The global rise of urban rooftop agriculture: A review of worldwide cases

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Abstract

Rooftop agriculture (RA) is a building-based form of urban agriculture that includes both protected and nonprotected farming practices, such as rooftop greenhouses as well as open-air rooftop gardens and farms. The use of underexploited urban spaces on buildings for farming purposes is considered a useful strategy for targeting global concerns (e.g., the limitations in food security and land access, impacts of climate change or social exclusion). While previous studies have addressed selected RA cases and the general worldwide dissemination of RA, a systematic evaluation integrating the constantly evolving sector and its diversity (both commercial and noncommercial) is currently lacking. Here, we provide an overview of the current status of RA based on a metadata analysis of 185 publicly accessible cases. This paper summarizes the global trends and spatial distribution of RA cases and presents their main features. The results present the global distribution of different RA types over time, their diverging farming purposes and further characteristics (such as farm sizes, building typologies, growing systems, products and reported yields, activities, implementation of resource-efficient practices, or economic and social activities). The results indicate an emphasis on RA cases in North America (44% of the analyzed cases) and show that RA practices are mainly represented by open-air farms and gardens (84%), as the growing sector of rooftop greenhouses is still relatively small. Similarly, commercial cases are scarce, with the majority of RA cases targeting social-educational goals or the improvement of urban living quality. This tendency suggests a range of currently untapped business opportunities that, if developed, may contribute to the evolution of more sustainable and resilient city food systems providing fresh crops from the inner urban fabric. In conclusion, the research showed a rising global interest in RA, although stronger policy intervention is crucial to upscale RA practices to reach decisive environmental, economic and social benefits at the city level.

Keywords: Urban Agriculture; Urban Sustainability; Urban Planning; Innovation; Urban Farming; Building-integrated Agriculture.

1. Introduction

After the Rio+20 Conference in 2012, the United Nations instructed governments to create effective policies targeting an ensemble of sustainable development goals (SDGs) to guide the post-2015 development agenda (Griggs et al., 2013). A set of 17 SDGs were defined and subdivided into 169 objectives addressing, among various issues, environmental impacts and their interconnections with poverty and marginalization (Stevens and Kanie, 2016). In this context, the development of a "green economy", including aspects of circularity and biobased industries, has been identified as a central theme for addressing both economic and environmental crises related to the current global situation, also referred to as the Anthropocene era (Steffen et al., 2007; Bina, 2013). Urban areas play a central role in achieving green growth and sustainable development, as more than half of the global population currently lives in urban areas (FAO-FCIT, 2018), and the evolution of the urban fabric is relevant to the further development of green practices such as urban agriculture (UA) (Mougeot, 2006). In fact, as already observed in North America (Palmer, 2018) and Europe (Lohrberg et al., 2016), farming within or on the fringes of cities may become an innovative practice for improving urban sustainability by promoting ecological, social and economic benefits. Furthermore, urban green and productive areas may fundamentally increase cities' resilience to unexpected events such as the recent COVID-19 pandemic, which affected the food purchasing of many urban dwellers, highlighting weaknesses in the current food systems (Lal, 2020). Since 2015, 210 cities worldwide have signed the Milan Urban Food Policy Pact, which supports building more resilient urban food systems by further developing urban and periurban agriculture (Filippini et al., 2019).

Since competing uses and the consequent high costs of land might put a strain on UA development, the exploitation of unused city spaces, such as the rooftops of residential or commercial buildings, may represent a way to overcome development barriers (Gasperi et al., 2016). Plant cultivation on the rooftops of urban buildings – also defined as rooftop agriculture (RA) (Orsini et al., 2017) – has been identified as a functional way to increase ecological services (Oberndorfer et al., 2007; Harada and Whitlow et al., 2020), resilience to climate change (Georgiadis et al., 2017; Gupta and Mehta,

2017) and food availability (Baudoin et al., 2017; Gupta and Mehta, 2017) in cities in addition to contributing to the social and economic inclusion of marginal populations (Van Veenhuizen, 2014; Haase et al., 2017) and those that experience gender inequality (Velmurugan et al., 2019).

RA is a form of building-integrated agriculture (Caplow, 2009; Astee and Kishnani, 2011) or zero-acreage farming (Specht et al., 2014; Thomaier et al., 2015) that includes both protected (rooftop greenhouses) and nonprotected (open-air rooftop gardens or farms) technologies. Based on their main goals, RA projects can be classified into five types: (1) commercial, (2) social-educational, (3) image, (4) innovation or (5) urban living quality (Thomaier et al., 2015). Commercial rooftop farms are usually represented by business-oriented enterprises aimed at profitability. In contrast, social-educational and urban living quality RA projects are often developed without profit aims, concentrating more on the integration of minorities, the education of young people, and the amelioration of living conditions for urban dwellers by offering recreational and community spaces for personal food production. Image-oriented RA projects are often attached to hotels or restaurants and mainly use rooftop cultivation for marketing and aesthetic purposes. Finally, the innovation types of RA projects target the research and development of new technology for the improvement of sustainable food production and are mainly built by research centers, universities or start-ups (Thomaier et al., 2015).

Depending on their pursued goals and the local socioeconomic situation, RA projects apply different strategies in terms of the adopted growing systems, farm design and management (Viljoen, and Howe, 2012). For instance, while low-technology growing systems normally use inexpensive or recycled materials to improve urban food access with a minimum monetary investment (Orsini et al., 2015), business-oriented cases integrate RA into the food market chain using state-of-the-art farming technologies and intensive plant cultivation systems (Specht et al., 2015; Benis and Ferrão, 2018). Such intensive systems commonly apply soilless techniques with inert substrates and hydroponic growing methods to optimize farming inputs and yields and are mainly associated with commercial activities, whereas small-scale kitchen gardens and noncommercial projects often use soil either in raised beds or directly on rooftop surfaces.

Compared to conventional rural agriculture as well as ground-based urban farming, RA shows some distinct features (e.g., in terms of space access, technical requirements, unique legal environments or often nonproduction-related missions) (Sanyé-Mengual et al., 2019). Among the peculiar challenges of RA are the physical feasibility (structural loading, rooftop accessibility), restrictions from safety regulations and municipal codes (historical constraints, height limitations, fire code), and amplified climate conditions (heavy rains, elevated radiative fluxes and temperature ranges) that occur on rooftops (Hui, 2011; Caputo et al., 2017), which may limit its application and cultivation performance. However, RA bears the potential to improve building environmental performance (e.g., by increasing thermal insulation or integrating rainwater harvesting systems) and employ building byproducts (e.g., greywater, heat, CO_2 and organic waste) as farming inputs (Sanyé-Mengual et al., 2014; Grard et al., 2015; O'Sullivan et al., 2019), thereby integrating building and plant production areas (Pons et al., 2015; Sanjuan-Delmás et al., 2018) to reduce the environmental impact of both cultivation and housing. Further environmental benefits at the city level include biodiversity conservation, water runoff management, air pollution and carbon sequestration, as well as reducing both the urban heat island effect and noise pollution (Van Woert et al., 2005; Takebayashi and Moriyama, 2007; Dunnett and Kingsbury, 2008; Rowe, 2011; McIntyre and Snodgrass, 2017).

Despite worldwide interest and demonstration of effective productive capacity of rooftop farms (Grewal and Grewal, 2012; Orsini et al., 2014), urban farmers still have to face the challenges that have constrained the adoption of this practice on a larger scale, including high initial costs and uncertain returns of investment, as well as a lack of policies that are supportive of the development of the sector (Delshammar et al., 2017). Similarly, urban dweller perceptions and the low acceptance of nontraditional agricultural systems such as hydroponics also hinder potential RA development (Sanyé-Mengual et al., 2018; Ercilla-Montserrat et al., 2019).

Due to the complexity of RA implementation, there is a need to comprehensively evaluate the current worldwide status to examine the potential effect of the urban and climatic context, the distribution of existing RA initiatives, and their agronomical characteristics and sustainable practices. Such assessments should focus not only on commercial activities (Buehler and Junge, 2016) but also on noncommercial activities with the aim of better individuating best practices for future sector advancement.

This paper aims to present the current status of RA. To do so, a database of 185 existing RA cases was compiled that includes both commercial and noncommercial (e.g., socially oriented, research) cases. A metadata analysis was performed, focusing on the following objectives:

- Providing an overview of the worldwide implementation and spatial distribution of RA;
- Analyzing and comparing the collected cases based on their main characteristics (such as farm sizes, building typologies, growing systems, products and reported yields, activities, implementation of resource-efficient practices, or economic and social activities);
- Identify weaknesses in and opportunities for RA to develop guidelines for future advances in this sector.

2. Methods

The core of this research study is the compiled database of 185 RA cases from around the world and the metadata analysis performed on the collected cases.

2.1 SETTING UP THE DATABASE AND COLLECTION OF WORLDWIDE RA CASES

The database was built upon an existing database established in 2011-2012 (Thomaier et al., 2015), which was updated and extended by the authors between 2017 and 2019. The updating process included the verification of already compiled cases and their current status as well as the extension of the database. After verification of the previously compiled cases, the existing database was merged with two other recently established inventories: the inventory of RA cases reported in the Rooftop Agriculture Handbook by Orsini et al. (2017) and the RA case study collection as presented by Sanyé-Mengual et al. (2017). Further scientific and grey literature as well as websites were explored to identify RA cases that were not captured by the first types of sources. Therefore, some case studies did not appear in the scientific bibliography and were the result of a meticulous search of the web. In this case, the search was performed using the following keywords: "rooftop agriculture", "rooftop farming", "rooftop garden", "rooftop greenhouse", "building-based agriculture", "zero-acreage farming", "rooftop aquaponics" and "building agriculture". The exclusion and selection process was performed based on strict criteria. The final inventory only included RA case studies, that is:

1. located on rooftops;
2. report basic information about their location, RA type, building type and farming purpose;
3. have substantial information available online, either from webpages or secondary reports; and
4. display case information in English language.

Accordingly, green façades, indoor farms, farming cases inside shipping containers or other types of structures not located on rooftops, which made up a total of 33 cases, were excluded from the first inventory of Thomaier et al. (2015). Since the main objective of the analysis was to understand the global interest in RA and its diffusion worldwide, both ongoing and (potentially) closed cases were included. Reasons for closure were not often declared, although in the case of *UF002 De Schilde* farm in The Hague (Netherlands), closure occurred due to bankruptcy problems, and the *Rooftop Garden of Via Gandusio* in Bologna (Italy) was interrupted due to renovation of the building. Finally, since case searches and data collection were performed in English and based on information available on the web, language limitations and online presence of cases may have led to a bias in the resulting database.

2.2 DATA CLASSIFICATION

The database adopts a classification of RA typologies (**Figure 1**) based on growing conditions (protected or nonprotected) (RA type), cultivation aim (farming purpose) and building characteristics (building type) (Thomaier et al., 2015; Buehler and Junge, 2016; Nasr et al., 2017) and includes a subdivision depending on whether the structure is devoted to food production only (monofunctional building) or to other uses (multifunctional building) (Buehler and Junge, 2016). The data compiled for each case study included both general and operational aspects. Concerning the general aspects of each case, the data included RA type, building type and farming purpose, as organized and explained in the classification developed by Thomaier et al. (2015) (**Table 1).** Operational aspects were further divided into basic and structural observations (starting and closing date, size, activities performed, typology of organization), agronomical parameters (growing system, type of crop/product, crop yield), resource use (water source, energy source, nutrient typology, nutrient form), social and economic aspects (members, women members, population at risk of social exclusion, costs, income, installation costs) and societal impact (consumers, visits, trainees, users). Sustainability actions were built on the description developed by Buehler and Junge (2016). In a few cases that had substantial information available online but certain relevant data were missing, surveys were sent to rooftop gardens/farm administrators (n=13).

2.3 DATA ANALYSIS AND PRESENTATION

The metadata analysis was based on descriptive statistics, mainly including the frequency, mean, mode and median. Descriptive statistics and correlation analysis were applied to the collected data. The descriptive statistics particularly included frequency analyses of the data compiled for each case study, including the RA distribution on each continent and the general and operational data collected. Correlation analysis (Pearson correlation) was performed to identify the existence of relationships (at the 5% level of confidence) at three different levels. At the case study level, we observed a correlation between rooftop surface and rooftop productivity. At the city level, we observed correlations between RA case distributions (frequency by city) and city characteristics (surface, density, and population). At the country level, we observed a correlation between RA case distribution (frequency by country) and the Human Development Index (HDI) (UNDP,2018). The case distribution by climatic area was also evaluated by classifying cities into five global macro agroecological zones (tropics, subtropics, temperate, boreal and Arctic) (Fischer et al., 2012). Finally, Fisher's exact tests were used to evaluate at the case study level the association between farm type and farming purpose and the association between farm type and building typology.

3. Results and discussion

3.1 GLOBAL DISTRIBUTION AND TRENDS

The inventory compiled 185 RA case studies from around the world. The distribution of the analyzed RA cases around the world by type (open-air or greenhouse) and farming purpose (image, commercial, urban living quality, innovation or social-educational) as well as the evolution of RA cases in the last 30 years are shown in **Figure 2**.

According to the analysis of our samples, North America emerged as the continent with the most RA cases (81), followed by Europe (49) and Asia (39). Conversely, Africa-Middle East (9), Oceania (4) and South America (3) presented lower numbers of cases (**Figure 2**). Globally, the general trend seems to remain unchanged compared to that in previous research studies (Thomaier et al., 2015; Buehler and Junge, 2016), although new cases have been registered on each continent. Rooftop farms and gardens were mostly identified in the cities of New York (26) and Toronto (15). The overall increase in cases can be interpreted as a rising interest in practice as a solution to overcome some specific urban issues (Ackerman et al., 2014). However, the reduced number of reported cases in the Global South, on the one hand, highlights the bias in the search methodology and, on the other hand, points to the potential of further applications guided by international organizations or local policy makers to address food security concerns, small income creation and social integration.

No significant correlation was observed between the RA case distribution within cities and the city surface (r=-0.044, p=0.71, n=72), city population (r=0.189, p=.112, n=72) or city density (r=0.183, p=0.123, n=72) (data not shown), overall suggesting that RA can easily adapt to different societal needs and challenges. Accordingly, the RA case distribution within a country was not correlated with the HDI (Human Development Index) of the country (r=0.232, p=0.218, n=30) (data not shown).

Classifying cases by climatic zone, the results showed that 69% of RA cases were located in temperate areas, 19% in subtropical areas, and 11% in tropical areas, while no cases were observed in boreal or arctic areas. These results show the variety of climates in which RA can be implemented; furthermore, RA was more widely applied in areas with cooler temperatures despite the greater difficulty of year-round or three-season production. In these cases, RA should apply cold-climate strategies (e.g., protective structures, heating systems) to allow a longer cultivation period.

Rooftop farming can be performed in both nonprotected (open-air farms/gardens) and protected conditions (rooftop greenhouses) (**Table 1**). Protected conditions can help more easily satisfy cultivation requirements such as temperature and relative humidity. In fact, an uncovered rooftop can present extreme climatic characteristics comparable to an arid or semiarid zone, with poor relative humidity and drastic daily and yearly temperature fluctuations (Bazzocchi and Maini, 2017). Although these harsh conditions can require higher watering inputs, as well as eventual shading supports (e.g., shading net), lowering of chemical use can be obtained thanks to the hostile climatic characteristics against pest development, especially in the case of fungi (Bazzocchi and Maini, 2017).

Despite the above considerations and the indisputable advantage of protected conditions in preserving crops from unfavorable climates and extending the growing season, the frequency of open-air rooftop farms (156 RA projects, 84%) was 5-fold higher than the frequency of rooftop greenhouses (29 RA projects, 16%). However, these results could be explained by the prevalence of cases with urban quality of life and social-educational aims, often applied with reduced economic inputs and farming resources. Regarding rooftop greenhouses, although North America had the highest absolute number (12 projects, 15% of RA projects in the region), Europe had the highest relative frequency by continent (20% of RA projects in Europe are rooftop greenhouses) (**Figure 2**). A limited number of rooftop greenhouses were found in Asia (3), Oceania (2), Africa-Middle East (1) and South America (1) (**Figure 2**), possibly because the observed RA projects mainly targeted recreational and noncommercial purposes normally applying open-air agriculture. Regarding farming purposes (**Table 1**), RA for urban living quality improvement emerged as the most common objective globally (72 RA projects, 39%) and was similarly distributed across different world regions (**Figure 2**). On the other hand, cultivation for sector innovation was documented only in Europe and was therefore the least common farming purpose (5 RA cases, 3%) (**Figure 2**). Fisher's exact tests showed a statistically significant association between farm type and farming purpose ($p \leq 0.001$). Interestingly, image, social-educational and urban living quality purposes were generally linked with open-air rooftop farms and gardens, while innovation purposes were more common in rooftop greenhouses (only 1 open-air case was identified out of 5 detected cases). Commercial farms that were intended as food production businesses showed a balance between cases conducted in protected and nonprotected conditions (13 open-air and 13 rooftop greenhouse cases), therefore confirming the possibility of running commercially oriented farms with both models; however, there are some differences between the models related to product variability, yield capacity, adaptability to market demand and labor costs (Buehler and Junge, 2016).

Regarding the evolution of RA (n=104), the first examples of rooftop farming cases appeared in the late 1980s and persisted at lower numbers during the 1990s and 2000s. A peak in new rooftop farming cases was noted in 2010, particularly concentrated in North America (**Figure 2**). The growing trend progressively stabilized in the following years, possibly as a consequence of the slowly developing policies in the sector. Nonetheless, it is important to note that most existing cases are still operating, as determined based on updates on their websites. Indeed, only 8 out of 185 cases were officially considered closed, of which 1 was commercial, 3 were social-educational and 4 were urban living quality oriented.

3.2 SIZES OF ROOFTOP FARM AND GARDEN

Of the 185 case studies analyzed, only 105 cases reported their farming area (data not shown), revealing a global median surface area of 600 m^2; the farming areas ranged from a minimum of 4 m^2 to a maximum of 35000 m^2 in the case of a public garden on top of a train station in Paris (*Jardin Atlantique Montparnasse*). The median dimensions of projects were above the global median dimensions in both Europe (750 m^2, n=24, SE=1225) and North America (750 m^2, n=46, SE=257), while the Asian cases had a lower median size (370 m^2, n=19, SE=1867). Lower median surface areas were observed in both the Africa-Middle East (20 m^2, n=5, SE=884) and Oceania (130 m^2, n=3, SE=521), which may be attributed to the family-based and residential nature of the cases detected. Concerning the relationship between RA size and type, the median size of rooftop greenhouses was 1390 m^2 (n=25, SE=526), which was larger than the 500 m^2 of open-air RA projects (n=80, SE=640). This difference in size may be attributed to the different main purposes addressed, as rooftop greenhouses are usually applied for businesses and therefore require larger surfaces to achieve economic viability. However, while rooftop greenhouses never exceeded 1 hectare, four open-air RA cases reported dimensions equal to or greater than 1 hectare. Of those open-air cases, all of which were located on large surfaces, such as the roofs of warehouses/manufacturing buildings or transportation facilities, three were located in Asia, and one was located in Europe. In terms of the relationship between the farmed surface and farming purposes, RA projects for commercial purposes had the highest median surface area (1860 m^2, n=21, SE=426), followed by projects for urban living quality improvement (560 m^2, n=43, SE=1152) and social-educational aims (500 m^2, n=27, SE=420). Projects for innovation had a median surface area of 250 m^2 (n=3, SE=2583), while cases for image purposes had a median area of 280 m^2 (n=11, SE=234). Regarding the relationship between case size and growing method (n=71), RA initiatives adopting a soilless system (n=24) had a median surface area that was similar to that of soil-based (soil and organic substrate) systems (n=47), i.e., 555 m^2 (SE=394) and 500 m^2 (SE=264), respectively.

3.3 BUILDING TYPOLOGIES FOR ROOFTOP AGRICULTURE APPLICATION

RA can be integrated with both new and existing buildings (Caputo et al., 2017). *Maison Productive* in Montreal and *Louis Nine House* in New York are examples of sustainable and affordable housing projects that incorporated rooftop gardens from the beginning into their architectural plans. However, the integration of RA in new buildings accounts for only a limited number of cases; the retrofitting of existing rooftop structures is the more common situation. **Figure 3** displays the absolute distribution of building types by RA types and farming purposes using the classification developed by Thomaier et al. (2015). Fisher's exact tests showed a statistically significant association between farming purpose and building typology ($p \leq 0.005$). Accordingly, structures oriented toward research and education (e.g., schools and universities), as well as residential buildings, were the most common types of constructions used for RA development, accounting for approximately 30% of the total cases (**Figure 3**). On the other hand, buildings entirely oriented toward farming or food businesses that also integrate food production within the building were rarer (2%), although they presented the highest relative frequency of rooftop greenhouses together with warehouses and manufacturing structures (**Figure 3**). Predictably, buildings intended for farming and food businesses presented only a commercial purpose, while housing buildings hosting an RA project specifically targeted urban living quality (**Figure 3**). Social-educational purposes were especially common in research and educational centers (54%) (**Figure 3**). Eighty-five percent of the RA projects on hotels and restaurants were devoted to image improvement (**Figure 3**).

It is important to note that buildings oriented toward farming and food businesses, such as *Ecco Jäger Farm* in Bad Ragaz (Switzerland) or *Toit Tout Vert* in Paris (France), employed not only the rooftop surface but also the indoor building area for food production and were therefore classified as monofunctional buildings that were entirely dedicated to that business. In contrast, other building typologies applied rooftop cultivation on buildings with other primary functions, such as retailing, manufacturing, housing or education, and were therefore classified as structures with multifunctional purposes (Buehler and Junge, 2016). See **Table 1** for further specifications on building typologies.

3.4 GROWING SYSTEMS, PRODUCTS AND YIELDS

Among the 92 cases that reported data on their growing system, those growing plants on soil (54%) were the most common, followed by RA cases operating on soilless media (33%) and cases using an organic substrate derived from organic matter (e.g., peat, compost) (13%) (data not shown). Cultivation in soil was performed with either filled raised beds or the direct application of soil on roof surfaces. In the case of the direct application of soil, specific green-roof technologies using roof insulation, drainage systems and low-weight substrates have been used to reduce roof load (Caputo et al., 2017), as observed in the case of *Ortalto – Le Fonderie Ozanam* in Turin (Italy). Among the soilless systems, the analyzed cases reported the use of hydroponic technologies (15), aquaponic technologies (9) and aeroponic technologies (2), and these growing systems were mostly used in rooftop greenhouses (66%, n=20). In contrast, open-air projects (n=70) mostly used soil-based cultivation systems (70%, n=49).

Soilless cultivation was largely applied for commercial (n=15) and urban living quality improvement (n=7) purposes. Specifically, approximately two-thirds of commercial farms used soilless growing techniques; this may be related to the high productivity that hydroponics can achieve, especially when applied in combination with rooftop greenhouses (Buehler and Junge, 2016). Furthermore, soil-based RA projects were mostly connected with social-educational (n=17) and urban living quality improvement (n=16) purposes.

The most commonly produced products were lettuce and herbs (49% and 72%, respectively, of 102 cases), both in open-air and protected systems (data not shown). While soil-based cases normally produce a higher variety of vegetables, soilless systems are usually used to grow herbs, leafy greens or tomatoes. Animal-based products were also reported and mainly included fish (n=8), honey (n=14) and eggs (n=5). Aquaponics was mostly applied in commercial cases (e.g., *Ecco Jäger Farm* in Bad Ragaz, *Comcrop* in Singapore), although one case of private fish production was also registered in the Gaza strip. One unique example of RA use is the production of spirulina, a nutritive microalga that can be applied as an integrator in different types of products (e.g., pasta, ice cream, chocolate), produced by the *EnerGaia* team in Bangkok.

For 28 cases reporting their productive capacity, the average crop yield was approximately 15 kg m^{-2} $year^{-1}$ (data not shown), overall resembling commercial farming productivity in vegetable crop production, e.g., in the Mediterranean (Orsini et al., 2014). Among those, 11 cases were rooftop greenhouses (10 out of 11 using soilless systems) with an average yield of 28 kg m^{-2} $year^{-1}$, while 17 cases were open-air (2 out of 17 using soilless systems) with an average yield of 6 kg m^{-2} $year^{-1}$. It also emerged that the average yield in soilless systems (30 kg m^{-2} $year^{-1}$) was much higher than the reported yield in soil-based gardens (4 kg m^{-2} $year^{-1}$).

3.5 ORGANIZATION TYPES AND ROOFTOP AGRICULTURE ACTIVITIES

Regarding the organization typology, **Figure 4** provides the case distribution by RA type, continent and farming purpose. Of the total number of cases that reported their organization typology (n=145), for-profit initiatives accounted for the highest share (47%). This variable includes not only commercial farms oriented to food production and selling as their main purpose but also other business models with different principal aims (i.e., urban living quality, social education, innovation, image). These businesses were hotels, restaurants, RA planning and design consultancies (e.g., *Topager* in Paris, *SUFCo* in Seattle), producers of innovative technologies for rooftop cultivation (e.g., *EFC Systems* and *Zinco Company* in Germany), and event, workshop and tour organizers. It appears that RA may support highly diversified and multifunctional business models and could become an interesting professional opportunity for different types of urban entrepreneurs. It is also important to note that in some cases, the companies involved were real estate agencies or architecture studios that aimed to promote affordable and sustainable housing (e.g., *Banyan Street Manor Rooftop Farm* in Honolulu, *Louis Nine House* in New York, *Maison Productive* in Montreal). **Table 2** provides the absolute frequencies and share of cases performing certain activities in RA projects. In addition to vegetable production (87%), most of the activities performed were linked with education (37%) and recreation (34%). Accordingly, one of the main roles of RA is the opportunity for urban residents to ameliorate their living conditions by exploiting green rooftop spaces for horticultural and gardening workshops, yoga classes, art seminars or relaxation as an escape from the chaotic urban environment.

3.6 RESOURCE-EFFICIENCY AND SUSTAINABILITY ACTIONS

Table 3 shows the resources applied for crop cultivation, including absolute frequency and share for each type of input. Some cases used more than one type of input. Rainwater was the most common irrigation source, followed by greywater, well water and tap water (**Table 3**). However, due to the limited number of cases that reported their water source, as well as farmers' tendency to report and highlight virtuous actions for environmental preservation, these data should be confirmed through further investigation. The most commonly used energy source was on-grid electricity, although solar panels were also widely applied (**Table 3**). Wind turbines appeared only once in association with solar energy, in the case of the *Gotham Greens Pullman Farm* in Chicago. In some cases, energy was not used or used in negligible amounts for irrigation purposes. Therefore, for the sake of this publication, only cases where energy use was clearly stated were considered. Organic fertilization, generally in the form of compost, was the most common form of nutrient supply (**Table 3**). As mentioned above, further investigations should examine a wider number of cases to better report farmers' practices.

Applied sustainability actions were also investigated. Among the 79 cases that clearly stated their sustainable management practices, the highest proportion of cases were committed to chemical-free crop production (66%), and this practice was distributed across cases independent of farming purpose and building type. These cases included both soil and soilless systems, even in countries where soilless systems are not eligible for organic certification. The attention given to chemical-free crop production may be attributed only partially to the necessity of rooftop farmers reducing economic costs; the main reason may be the growing public concern about the use of chemicals in food production and the increasing demand for organic food. As a consequence, reusing recycled nutrients, especially those from compost, was also common; this practice addresses the issue of residual biomass management and favors a circular economy (Manríquez-Altamirano et al., 2020). Technology that improves energy efficiency (e.g., supplementary LED lighting, highly insulating glass) was mainly associated with commercial purposes and rooftop greenhouses and was applied to improve crop yields and reduce production costs. Waste heat reuse (10%), gas exchange (5%) and greywater recycling (4%) were the least-applied sustainable practices, although integrating these techniques into a rooftop greenhouse may help achieve savings of 128 kWh/m^2 of energy and 45.6 kg of CO_2 eq/m^2 (Muñoz-Liesa et al., 2020). Predictably, water reuse was particularly common in projects that used soilless systems; it has been demonstrated that a closed-loop system in a soilless rooftop greenhouse can use 40% less irrigation water and 35-54% less nutrients per day than an open-loop system rooftop greenhouse (Rufí-Salís et al., 2020).

3.7 COSTS AND ECONOMIC PERFORMANCE

The economic impact evaluation of 23 RA cases (from which this information was available) demonstrated an average installation cost of 880 € m^{-2} (data not shown). Installation cost is one of the main constraints that may dissuade from the realization of a rooftop farm or garden. In fact, compared to ground level cultivation, a rooftop farm also has to consider the costs for the movement of cultivation materials and structures on top of the building, as well as an engineer consultancy to evaluate the structure and eventual adaptation interventions to guarantee the safety of users and visitors (roof structure reinforcement, safety barriers, emergency exit). Installation costs may vary widely depending on cultivation purposes and farm typology (open-air or greenhouse), ranging from inexpensive outdoor household experiences obtained with recycled materials to high-tech greenhouses. In the case of open-air conditions, installation costs can also be influenced by the choice of an intensive cultivation system applying specific technologies to create a soil layer of approximately 20-30 cm or an extensive cultivation system using off-soil containers such as geotextile bags. In the first case, installation costs have been estimated to be approximately 100 € m^{-2}, while in the second case, they have been estimated to be approximately 30 € m^{-2} (CRETAU, 2020). Concerning farming purposes, the research results showed that commercial and innovation farms usually had higher economic costs than urban living quality and social and educational farms, in which investment costs were probably limited due to unpredictable economic returns. For instance, commercial cases such as *Comcrop* in Singapore or *Gotham Greens* in Chicago showed an average installation cost of approximately 1000 € m^{-2}, while that of urban living quality cases such as *Garden City Farmers* in Bengaluru or *Risc's Roof Garden* in Reading was approximately 300 € m^{-2}.

The running costs and net incomes could be evaluated only for 9 cases, showing 80 € m^{-2} $year^{-1}$ and 26 € m^{-2} $year^{-1}$, respectively, on average. In this case, empirical observations showed that the economic impact could widely vary among the same farming purposes. For instance, the case study of *Ortoalto Ozanam* in Turin, an open-air rooftop garden with social and educational aims, had a running cost of 50 € m^{-2} $year^{-1}$ and an income of 20 € m^{-2} $year^{-1}$. On the other hand, another example of a social-educational open-air farm at *NIST International School* in Bangkok presented a sixth of the running costs along with a tenth of the income. Although this large difference may be imputed to countries purchasing powers and diverging material and labor costs, variations can also be determined by different management conditions (e.g., composting of organic wastes for fertilization, collection of rainwater for watering) impacting running costs, as well as incomes coming not only from crop selling but also from the offer of services such as workshops or renting for events. Cost and incomes may also vary depending on necessary working hours, by human resources employed (volunteers or salaried workers) and relative employment contract typology, as in some experiences wage subsidies for professional integration had a strong impact on offsetting hiring costs (CRETAU, 2020). Unfortunately, drawing further conclusions on the economic performance of rooftop farming cases may be difficult due to the limited sample size that reported economic data.

3.8 INVOLVING STAKEHOLDERS AND THE PUBLIC

The societal impact of RA was also examined based on the number of people engaged in RA not only as consumers but also as volunteers, trainees or recreational users. A notable case of community involvement was *Schieblock DakAkker* in Rotterdam, which reaches approximately 15000 consumers and 20000 visitors per year. In the Global South, particularly in the Africa-Middle East and South America, the feasibility of applying RA to projects involving government and nongovernmental bodies that address poverty and food insecurity has been demonstrated. The potential to involve women in RA was also observed, as in the case of small hydroponic systems in

El Salvador (Lima, Peru) that were implemented to improve employment opportunities for women. The involvement of students and children was another important social aspect of RA detected both in the Global South and Global North (e.g., *Rosary High School* in Mumbai, *NIST International School* in Bangkok, *Manhattan School for Children* in New York), with 23 educational centers engaged in rooftop farming projects. Furthermore, the RA projects on top of 8 hospitals and clinics showed an additional social role of RA as a therapeutic treatment for patients. Due to the limited amount of available societal data, however, it was not possible to make deeper quantitative observations.

4. The overall picture of rooftop agriculture

The analysis of worldwide practices over time and geographical distribution confirmed the trends of increasing RA around the world and the predominance of certain RA types. In our sample, we detected an emphasis on RA cases in countries in the Global North and in the form of open-air rooftop farms/gardens. Although Thomaier et al. (2015) revealed greater interest in social-educational and image-oriented farming purposes, the current investigation showed a wider number of cases intended to improve urban living conditions. However, this study outlined the multifunctionality of RA, as most cases presented a secondary farming purpose, usually combining urban living quality with social education or image improvement. At the continent and country levels, the presence and distribution of RA cases showed strong variations. In North America, rooftop farming projects are mainly found in larger cities where innovation in urban agriculture is promoted through specific policies, such as New York and Toronto. The presence of a high number of cases can be explained by the substantial importance that municipalities in North America place on developing food system strategies and plans to overcome food insecurity in the urban context (Sonnino, 2016). The main farming objectives are often related to urban dwellers' quality of life or social and educational actions connected to school projects or community integration initiatives. These kinds of projects are usually developed as open-air farming systems, although a few examples, such as the *Manhattan School for Children* in New York or *Concordia Greenhouse* in Montreal, use rooftop greenhouses. For-profit companies, including those with commercial and image-oriented farming purposes, are also common in North America, where these RA types occurred at a higher frequency than in other world regions. In terms of commercial farms, North America is also the location of some of the best-known RA food businesses in the world, such as *Gotham Greens* in the US and *Lufa Farms* in Canada. These types of farms are usually rooftop greenhouses, although open-air commercial rooftop farms may also occur, as in the case of *Brooklyn Grange* in New York or *McCormick Place* in Chicago. Although North America showed a higher occurrence in RA than other regions, cases of RA with purely innovation-oriented purposes were lacking. In contrast, Europe was the continent promoting innovation in RA at both the academic and private for-profit levels. *AgroParisTech* in Paris and *RTG-Lab* in Barcelona are two examples of European research centers investing in rooftop farming development, while companies such as *UrbanFarmers* in Switzerland and *ECF Systems* in Germany have already developed innovative rooftop aquaponic systems for commercial food production.

Although they are less numerous than in North America, some examples of commercial rooftop greenhouses were also found in Europe, while there were no open-air farms with a commercial purpose as their primary goal in Europe. However, the economic sustainability of commercial rooftop farming is still questioned by European investors; new RA projects such as *Toit Tout Vert* in Paris are opening, but other cases, such as *UF002 De Schilde farm* in The Hague (Netherlands), have had to declare bankruptcy. The latter opened in 2016 and officially closed in 2018. The main reasons for its failure were misunderstandings of both customers and competitors (i.e., due to low receptivity and the high selling price of the products) and the location of the farm in one of the poorest neighborhoods in the Netherlands, far from environmentally conscious and interested customers (Ancion et al., 2019).

The difference in the number of rooftop farming cases in Europe and North America was still notable; there were approximately twice as many North American cases as European cases. This discrepancy may be connected to the slight delay in the increase in European rooftop farming cases compared to that in American cases, as shown in **Figure 2**, as well as other reasons. Due to the large city sizes and strong interest in an organic and safe food supply in Asian countries such as Japan, China and Hong Kong, a higher number of examples from these countries was expected, especially for commercial rooftop greenhouses. The low number in the results may be ascribed to unpublished information or language limitations and should therefore be investigated by native speakers. However, urban living quality and socially oriented cases turned out to be quite common in Asia in both wealthy countries and less wealthy countries, where this form of agriculture was often employed as a tool to address food insecurity among low-income families. The *Fringe Club Rooftop Republic* in Hong Kong, *Ebisu Garden East Japan Railway* in Tokyo, *Urban Leaves* in Mumbai and the *NIST International School Rooftop Farm* in Bangkok are just some examples of farming projects with social and life quality aims.

Africa and the Middle East had a particularly high proportion of urban living quality and social-educational cases; these were often promoted by local authorities and NGOs, as in some cases of private farming projects established in Egypt, Palestine and Jordan. However, one commercial rooftop greenhouse was registered in Israel.

In South America, RA projects were devoted mostly to social goals to address family food insecurity and urban poverty. Nonetheless, two examples of small-scale hydroponic rooftop farms with commercial purposes were registered in Lima (Peru) and Toluca (Mexico), demonstrating that even under less advantageous conditions, rooftop farming can be used for business development.

Oceania had a very low number of cases compared to those on other continents of the Global North, which some authors attribute to local restrictions on the productive use of rooftops (De Zeeuw et al., 2017).

As previously anticipated, the absence of statistical correlations between the geographical distribution of RA and the size, population and density of cities or HDI suggests that RA is widely applicable for different purposes independent of contextual conditions. However, it is important to highlight that the correlations between the RA case distribution within a city and the city surface area, density and population were not evaluated for all cases due to the difficulty of obtaining comprehensive data from each site and city.

Regarding RA production management, the results of this study are aligned with others in the literature (Buehler and Junge, 2016). Noncommercial cases typically use soil-based open-air systems, which can offer a wider variety of products than protected soilless systems but produce lower crop yields. Conversely, commercial farms preferred soilless systems and greenhouse facilities to maintain a higher production capacity and often focused on specific products such as leafy greens, herbs and tomatoes. The average crop yields of soilless and soil-based systems in UA have been previously studied in published research (Grewal and Grewal, 2012; Orsini et al., 2014; Boneta et al., 2019) that obtained productivity figures similar to or lower than the values presented in this study. This suggests that RA may play a key role within UA in enhancing urban food security. However, the integration of sustainable practices in RA is still limited, specifically regarding technological advancements that integrate plant production with building metabolism and its byproducts (e.g., heat, gas and greywater), which could increase commercial rooftop greenhouse sustainability.

Particular attention should be paid to the main activities performed on RA farms and the types of organizations that promote RA; these aspects are hardly addressed in the existing literature. Most RA projects provided functions to citizens beyond food production that were combined with a variety of associated services, including event space rentals, rooftop farm/garden planning and design, farming training courses and garden tours. This multifunctionality responds to the increasing need for and awareness of the environment and nature among city dwellers and suggests that RA may offer a wide range of business opportunities for urban entrepreneurs.

The data for the analysis of cases were gathered from the available scientific literature and from publicly accessible RA project websites, both presented in English language (including surveys of administrators). Accordingly, the number of worldwide rooftop agriculture cases is certainly higher than that presented in this study, especially in the case of low-technology projects that do not have a website presence or any links with academia. The large amount of data collected per case study in the database led to missing information in specific fields, such as activities performed or organization type, due to incomplete websites or vague information. Moreover, the data were too limited to perform a full social and economic evaluation, and a deeper investigation would be required to obtain a full picture.

5. Guidelines for future development

RA represents a complementary solution to ground-based and indoor UA, ensuring similar multifunctional benefits while avoiding competition and conflicts over land access. Despite the already established roles that RA could play to improve environmental, social and economic sustainability in urban contexts, some potential benefits of RA are still underrated. In fact, while RA projects designed for social and recreational purposes seem to have a broad range of applications, the intensive food production capacity of RA is still limited, highlighting its inability to meet current food and nutritional needs in cities at a larger scale. Regulating RA practices, including the agreements between building owners and rooftop farmers, may represent a fundamental step in resolving eventual conflicts and setting the ground for the implementation of RA projects. Moreover, the recognition of a certification program to ensure product quality and safety, such as certification for chemical-free production or the absence of heavy metals, may also be a key factor in enhancing consumer acceptance and preventing health risks. Similarly, environmental benefits and sustainable practices used in RA could also be included in certification schemes, such as sustainable urban resource use (e.g., rainwater harvesting), building byproduct reuse, urban environmental management (e.g., heavy rain management) or carbon footprint reduction. To enable future RA implementation, the regulatory framework from both the building and farming standpoints should specifically be addressed and customized. This will require efforts from policy makers to fill legislative gaps and fully develop specific policies that target the promotion and support of UA. Legislators should consider local conditions and constraints and adapt norms through casuistry to address specific issues. In addition to the need for specific regulations, RA is already shaped by municipal planning codes. Zoning and historical constraints may limit building height and floor number, while safety codes may hinder rooftop accessibility and structural loads. In the latter cases, existing buildings could overcome limitations by adapting the farm design to the circumstances, e.g., using soilless systems to reduce roof loads or installing safety barriers. Because rooftop retrofitting for RA bears some limitations, RA should be considered for integration from the beginning into the design of new buildings. This would help to include food production spaces in the urban fabric to more effectively plan urban food supplies in the future.

Although it is difficult to precisely predict its future development, RA may certainly play a fundamental role in future cities. Building on its multiple functions, RA may become a strategy for targeting urban issues at different levels, including heat island mitigation, stormwater management, biodiversity improvement, social inclusion, food desert and urban poverty reduction, and health and nutrition advancement. Accordingly, future research should focus more on how to improve the integration of sustainable practices into RA, such as by investigating the social impacts of RA, developing a functional metabolism between the building and the farmed surface (particularly for water, energy and CO_2 cycles), and how to improve cropping practices by building on existing advances in modern agriculture. However, given the need to optimize resource use efficiency and define economically and environmentally sustainable systems, planning and legislation will need to go hand in hand with applied research and innovation.

6. Conclusions

In conclusion, this study revealed an increase in global interest in RA in recent years, with more projects developing throughout the world in different climatic areas and independent of city size or demography. Most RA projects have a noncommercial farming purpose, especially those established as open-air and soil-based systems. On the other hand, commercial rooftop farms are still scarce despite their high food production capacity (based on integrating greenhouse technologies and soilless systems).

The study shows that RA can ensure multifunctional benefits (in the social, environmental and economic dimensions) while avoiding land use conflicts and additional pressure on urban land. However, national regulations still limit the full development of RA, which highlights the need to fully comprehend and consider the opportunities that these systems may provide. RA should be considered by organizations such as NGOs as well as by local municipalities to be used as a means to tackle food insecurity and to create small incomes, as already demonstrated by successful examples described in the paper. The improvement of RA must build on its proven potential to substantially contribute to providing urban food security and reducing the food miles and environmental impacts associated with current food systems. However, the recent events related to the COVID-19 pandemic bode well for the creation of new awareness in citizens and policy makers to develop more sustainable and resilient cities. This action should necessarily pass through the rethinking of urban food systems that food from the inner urban fabric may have a positive impact. Since the present paper provides an overview of RA cases until 2019, an update and analysis of cases established within or after the 2020-21 COVID-19 pandemic may represent interesting future research to understand the impact of this historical event on citizens' awareness of RA potential.

Our findings provide not only a picture of the current state of worldwide RA implementation by analyzing the different forms and aspects of its application but also an objective view of the points that should be implemented in the future to favor effective environmental, economic and social benefits on urban life. Although many countries and governmental institutions are already moving forward a green development of the city context, in other realities, some barriers, such as old urban plans and codes, are still hindering the process. The evolution of RA should be put under a lens in the coming years, accompanied by political support and further research on sustainability practices to become a worldwide practice with a decisive impact on city regeneration.

Figures

Figure 1. Visualization of case variability with regard to RA type, building type and farming purpose.

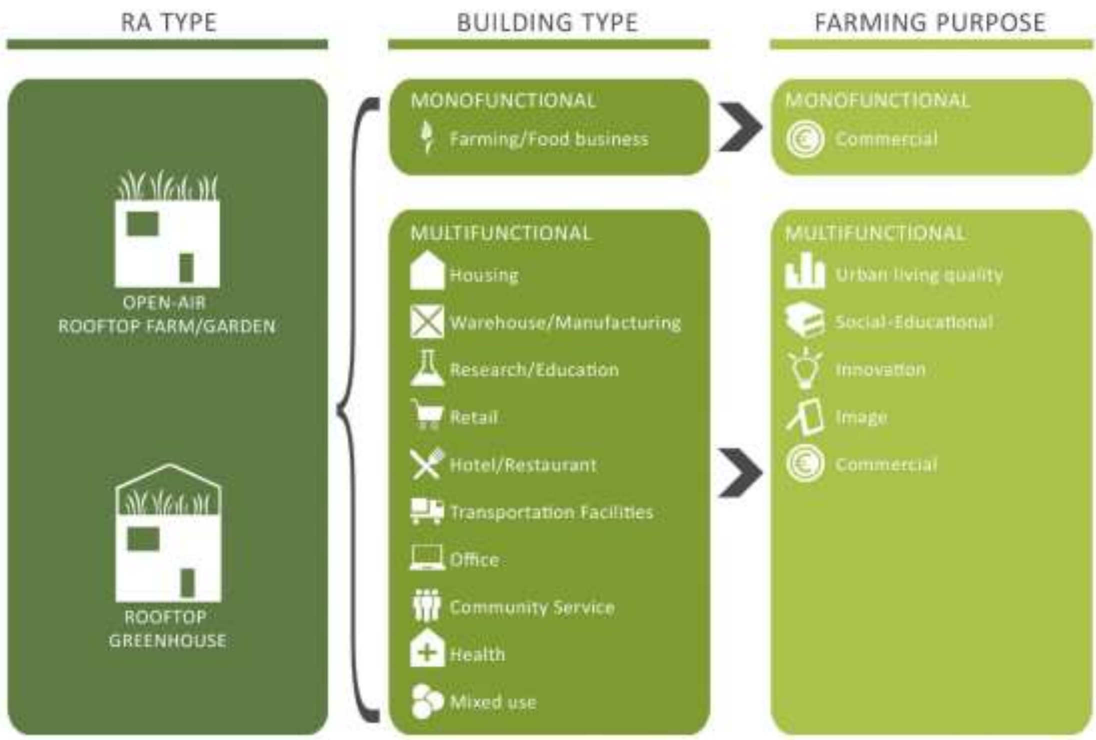
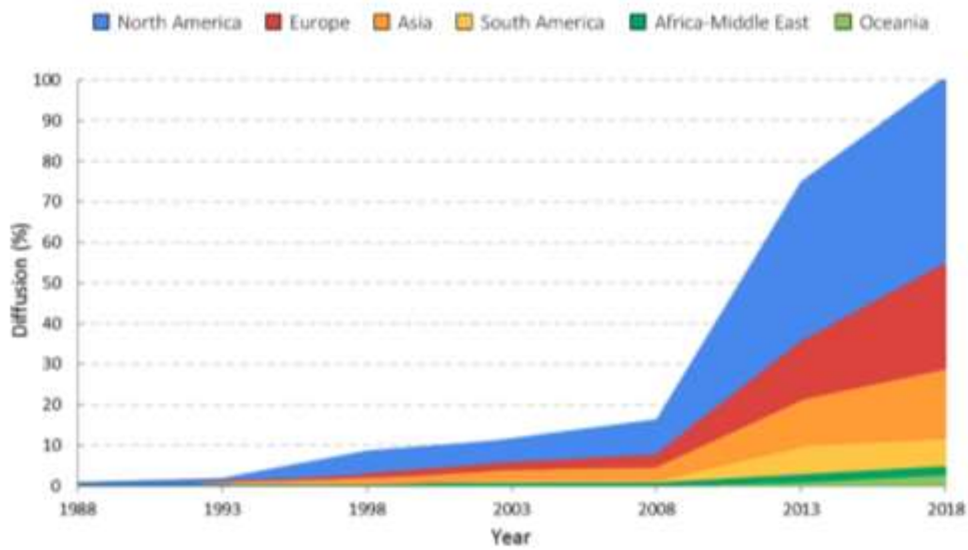


Figure 2. The evolution of RA by continent in the last 30 years (top). The worldwide distribution with a specific focus on world cities with RA projects and the absolute frequency of farming purposes (urban living quality, social-educational, innovation, image, commercial) and RA types (open-air, greenhouse) on each continent (bottom).


North America
Europe
Asia
South America
Africa-Middle East
Oceania
Diffusion (%)
Year
1988
1993
1998
2003
2008
2013
2018

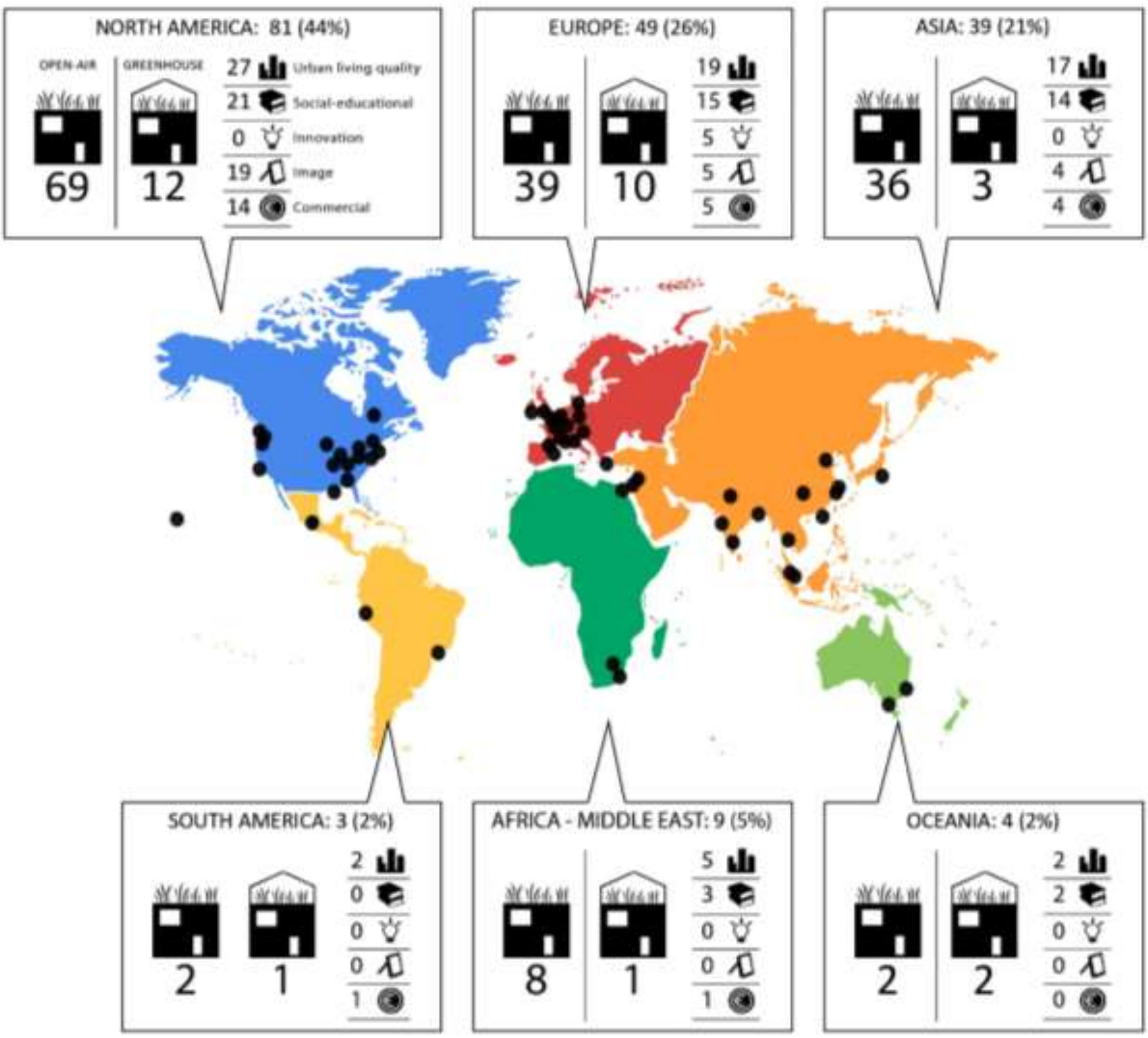
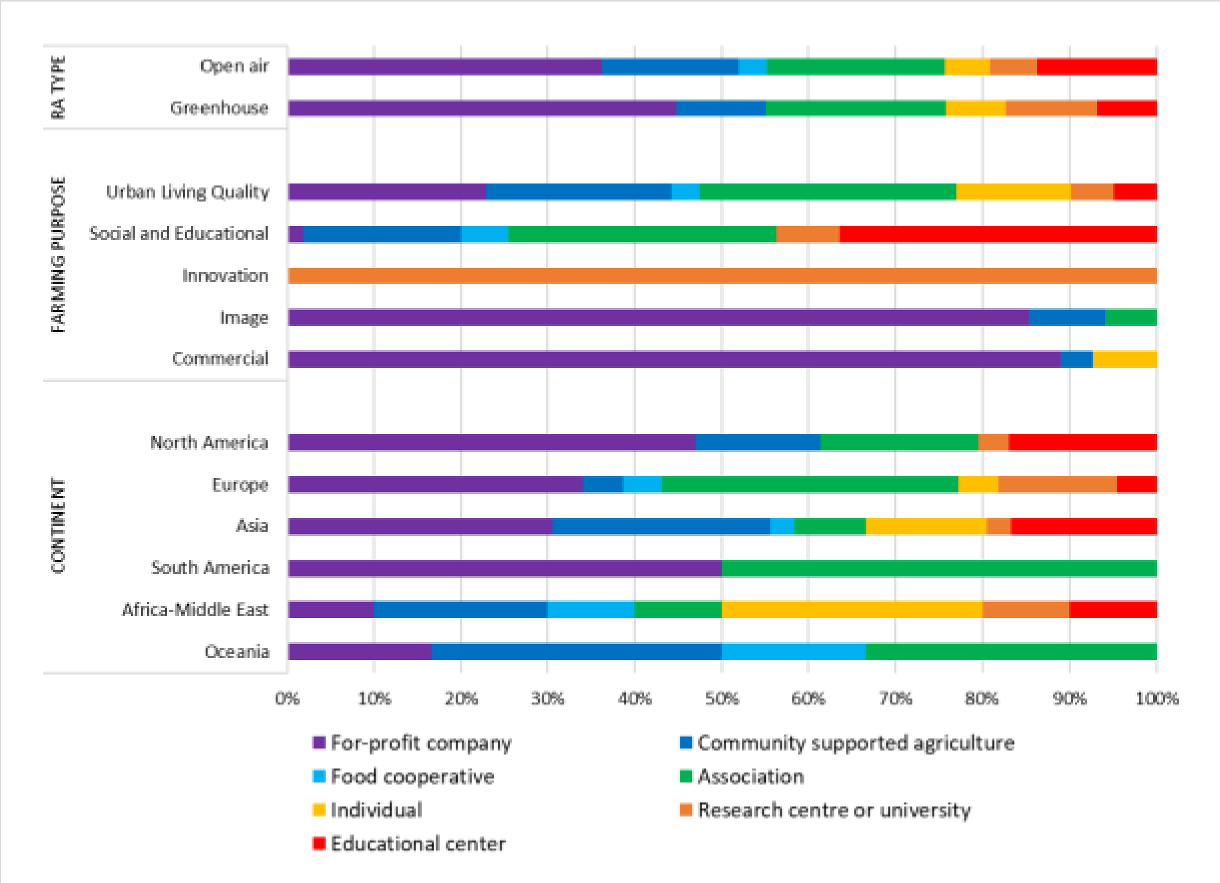

NORTH AMERICA: 81 (44%)
OPEN-AIR
GREENHOUSE
69
12
27 Urban living quality
21 Social-educational
0 Innovation
19 Image
14 Commercial
EUROPE: 49 (26%)
39
10
19
15
5
5
5
ASIA: 39 (21%)
36
3
17
14
0
4
4
SOUTH AMERICA: 3 (2%)
2
1
2
0
0
0
1
AFRICA - MIDDLE EAST: 9 (5%)
8
1
5
3
0
0
1
OCEANIA: 4 (2%)
2
2
2
2
0
0
0

Figure 3. The absolute distribution of building types by RA type and farming purpose (n=185).

RA TYPE		BUILDING TYPE	FARMING PURPOSE				
OPEN-AIR	GREENHOUSE		URBAN LIVING QUALITY	SOCIAL-EDUCATIONAL	INNOVATION	IMAGE	COMMERCIAL
1	3	FARMING / FOOD BUSINESS	0	0	0	0	4
28	4	HOUSING	28	3	0	1	0
7	5	WAREHOUSE / MANUFACTURING	4	2	1	2	3
28	6	RESEARCH/EDUCATION	1	30	3	0	0
9	4	RETAIL	5	2	0	3	3
19	1	HOTEL / RESTAURANT	1	1	0	17	1
7	2	TRANSPORTATION FACILITIES	7	0	1	0	1
18	2	OFFICE	8	3	0	4	6
13	0	COMMUNITY SERVICES	6	6	0	1	0
11	0	HEALTH	3	8	0	0	0
15	2	MIXED-USE	9	0	0	1	6

Figure 4. Relative distribution of organization types depending on RA type, farming purpose and continent (n=145).



Tables

Table 1. Classification of RA types based on protected or nonprotected cultivation conditions (RA type), building on which RA is located (building type) and farming purpose (Z-farm type, according to Thomaier et al., 2015)

	Subcategory	Description
RA type	*Rooftop Farm/Garden*	Open-air rooftop agriculture
	Rooftop Greenhouse	Protected rooftop agriculture
Building type	*Farming/Food Business*	Farming-oriented building, possibly integrated with a grocery store or a wholesale shop
	Housing	Residential building
	Warehouse/Manufacturing	Industrial or storage structure
	Research/Education	University, school, research center, educational center, etc.
	Retail	Retail shop, mall, supermarket, etc.
	Hotel/Restaurant	Hotel, restaurant, cafe, etc.
	Transportation Facility	Train station, bus station, parking lot, etc.
	Office	Bank, post office, company building, etc.
	Community Services	Church, reception or social center, government building, etc.
	Health	Hospital, clinic, retirement home, gym, etc.
	Mixed-use	Building with different uses
Farming purpose	*Urban Living Quality*	Projects created to improve the living quality conditions of urban residents and employees, offering a green space for producing their own food and recreating (farms or gardens); projects of local or international organization to promote food security and economic development
	Social-Educational	Cases often located at schools, hospitals or social centers with educational, social and integration purposes
	Innovation	Research cases or innovative production systems
	Image	Cases with an image or marketing aim, especially cultivated for the production of food to use in hotel, restaurant and cafeteria kitchens
	Commercial	Food production businesses

Table 2. Absolute frequency and share of case studies that perform specific activities. Note that each case study may perform multiple activities (n=152)

Rooftop agriculture activity	Absolute frequency	Share (%)
Vegetable production	133	87
Education	56	37
Recreational space	52	34
Restaurant or bar	21	14
Direct sales of products	20	13
Agricultural training	16	10
Beekeeping	14	9
Distribution of products	12	8
Animal production	10	7
Production of added-value products	9	6
Planning and design services	9	6
Food-related training	8	5
Event rental	7	5

Table 3. Absolute frequency and share of case studies using specific water, energy and nutrient resources

Resource		Absolute frequency (n)	Share of case studies (%)
Water source		**40**	**100**
	Well water	1	3
	Tap water	13	33
	Rainwater	25	63
	Greywater	3	8
Energy source		26	100
	Electricity grid	14	54
	Solar energy panel	12	46
	Wind turbine	1	4
Nutrient type		39	100
	Mineral	12	31
	Organic	17	44
	Compost	24	62
Nutrient form		33	100
	Solid	22	56
	Liquid	13	33

ADDITIONAL MATERIALS

Of the 185 analyzed case studies, 165 reported valid addresses used for the creation of a prototype map. The map was inspired by existing examples (e.g., the *Toronto Urban Growers Map*) and was created to easily locate RA cases worldwide. As this map is a prototype, it should be improved and implemented to become a useful tool for potential users. The map can be found at the following link: https://www.google.com/maps/d/u/0/viewer?mid=1apMREBaATUTldxyRx7JNg0gasbD-tu1U&ll=2.5756014516108294%2C-125.98531144999993&z=1.

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