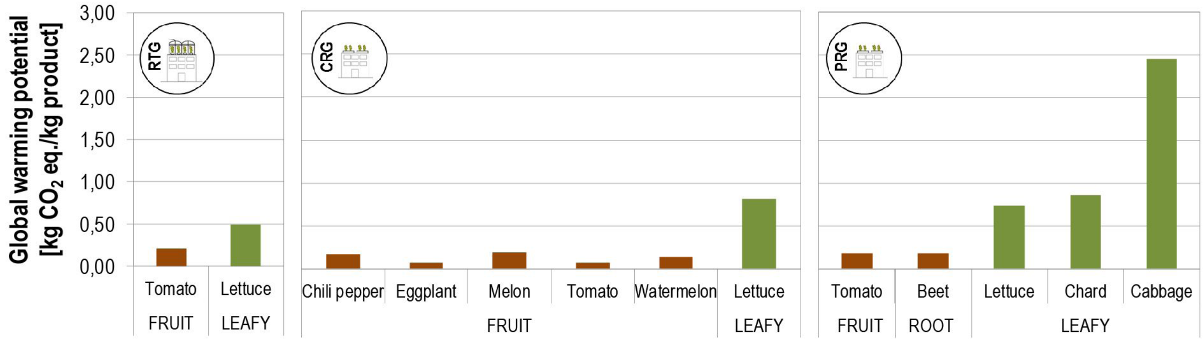

Figure 3: Comparison of the global warming impact of crop production (kg CO2 eq.·kg-1) in a rooftop greenhouse (RTG), a community rooftop garden (CRG) and a private rooftop garden (PRG). Edited from Sanyé-Mengual et al. (2015).

open-air cultivation, the eco-efficiency was lower due to the high cost of the greenhouse system (11.9€·m-2).

Finally, hydroponic techniques were the least eco-efficient options. The nutrient film technique (NFT) and the floating production of lettuce had greater water and energy demands, resulting in a negative environmental impact of these cultivation options. For example, the recirculation pump was responsible for 75% of the environmental burden in the NFT option. In addition, the costs of the irrigation equipment, such as the aerator for the floating technique, negatively affected the economic balance. Furthermore, the crop yield of NFT products was lower than expected.

Prioritising crops

The evaluation of various crops outlined the differences between fruit and leafy vegetables across the different URA forms (**Figure 3**). Although fruit crops had a longer crop period and consumed more resources (e.g., water and fertilizer), the higher crop yields of fruit reduced the environmental impact and the economic cost per kg of product. Among the fruits evaluated, eggplant and tomato showed the best environmental profile in the case of CRG. Root vegetables were only cultivated in the PRG case (i.e., beet) and showed a similar environmental profile to fruit.

According to these results, environmentally-friendly designs of rooftop gardens may prioritise fruit, particularly high-yielding products (e.g., tomato). However, one should consider the goal of the URA initiative in determining the design criteria. For a business-oriented project, high-yielding products might also satisfy the business plan since cost minimization is a priority. In contrast, when designing initiatives to promote food security and self-sufficiency, gardens with a diverse polyculture might better satisfy the food demand of citizens.

In the case of polyculture designs, we strongly recommend including differentiated areas where one can adjust the specific requirements of each crop (e.g. irrigation) to minimize the waste of resources. In the case studies evaluated, leafy vegetables were over-irrigated since the irrigation parameters were homogeneously set for the entire garden, thereby reducing the resource-use efficiency of these crops.

ISSN-Internet 2197-411x OLCL 862804632
UniKassel & VDW, Germany- June 2017

Conclusions

URA is a complex system that affects all the dimensions of sustainability: environment, economy and society. This study presents an interdisciplinary methodology to evaluate the implementation of URA in cities as a sustainable strategy. The combination of methods from four different disciplines was essential to obtain a deeper understanding of the implementation process and the potential benefits of URA. The combined methods and disciplines included interviews (social sciences), geographic information systems (geography), life cycle assessment (industrial ecology) and life cycle costing (economy).

Each method provided information through a different lens to create a comprehensive picture of the sustainability potential of implementing URA systems. Qualitative research collected with interviews contributed insights into individual perceptions and experiences of the different stakeholders involved in UA and URA. The quantification of the potential with GIS enabled the identification of appropriate placements for URA projects in cities, as well as provided information regarding implementation barriers (e.g., architecture and planning), and quantified the potential contribution to food security. The results from the LCA and the LCC enlarged the current knowledge about URA systems from an environmental and economic perspective.
Regarding the potential implementation of URA, the city of Barcelona shows a large potential from both the qualitative (social acceptance) and quantitative (implementation areas) perspective. Stakeholders identified several sustainability benefits associated with URA and local food production. Although some barriers were highlighted, URA promoters might overcome them through dissemination of information and demonstration activities. Industrial and retail parks would be suitable for the implementation of URA since they showed a large quantitative potential in terms of area that would comply with the requirements for implementing technically and economically feasible RTGs. In terms of URA design, LCA and LCC results highlighted the potential contribution of URA products for improving environmental and economic sustainability. However, design preferences might constrain eco-efficiency. Therefore, URA is a sustainable option for further development of urban food systems in developed countries of the Mediterranean region. The study also demonstrates the feasibility of URA implementation in cities like Barcelona as a complementary and alternative food production pathway to the conventional food industry, which some citizens reject. However, the contribution to the social sustainability depends on the typology and objectives of the URA initiatives, which will also determine some design aspects (e.g., technology level and products). However, the study faced some shortcomings, such as the absence of further case studies that exemplify other typologies of URA and the limitations of the current social-LCA methodology for evaluating URA systems. The scheme employed here could be applied to other case studies, forms of URA and UA as well as geographic regions with the aim of enlarging the current knowledge on this topic.

Acknowledgements

The authors thank the Spanish Ministerio de Economía y Competitividad (MINECO) for the financial support to the research project "Agrourban sustainability through rooftop greenhouses. Ecoinnovation on residual flows of energy, water and CO2 for food production" (CTM2013-47067-C2-1-R), and the Spanish Ministerio de Educación for awarding a research scholarship (AP2010-4044) to Esther Sanyé Mengual. This contribution is based on the PhD dissertation of the first author entitled Sustainability assessment of urban rooftop farming using an interdisciplinary approach (September 2015, Universitat Autònoma of Barcelona) and on the following conference proceedings piece: Sanyé-Mengual, E., Oliver-Solà, J., Montero, J. I., & Rieradevall J. (2015). Using a multidisciplinary approach for assessing the sustainability of urban rooftop farming. In G. Cinà & E. Dansero (Eds.), Localizing urban food strategies. Farming cities and performing rurality. 7th International Aesop Sustainable Food Planning Conference Proceedings. Torino: Politecnico di Torino.

Conflict of Interests

The authors hereby declare that there are no conflicts of interests.

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ISSN-Internet 2197-411x OLCL 862804632