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USING A MULTIDISCIPLINARY APPROACH FOR ASSESSING THE SUSTAINABILITY OF URBAN ROOFTOP FARMING

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

Abstract: Urban agriculture (UA) is blooming around cities of the developed world as a response to the increasing urban population, the growing environmental awareness of the industrial food system and the need of addressing social gaps. Within this expansion, urban rooftop farming (URF) is gaining importance as a way to further develop local food production. To assess the sustainability of implementing URF projects, a multidisciplinary methodological scheme was designed to approach such a complex system. The method combines four disciplines as follows: (a) qualitative research, to evaluate the qualitative potential by evaluating the perceptions of different stakeholders; (b) geographic information systems (GIS), to quantify the potential roofs for implementing URF; (c) life cycle assessment (LCA), to quantify the environmental impacts of URF forms; and (d) life cycle costing (LCC), to quantify the economic costs of URF forms. Results highlighted the potential of URF in both qualitative and quantitative terms and the potential benefits of different URF types. First, URF can contribute to the three dimensions of sustainability, although the complexity and novelty of URF shows specific barriers that might be overcome through further dissemination and demonstration activities. Second, available and feasible spaces can be found in retail and industrial parks to deploy commercial URF activities through rooftop greenhouses. Finally, rooftop greenhouses and open-air rooftop gardens were evaluated. LCA and LCC results outlined the relevance of design decision in terms of cultivation technique, crop and management.

1. Introduction

Urban agriculture (UA) is expanding over cities worldwide as a way to boost local food production (Orsini et al. 2013; Mok et al. 2013). In developed countries, urban agriculture projects addresses social, economic and environmental gaps thereby becoming multifunctional food systems. Beyond improving urban food security (Carney 2011), particularly in areas known as "food deserts" (Wrigley et al. 2004; McClintock 2011), UA initiatives are linked to community empowerment, social inclusion and community building processes (Howe and Wheeler 1999; Armstrong 2000; Lyson 2004; Lawson 2005; Teig et al. 2009; Carney 2011; Block et al. 2011; Guitart et al. 2012). Furthermore, the development of UA as local food systems positively contribute to urban sustainability by enhancing local and environmentally-friendly economies (Howe and Wheeler 1999; McClintock 2010; Arosemena 2012; Guitart et al. 2012; Smith et al. 2013; Sanyé-Mengual et al. 2013).

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Within such development, urban rooftop farming (URF) has grown in popularity as an alternative way to soil-based UA forms (Specht et al. 2014; Thomaier et al. 2015). URF is “*the development of farming activities on the top of buildings by taking advantage of the available spaces in roofs or terraces, which can be developed through open-air and protected technologies and used for multiple purposes*” (Sanyé-Mengual 2015). URF encompasses four main typologies of projects. Rooftop greenhouses are business-oriented projects that employ protected culture, such as Gotham Greens (New York, United States) (http://gothamgreens.com). Rooftop farms are commercial initiatives which use open-air practices, like the Eagle Street Rooftop Farm (New York, United States) (http://rooftopfarms.org). Socially-oriented URF initiatives can be both protected and open-air projects, such as the Manhattan School for Children (http://www.ps333.org/) or the community rooftop garden in Via Gandusio’s social housing (Bologna, Italy) (Orsini et al. 2014). Currently, open-air rooftop initiatives which perform soil cultivation are the most common (Thomaier et al. 2015).

1.1 Urban rooftop farming research

The number of URF studies is reduced, limiting the scientific support to decision-making processes around URF at the policy and practice scales. To date, the barriers and opportunities behind URF have been observed from the experts’ point of view (Cerón-Palma et al. 2012) and from the available literature (Specht et al. 2014). Both studies highlighted the potential contribution of URF to the three dimensions of sustainability: society, economy and environment. However, URF is a complex system where multiple stakeholders play a key role (e.g., as consumers, policymakers, technicians or practitioners) and deepening in the perceptions (i.e., knowledge, conceptualizations, perceived barriers and opportunities) of the different stakeholders could unravel a better understanding of URF implementation processes. Second, the identification of optimal spaces and the quantification of the potential area for implementing URF are basic for large-scale planning. Notwithstanding that some studies have approached the quantification of the URF potential (Berger 2013; Orsini et al. 2014), the development of quantitative tools to account the potential of URF could support planning decisions. Furthermore, the evaluation of different urban spaces and case studies could identify optimal areas for URF implementation. Finally, although several sustainability benefits are expected from urban rooftop farming (Cerón-Palma et al. 2012; Specht et al. 2014), studies have focused on the evaluation of the agronomic and biodiversity potential of URF (Whittinghill et al. 2013; Orsini et al. 2014; Freisinger et al. 2015). Furthermore, the lack of specific data forces the use of environmental values from conventional farming practices in UA studies (Kulak et al. 2013).

In this context, there is a need to cover such gaps in order to support the development process of urban agriculture and rooftop farming projects in developed countries. However, to approach such a complex process, multiple tools might be employed leading to a multidisciplinary evaluation scheme. This contribution describes a multidisciplinary methodological framework used to assess the sustainability of urban rooftop farming (URF) implementation and provides further knowledge on URF systems in the Mediterranean.

2. Proposing a multidisciplinary assessment scheme

Figure 1 illustrates the proposed multidisciplinary scheme which combines tools from four disciplines: social sciences, geography, environmental sciences and economy. The assessment focuses on deepening in “what is the potential” and “what are the impacts” of URF by assessing the qualitative and quantitative potential, and quantifying the environmental and economic impacts. This scheme allows performing the assessment from the city scale to the system-product scale.

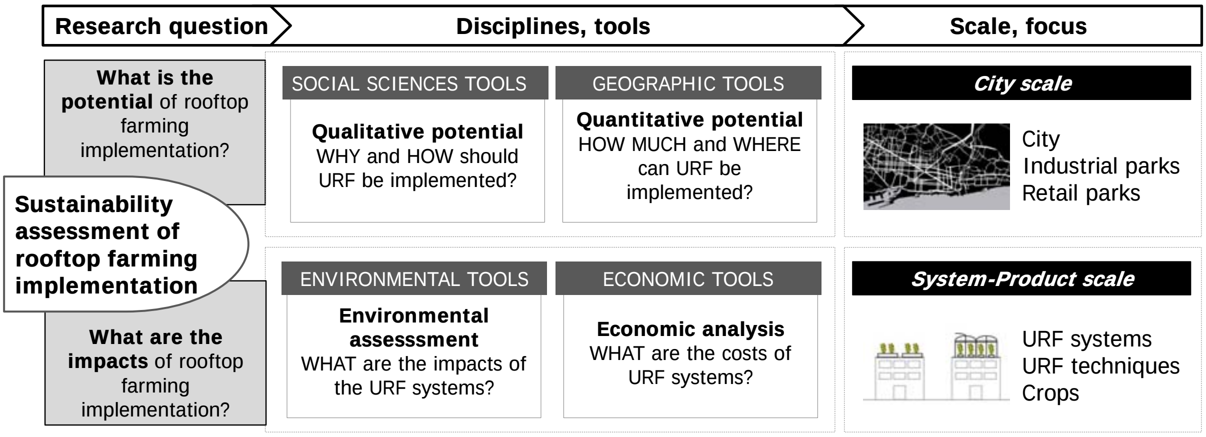

Figure 1. Multidisciplinary methodological scheme for assessing the sustainability of rooftop farming.

2.1 Social sciences

Social sciences research is used to interact with the different stakeholders involved in the development and implementation of URF. As a novel strategy, discovering the potential in qualitative terms is of great interest for planners and policymakers. The application of social sciences focuses on knowing "Why should URF be implemented?" and "How should URF be implemented?". To answer such questions, the background of URF, the interests of the different stakeholders, the opportunities and challenges associated to URF, and the potential URF models and users are key issues.

2.1.1 Semi-structured interviews

Semi-structured interviews are employed as qualitative tools that support the integration of multiple perspectives and the description of processes (Weiss 1995). Based on the transcripts and the coding of the interviews, grounded theory techniques (Kuckartz 2012) are used to unveil the concepts and discourses. After mapping the stakeholders related to the implementation of rooftop farming in Barcelona, 25 stakeholders were selected representing architects, urban planners, administration, gardeners, NGOs, food coops and URF promoters (i.e., restaurant manager that plans a rooftop greenhouse). Semi-structured interviews dealt with the concepts and definitions of urban agriculture, the perceptions around urban rooftop farming and the specific barriers and opportunities of such systems.

2.2 Geographic information systems (GIS)

Geographic information systems (GIS) are used to quantify the potential implementation of URF at different scales. As an urban strategy, the capacity to assess the implementation at the planning scale is essential to support urban planning decisions. The application of GIS aims to discover "Where can URF be implemented?" and "How much URF can be implemented?". In this sense, the identification of the optimal spaces for developing URF and the quantification of these potential areas are key in defining programs, urban strategies and planning actions. GIS are used to access spatial data (e.g., area, sunlight, availability) by consulting available maps, to create specific spatial data at the planning scale (e.g., retail parks) by digitalizing spatial elements and generating new data by creating databases (e.g., rooftop type, material).

2.2.1 An integrated GIS-LCA tool

For the purpose of quantifying and evaluating the potential implementation of URF, an integrated GIS-LCA tool was designed. The tool consists of three steps: requirements' definition, potential quantification and indicators evaluation.

- The requirements, based on experts' consultation, define the characteristics of an economically and technically feasible roof for implementing a rooftop greenhouse: allowed in the planning, available space, sunlight, minimum area of $500m^2$, adaptation to the technical building code, flat and resistant.
- Once the requirements are established, data can be compiled in a database using GIS in order to quantify the area for a potential short-term implementation.
- Finally, the evaluation of the potential area can be done in self-sufficiency terms (i.e., potential supply of food demand) and environmental terms (i.e., potential environmental savings related to avoided food imports).

2.3 Environmental accounting: Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is used to account for the environmental burdens of rooftop farming. As a sustainable strategy, the quantification and comparison of the environmental aspects of different URF types and practices can inform stakeholders in decision-making processes. Thus, LCA provides with quantitative data to know "What are the environmental impacts of different URF types?".

2.3.1 LCA specifications

LCA follows the ISO 14040-44 *(ISO 2006a; ISO 2006b)* standard which establish a four-stage scheme: Goal and scope definition, Life cycle inventory, Life cycle impact assessment and Interpretation. For the assessment of URF, the assessment considered two functional units: 1 kg for food products and $1m^2$ for cultivation systems. The system boundaries varied from cradle-to-grave (greenhouse structure) to cradle-to-farm gate and cradle-to-consumer (food products). Experimental trials were used for compiling foreground inventory data (water consumption, design, etc.) and the ecoinvent *(Swiss Center for Life Cycle Inventories 2014)* and the LCA Food *(Nielsen et al. 2003)* databases were used for background data (electricity production, materials processing). The impact assessment included indicators from the CML 2001 *(Guinée et al. 2002)*, ReCiPe *(Goedkoop et al. 2009)*, Cumulative energy demand *(Hischier et al. 2010)* and Global warming *(IPCC 2007)* impact methods. The simapro software *(PRé Consultants 2013)* was used for the calculations.

2.4 Economic accounting: Life Cycle Costing (LCC)

Life cycle costing (LCC) is employed to evaluate the economic costs of rooftop farming. As a sustainable strategy which provides new business opportunities, the quantification and comparison of the economic aspects of different URF types and practices can inform stakeholders in decision-making processes. Thus, LCC supplies with quantitative data to know "What are the economic costs of different URF types?".

2.4.1 LCC specifications

LCC is partially standardized in the ISO 15686-5 *(ISO 2008)* for the construction sector. LCC follows the same four-stage scheme as LCA: Goal and scope definition, Life cycle inventory, Costs aggregation and Interpretation. A cost-benefit approach that includes both the costs and revenues of the systems was employed. The same functional units and systems boundaries as in the LCA were used. Data from projects and producers were compiled for the inventory. The indicators of Total cost (€) and Total profit (€) were used.

3. Assessing the implementation of URF in the Mediterranean

3.1 Case studies

Observing the potential implementation of URF from a qualitative and quantitative perspective was performed at different scales and using diverse case studies, as compiled in Table 1. In qualitative term, interviews were performed to 25 stakeholders that represented the different roles in the implementation of URF at the city scale (i.e., administration, architects, gardeners, NGOs, urban planners). The quantification of the potential of URF was done for different planning pieces, case studies representing industrial and retail parks were analysed.

Table 1. Description of case studies of the qualitative and quantitative potential studies

Study	Assessment scale	Location	Case studies
Qualitative potential (interviews)	City	Barcelona, Spain	URF in Barcelona (25 stakeholders)
Quantitative potential (GIS-LCA tool)	Planning piece: Industrial park	Barcelona, Spain	Zona Franca park
Quantitative potential (GIS-LCA tool)	Planning piece: Retail park	Barcelona, Spain	Montigalà retail park Sant Boi del Llobregat retail park

To account for the environmental and economic burdens of URF, specific case studies that represent diverse forms of URF were chosen. Table 2 compile the main characteristics of the case studies, including the cultivation technique employed and the crops cultivated. The three case studies (Figure 2) provided experimental data on the agronomic performance of the different URF forms (crop yield, resources consumption, crop management, crop design).

Table 2. Description of case studies of the environmental and economic assessments

Case study	URF form	Location	Cultivation system	Crops
RTG-Lab	Rooftop greenhouse (RTG)	Bellaterra, Spain	Soil-less production (perlite)	Tomato
Via Gandusio	Community rooftop garden (CRG)	Bologna, Italy	Soil production Floating hydroponic Nutrient film technique (NFT)	Tomato, Pepper Melon, Watermelon Lettuce, Eggplant
Gran Via	Private rooftop garden (PRG)	Barcelona, Spain	Soil-less production (perlite)	Tomato, Chard, Beet Lettuce, Cabbage

Rooftop Greenhouse Lab (RTG-Lab) Bellaterra (Spain) | Community open-air rooftop garden Bologna (Italy) | Private open-air rooftop garden Barcelona (Spain)

Figure 2. Case studies of the environmental and economic assessments.

3.2 Results

3.2.1 Qualitative potential

The stakeholders' analysis of the potential implementation of URF in Barcelona indicated that the development of URF can provide several environmental, social and economic opportunities towards designing sustainable cities, although a lack of support and acceptance from some stakeholders is currently a limiting factor.

This trend is mainly related to the complexity and the novelty of URF initiatives.

- Stakeholders currently conceptualize urban agriculture in different terms, even identifying urban agriculture as a false agriculture. The lack of a common definition of urban agriculture slows down the establishment of a framework where stakeholders can discuss and work towards the development of global urban agriculture policies and projects.
- Urban agriculture in Barcelona was developed for hobby purposes in the 80s, contrary to food security needs during war and economic crises in North America, United Kingdom or Cuba. Such origin led into the conception that urban agriculture is a social tool rather than a productive system with commercial opportunities. Consequently, soil-based urban agriculture is more interesting than rooftop farming since fewer resources are required.
- Barriers and challenges to the implementation of URF in Barcelona are mostly linked to acceptance issues, investment costs and legal barriers. However, the progressive implementation of URF through pilot projects and generation of new knowledge will increase the demonstration and dissemination towards a larger support of urban rooftop farming among stakeholders (Figure 3).

3.2.2 Quantitative potential

The GIS-tool was applied to different case studies of industrial and retail parks to evaluate the potential implementation of URF in quantitative terms, leading to implementation recommendations for urban planners, entrepreneurs and practitioners.

- Selecting suitable roofs for implementing rooftop greenhouses is a complex process that requires a multicriteria set: availability of space, sunlight, resistance and slope, and legal and planning requirements.
- For Barcelona, the short-term potential of retail parks was greater (53-74%) than industrial parks (8%). This trend is related to the infrastructure characteristics of retail buildings which

are more resistant and thus more suitable for URF. However, industrial areas had a large absolute potential (13ha), becoming interesting urban pieces for the planning and implementation of large-scale URF projects (Figure 4).

- Both industrial and retail parks resulted in optimal spaces for implementing commercial URF initiatives, since food-related business are commonly placed in such urban spaces: food distribution centres and supermarkets.
- In this study, the assessment of the quantitative potential was limited to rooftop greenhouses, since it is the more restrictive form of URF. Implementing open-air URF forms has fewer requirements and is more flexible (e.g., plots, raised beds and other growing systems can be adapted to the spaces available in roofs).

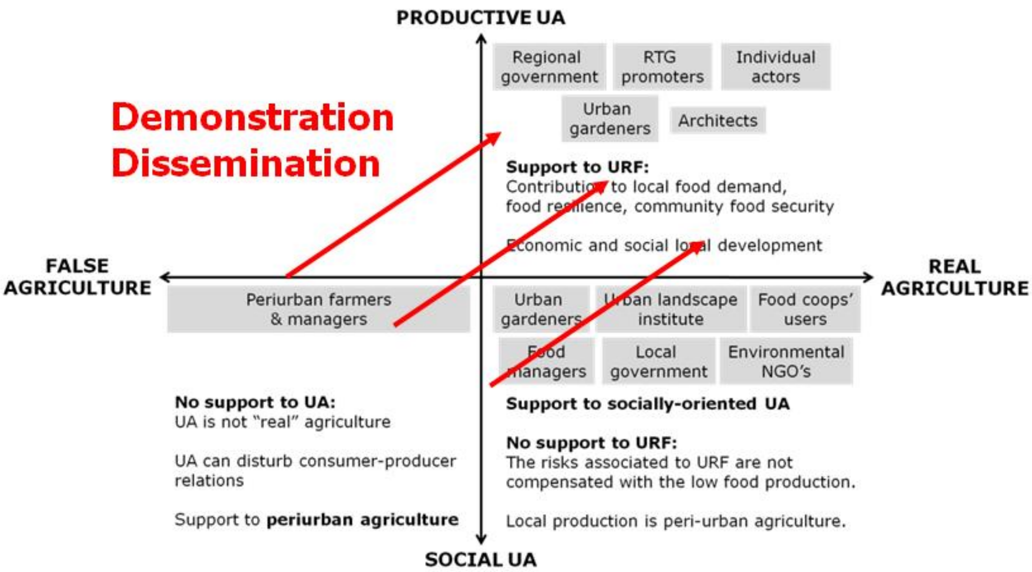

Figure 3. Stakeholders' position on conceptualizing UA and supporting URF in Barcelona, and expected trends through demonstration and dissemination activities.

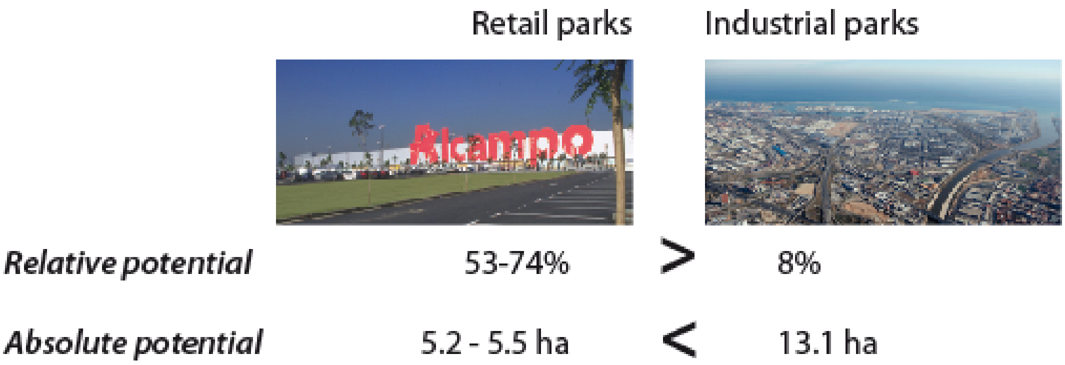

Figure 4. Identification of suitable areas for implementing rooftop greenhouses in Barcelona (Spain).

3.2.3 Deepening in the sustainability profile of different forms of rooftop farming

The three case studies analysed (RTG-Lab, Via Gandusio, Gran Via) are pilot projects and, thus, the study provides the first environmental and economic results on urban rooftop farming, unravelling some trends and patterns of the environmental and economic burdens of rooftop greenhouses, community and private rooftop gardens.

Rooftop greenhouses:
The structure of the greenhouse of the RTG-Lab played the major role. To comply with the Technical Building Code (BOE 2006), the structure must be reinforced thereby ensuring resistance and security. However, the short-supply chain resulting from a local production gives advantage to the production in RTGs from both the environmental and economic perspectives, when compared to conventional supply-chains. The assessment of the RTG-Lab highlighted the following trends:

- The structure of the greenhouse was the most contributing element to the environmental burdens (41.0-79.5%) and to the economic costs (64%), as in conventional greenhouse systems. In some categories, fertirrigation played the major role. Compared to a multitunnel greenhouses (i.e., commonly used in conventional greenhouse production in the South of Spain), the structure of an RTG had an environmental impact between 17 and 75% larger.
- Considering the food product, tomatoes from an RTG in Barcelona had lower environmental burdens than conventional tomatoes not only at the production point (between 9 and 26% lower) but also at the consumer (between 33 and 42 % lower).
- Regarding the economic costs, local tomatoes would only be cheaper (21%), and thus competitive, when the entire supply-chain is considered. In this case, the conventional supply-chain includes the transportation, packaging and food waste costs.
- Future RTGs may optimize the structure requirements to minimize the environmental impacts and economic costs of this element.

Community and private rooftop gardens:
Rooftop gardens use open-air cultivation techniques. The assessment of the Via Gandusio and Gran Via case studies outlined the following trends:

- Crop inputs contributed the most to the environmental impacts (85%), where irrigation played the major role (60-75%). Even more, the needed equipment and the consumed resources for the irrigation were the most expensive elements.
- Fruit vegetables (in particular, eggplant and tomato) had the larger crop yield, leading to lower environmental burdens and economic costs.
- The integration of re-used elements, such as pallets, into the design of the gardens reduces the environmental burdens and costs of the required structure (e.g., pots, raised beds). In the community garden, the burdens of the structure were negligible to the final impacts as the users designed the garden with former pallets and PVC pipes. In the private garden, the structure was made of new elements and contributed to between 28 and 35% of the environmental impacts.
- The level of horticultural knowledge of the users in community and private gardens is determinant in the sustainability performance of this type of local products, since directly affects the efficiency of the production (e.g., crop yield, water consumption).
- Future designs may consider the integration of re-used elements, the optimization of water requirements and the training of users to enhance the sustainability of rooftop gardens.

3.2.4 Comparing rooftop farming forms and conventional production

Figure 5 shows the global warming potential of lettuce production and tomato production in the three URF forms assessed in this study, as well as the minimum and maximum values related to conventional production found in the literature.

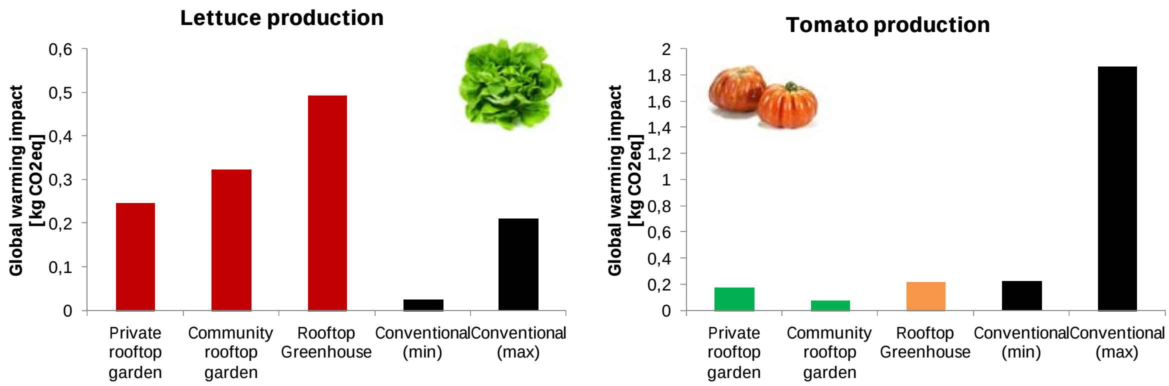

Figure 5. Comparison of the global warming impact of lettuce and tomato production in rooftop greenhouses, community rooftop garden, private rooftop garden and conventional production (minimum and maximum literature values).

The following patterns are observed:

- According to the results obtained from the case studies, products from open-air rooftop farming (both community and private) had a lower environmental impact and a lower cost than products from rooftop greenhouses, due to the burdens associated to the greenhouse structure. However, one may note that each type of rooftop farming aims to address different issues. Thus, although rooftop greenhouses showed larger environmental burdens, companies can benefit from a more-controlled environment and from the potential transformation to integrated RTGs. On the contrary, socially-oriented or self-managed initiatives may prefer rooftop systems more simple, placed in an open and fresh environment.
- Notwithstanding that lettuce production in rooftop farming forms had a larger environmental impact than in conventional production, the case studies analysed were polyculture gardens with a homogeneous design, resulting in a low plant density and high water irrigation for leafy vegetables since design parameters were established for fruit vegetables. Thus, an optimization of polyculture gardens by differentiating diverse design areas could improve the performance of leafy vegetables.
- Tomato production showed a lower environmental impact than values for conventional production. Among the different URF forms, tomato production in the RTG-Lab had the larger impact. However, the RTG-Lab can be integrated in the buildings where they are placed on by exchanging the flows of energy, water and CO_2, thereby improving the efficiency of the agriculture production and reducing the environmental burdens and costs of the activity.

3.2.5 Design recommendations: Prioritising growing systems and crops

Different growing systems and crops were analysed throughout the study, providing quantitative data to draw some design recommendations:

- Soil production with the use of compost as fertilizer is the most eco-efficient cultivation technique in rooftop farming. Similar eco-efficient values were obtained for the theoretical production in an integrated rooftop greenhouses (i.e., taking advantage of the residual flows from the building of energy, water and CO_2) (Figure 6). Notwithstanding that the values of crop yield were higher in the rooftop greenhouse case (25 kg·m^{-2}), the higher costs of the greenhouse system (11.9€·m^{-2}) reduced the eco-efficiency of this form of URF.
- Hydroponic techniques were the least eco-efficient ones due to the higher environmental impact of electricity (e.g., recirculation pump in the Nutrient Film Technique) (75% of burdens) and the large cost of irrigation equipment (e.g., aerator in the floating).

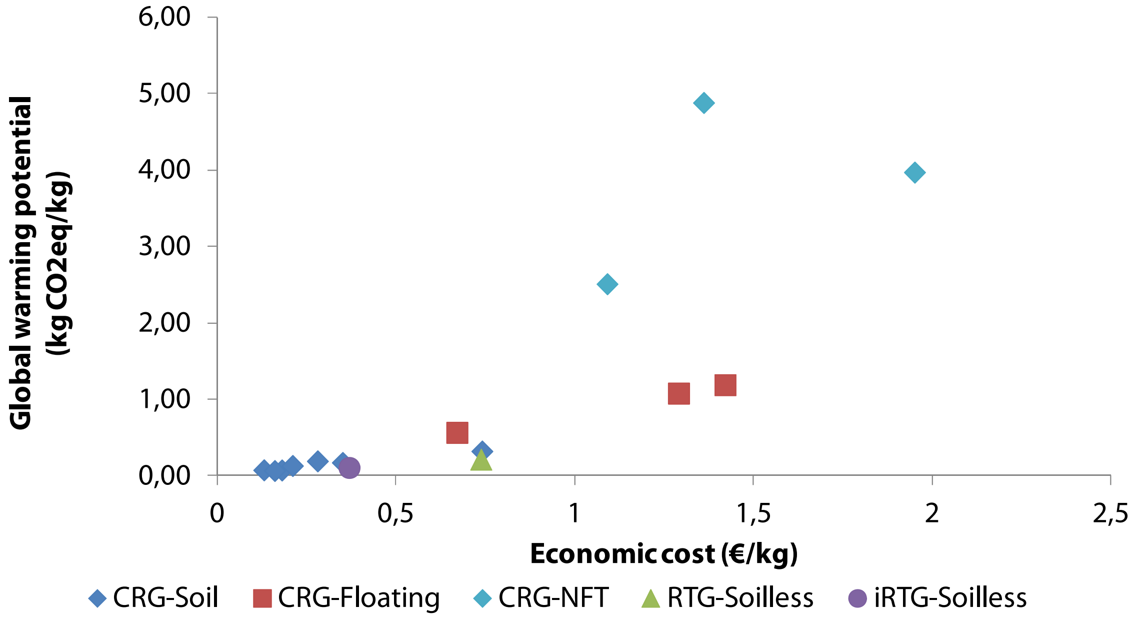

Figure 6. Eco-efficiency of crop production in rooftop greenhouses (RTG) and community rooftop farming (CRG).

- Regarding crop selection, fruit vegetables yielded better than leafy vegetables in all the URF forms assessed in this study. Notwithstanding that fruit vegetables have longer crop periods and consume a larger amount of resources, higher crop yields reduced the environmental impact per kg of product (Figure 7). Indeed, leafy vegetables could improve their efficiency by optimizing the design of polyculture gardens, as abovementioned.
- In terms of crop planning, self-sufficiency gardens are aimed to provide a diversified production in order to satisfy the food demand of the users during the different seasons of the year by combining fruit and leafy vegetables. On the contrary, commercial initiatives employing rooftop greenhouses would prefer monoculture crops to maximize the production efficiency.

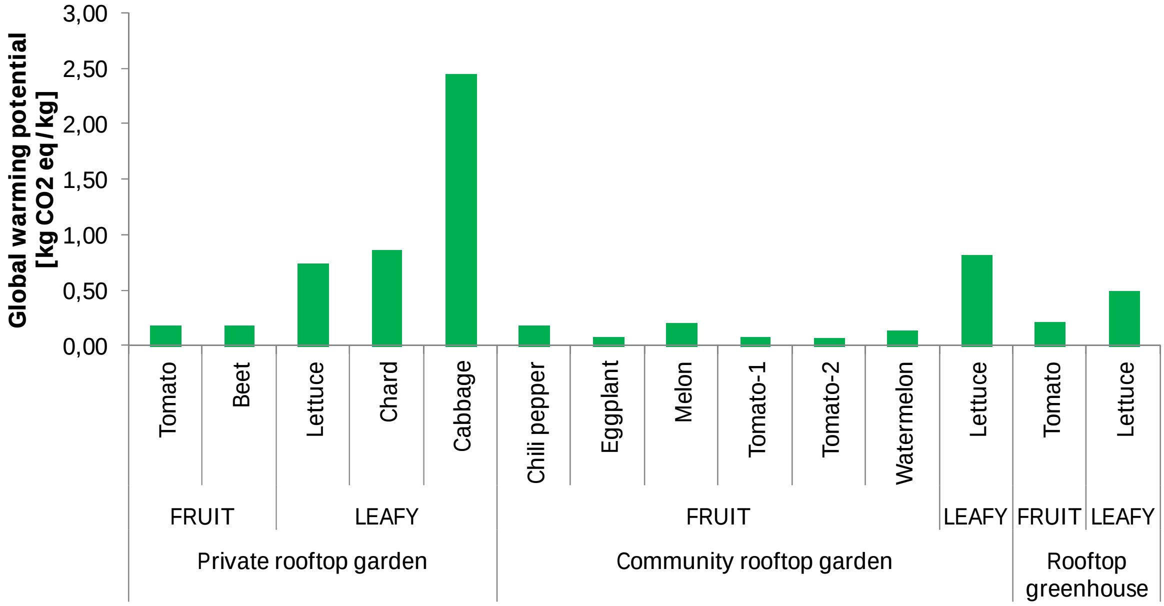

Figure 7. Comparison of the global warming impact of crop production in rooftop greenhouses (RTG), community rooftop farming (CRF) and private rooftop farming (PRF).

4. Conclusions

The multidisciplinary methodological scheme was essential to improve the current understanding of the implementation process and the potential benefits of urban rooftop farming in Barcelona. The combination of tools from different disciplines was fundamental to approach the complexity of implementing a new sustainable strategy in cities. A comprehensive picture of the potential and sustainability of URF was obtained from assessing the perceptions of the different stakeholders (social sciences), evaluating the potential in quantitative terms and from a planning perspective (geographic tools), and quantifying the environmental burdens (LCA) and the economic costs (LCC). This approach could be further applied to different regions, case studies and other forms of rooftop farming and urban agriculture in order to improve the current knowledge.

In terms of potential, urban rooftop farming in Barcelona shows a great potential in both qualitative and quantitative terms although specific barriers constrain this development at the small-scale. URF promoters may overcome social acceptance, economic and legal barriers to reach a large-scale implementation of these new forms of urban agriculture. For this development, industrial and retail parks showed a significant quantitative potential for the deployment of commercial initiatives through rooftop greenhouses.

According to the LCA and LCC results, URF can become an environmentally-friendly option for further developing local food systems in urban areas. Results depend on the type of URF, the cultivation technique and the crop under assessment, highlighting the importance of design decisions in the final impacts of rooftop farming products. Open-air systems, soil production and fruit vegetables were the most eco-efficient options.

In conclusion, rooftop farming in developed countries can positively contribute to urban sustainability and urban food security as their environmental impacts and costs highlights the feasibility of URF within the expansion of urban agriculture and local food systems. However, one may note that urban food systems are a complementary pathway to the conventional agriculture industry thereby supplying the demand of citizens with a higher environmental awareness which positively value localism, seasonality and environmentalism.

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