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

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# **The global rise of urban rooftop agriculture: a review of worldwide cases**

## **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

84 commercial activities, whereas small-scale kitchen gardens and noncommercial projects often use  
85 soil either in raised beds or directly on rooftop surfaces.

86 Compared to conventional rural agriculture as well as ground-based urban farming, RA shows some  
87 distinct features (e.g., in terms of space access, technical requirements, unique legal environments  
88 or often nonproduction-related missions) (Sanyé-Mengual et al., 2019). Among the peculiar  
89 challenges of RA are the physical feasibility (structural loading, rooftop accessibility), restrictions  
90 from safety regulations and municipal codes (historical constraints, height limitations, fire code),  
91 and amplified climate conditions (heavy rains, elevated radiative fluxes and temperature ranges)  
92 that occur on rooftops (Hui, 2011; Caputo et al., 2017), which may limit its application and  
93 cultivation performance. However, RA bears the potential to improve building environmental  
94 performance (e.g., by increasing thermal insulation or integrating rainwater harvesting systems) and  
95 employ building byproducts (e.g., greywater, heat, CO<sub>2</sub> and organic waste) as farming inputs  
96 (Sanyé-Mengual et al., 2014; Grard et al., 2015; O'Sullivan et al., 2019), thereby integrating  
97 building and plant production areas (Pons et al., 2015; Sanjuan-Delmás et al., 2018) to reduce the  
98 environmental impact of both cultivation and housing. Further environmental benefits at the city  
99 level include biodiversity conservation, water runoff management, air pollution and carbon  
100 sequestration, as well as reducing both the urban heat island effect and noise pollution (Van Woert  
101 et al., 2005; Takebayashi and Moriyama, 2007; Dunnett and Kingsbury, 2008; Rowe, 2011;  
102 McIntyre and Snodgrass, 2017).

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

110 Due to the complexity of RA implementation, there is a need to comprehensively evaluate the  
111 current worldwide status to examine the potential effect of the urban and climatic context, the  
112 distribution of existing RA initiatives, and their agronomical characteristics and sustainable  
113 practices. Such assessments should focus not only on commercial activities (Buehler and Junge,  
114 2016) but also on noncommercial activities with the aim of better individuating best practices for  
115 future sector advancement.

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

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

125

## 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



152 inventory of Thomaier et al. (2015). Since the main objective of the analysis was to understand the  
153 global interest in RA and its diffusion worldwide, both ongoing and (potentially) closed cases were  
154 included. Reasons for closure were not often declared, although in the case of *UF002 De Schilde*  
155 farm in The Hague (Netherlands), closure occurred due to bankruptcy problems, and the *Rooftop*  
156 *Garden of Via Gandusio* in Bologna (Italy) was interrupted due to renovation of the building.  
157 Finally, since case searches and data collection were performed in English and based on  
158 information available on the web, language limitations and online presence of cases may have led to  
159 a bias in the resulting database.

160

## 161 2.2 DATA CLASSIFICATION

162 The database adopts a classification of RA typologies (**Figure 1**) based on growing conditions  
163 (protected or nonprotected) (RA type), cultivation aim (farming purpose) and building  
164 characteristics (building type) (Thomaier et al., 2015; Buehler and Junge, 2016; Nasr et al., 2017)  
165 and includes a subdivision depending on whether the structure is devoted to food production only  
166 (monofunctional building) or to other uses (multifunctional building) (Buehler and Junge, 2016).  
167 The data compiled for each case study included both general and operational aspects. Concerning  
168 the general aspects of each case, the data included RA type, building type and farming purpose, as  
169 organized and explained in the classification developed by Thomaier et al. (2015) (**Table 1**).  
170 Operational aspects were further divided into basic and structural observations (starting and closing  
171 date, size, activities performed, typology of organization), agronomical parameters (growing  
172 system, type of crop/product, crop yield), resource use (water source, energy source, nutrient  
173 typology, nutrient form), social and economic aspects (members, women members, population at  
174 risk of social exclusion, costs, income, installation costs) and societal impact (consumers, visits,  
175 trainees, users). Sustainability actions were built on the description developed by Buehler and Junge  
176 (2016). In a few cases that had substantial information available online but certain relevant data  
177 were missing, surveys were sent to rooftop gardens/farm administrators (n=13).

178

## 179           **2.3     DATA ANALYSIS AND PRESENTATION**

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

194

## 195           **3.   Results and discussion**

### 196           **3.1 GLOBAL DISTRIBUTION AND TRENDS**

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

201   According to the analysis of our samples, North America emerged as the continent with the most  
202   RA cases (81), followed by Europe (49) and Asia (39). Conversely, Africa-Middle East (9),  
203   Oceania (4) and South America (3) presented lower numbers of cases (**Figure 2**). Globally, the

204 general trend seems to remain unchanged compared to that in previous research studies (Thomaier  
205 et al., 2015; Buehler and Junge, 2016), although new cases have been registered on each continent.  
206 Rooftop farms and gardens were mostly identified in the cities of New York (26) and Toronto (15).  
207 The overall increase in cases can be interpreted as a rising interest in practice as a solution to  
208 overcome some specific urban issues (Ackerman et al., 2014). However, the reduced number of  
209 reported cases in the Global South, on the one hand, highlights the bias in the search methodology  
210 and, on the other hand, points to the potential of further applications guided by international  
211 organizations or local policy makers to address food security concerns, small income creation and  
212 social integration.

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

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

226 Rooftop farming can be performed in both nonprotected (open-air farms/gardens) and protected  
227 conditions (rooftop greenhouses) (**Table 1**). Protected conditions can help more easily satisfy  
228 cultivation requirements such as temperature and relative humidity. In fact, an uncovered rooftop  
229 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.

267

### 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<sup>2</sup>; the farming areas ranged from a minimum of 4 m<sup>2</sup> to a maximum of 35000 m<sup>2</sup> 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<sup>2</sup>, n=24, SE=1225) and North America (750 m<sup>2</sup>, n=46, SE=257), while the Asian cases had a lower median size (370 m<sup>2</sup>, n=19, SE=1867). Lower median surface areas were observed in both the Africa-Middle East (20 m<sup>2</sup>, n=5, SE=884) and Oceania (130 m<sup>2</sup>, 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<sup>2</sup> (n=25, SE=526), which was larger than the 500 m<sup>2</sup> 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<sup>2</sup>, n=21, SE=426), followed by projects for urban living quality improvement (560 m<sup>2</sup>, n=43, SE=1152) and social-educational aims (500 m<sup>2</sup>, n=27, SE=420). Projects for innovation had a median surface area of 250 m<sup>2</sup> (n=3, SE=2583), while cases for image purposes had a median area of 280 m<sup>2</sup> (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<sup>2</sup> (SE=394) and 500 m<sup>2</sup> (SE=264), respectively.

294

### 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

308 within the building were rarer (2%), although they presented the highest relative frequency of  
309 rooftop greenhouses together with warehouses and manufacturing structures (**Figure 3**).  
310 Predictably, buildings intended for farming and food businesses presented only a commercial  
311 purpose, while housing buildings hosting an RA project specifically targeted urban living quality  
312 (**Figure 3**). Social-educational purposes were especially common in research and educational  
313 centers (54%) (**Figure 3**). Eighty-five percent of the RA projects on hotels and restaurants were  
314 devoted to image improvement (**Figure 3**).  
315 It is important to note that buildings oriented toward farming and food businesses, such as *Ecco*  
316 *Jäger Farm* in Bad Ragaz (Switzerland) or *Toit Tout Vert* in Paris (France), employed not only the  
317 rooftop surface but also the indoor building area for food production and were therefore classified  
318 as monofunctional buildings that were entirely dedicated to that business. In contrast, other building  
319 typologies applied rooftop cultivation on buildings with other primary functions, such as retailing,  
320 manufacturing, housing or education, and were therefore classified as structures with  
321 multifunctional purposes (Buehler and Junge, 2016). See **Table 1** for further specifications on  
322 building typologies.

323

### 324 **3.4 GROWING SYSTEMS, PRODUCTS AND YIELDS**

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

334 used in rooftop greenhouses (66%, n=20). In contrast, open-air projects (n=70) mostly used soil-  
335 based cultivation systems (70%, n=49).  
336 Soilless cultivation was largely applied for commercial (n=15) and urban living quality  
337 improvement (n=7) purposes. Specifically, approximately two-thirds of commercial farms used  
338 soilless growing techniques; this may be related to the high productivity that hydroponics can  
339 achieve, especially when applied in combination with rooftop greenhouses (Buehler and Junge,  
340 2016). Furthermore, soil-based RA projects were mostly connected with social-educational (n=17)  
341 and urban living quality improvement (n=16) purposes.  
342 The most commonly produced products were lettuce and herbs (49% and 72%, respectively, of 102  
343 cases), both in open-air and protected systems (data not shown). While soil-based cases normally  
344 produce a higher variety of vegetables, soilless systems are usually used to grow herbs, leafy greens  
345 or tomatoes. Animal-based products were also reported and mainly included fish (n=8), honey  
346 (n=14) and eggs (n=5). Aquaponics was mostly applied in commercial cases (e.g., *Ecco Jäger Farm*  
347 in Bad Ragaz, *Comcrop* in Singapore), although one case of private fish production was also  
348 registered in the Gaza strip. One unique example of RA use is the production of spirulina, a  
349 nutritive microalga that can be applied as an integrator in different types of products (e.g., pasta, ice  
350 cream, chocolate), produced by the *EnerGaia* team in Bangkok.  
351 For 28 cases reporting their productive capacity, the average crop yield was approximately 15 kg m<sup>-2</sup>  
352 year<sup>-1</sup> (data not shown), overall resembling commercial farming productivity in vegetable crop  
353 production, e.g., in the Mediterranean (Orsini et al., 2014). Among those, 11 cases were rooftop  
354 greenhouses (10 out of 11 using soilless systems) with an average yield of 28 kg m<sup>-2</sup> year<sup>-1</sup>, while  
355 17 cases were open-air (2 out of 17 using soilless systems) with an average yield of 6 kg m<sup>-2</sup> year<sup>-1</sup>.  
356 It also emerged that the average yield in soilless systems (30 kg m<sup>-2</sup> year<sup>-1</sup>) was much higher than  
357 the reported yield in soil-based gardens (4 kg m<sup>-2</sup> year<sup>-1</sup>).  
358

### 359 3.5 ORGANIZATION TYPES AND ROOFTOP AGRICULTURE ACTIVITIES



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

379

### 380 3.6 RESOURCE-EFFICIENCY AND SUSTAINABILITY ACTIONS

381 **Table 3** shows the resources applied for crop cultivation, including absolute frequency and share  
382 for each type of input. Some cases used more than one type of input. Rainwater was the most  
383 common irrigation source, followed by greywater, well water and tap water (**Table 3**). However,  
384 due to the limited number of cases that reported their water source, as well as farmers' tendency to  
385 report and highlight virtuous actions for environmental preservation, these data should be confirmed

386 through further investigation. The most commonly used energy source was on-grid electricity,  
387 although solar panels were also widely applied (**Table 3**). Wind turbines appeared only once in  
388 association with solar energy, in the case of the *Gotham Greens Pullman Farm* in Chicago. In some  
389 cases, energy was not used or used in negligible amounts for irrigation purposes. Therefore, for the  
390 sake of this publication, only cases where energy use was clearly stated were considered. Organic  
391 fertilization, generally in the form of compost, was the most common form of nutrient supply  
392 (**Table 3**). As mentioned above, further investigations should examine a wider number of cases to  
393 better report farmers' practices.

394 Applied sustainability actions were also investigated. Among the 79 cases that clearly stated their  
395 sustainable management practices, the highest proportion of cases were committed to chemical-free  
396 crop production (66%), and this practice was distributed across cases independent of farming  
397 purpose and building type. These cases included both soil and soilless systems, even in countries  
398 where soilless systems are not eligible for organic certification. The attention given to chemical-free  
399 crop production may be attributed only partially to the necessity of rooftop farmers reducing  
400 economic costs; the main reason may be the growing public concern about the use of chemicals in  
401 food production and the increasing demand for organic food. As a consequence, reusing recycled  
402 nutrients, especially those from compost, was also common; this practice addresses the issue of  
403 residual biomass management and favors a circular economy (Manríquez-Altamirano et al., 2020).

404 Technology that improves energy efficiency (e.g., supplementary LED lighting, highly insulating  
405 glass) was mainly associated with commercial purposes and rooftop greenhouses and was applied to  
406 improve crop yields and reduce production costs. Waste heat reuse (10%), gas exchange (5%) and  
407 greywater recycling (4%) were the least-applied sustainable practices, although integrating these  
408 techniques into a rooftop greenhouse may help achieve savings of 128 kWh/m<sup>2</sup> of energy and 45.6  
409 kg of CO<sub>2</sub> eq/m<sup>2</sup> (Muñoz-Liesa et al., 2020). Predictably, water reuse was particularly common in  
410 projects that used soilless systems; it has been demonstrated that a closed-loop system in a soilless

411 rooftop greenhouse can use 40% less irrigation water and 35-54% less nutrients per day than an  
412 open-loop system rooftop greenhouse (Rufí-Salís et al., 2020).

413

### 414 3.7 COSTS AND ECONOMIC PERFORMANCE

415 The economic impact evaluation of 23 RA cases (from which this information was available)  
416 demonstrated an average installation cost of 880 € m<sup>-2</sup> (data not shown). Installation cost is one of  
417 the main constraints that may dissuade from the realization of a rooftop farm or garden. In fact,  
418 compared to ground level cultivation, a rooftop farm also has to consider the costs for the  
419 movement of cultivation materials and structures on top of the building, as well as an engineer  
420 consultancy to evaluate the structure and eventual adaptation interventions to guarantee the safety  
421 of users and visitors (roof structure reinforcement, safety barriers, emergency exit). Installation  
422 costs may vary widely depending on cultivation purposes and farm typology (open-air or  
423 greenhouse), ranging from inexpensive outdoor household experiences obtained with recycled  
424 materials to high-tech greenhouses. In the case of open-air conditions, installation costs can also be  
425 influenced by the choice of an intensive cultivation system applying specific technologies to create  
426 a soil layer of approximately 20-30 cm or an extensive cultivation system using off-soil containers  
427 such as geotextile bags. In the first case, installation costs have been estimated to be approximately  
428 100 € m<sup>-2</sup>, while in the second case, they have been estimated to be approximately 30 € m<sup>-2</sup>  
429 (CRETAU, 2020). Concerning farming purposes, the research results showed that commercial and  
430 innovation farms usually had higher economic costs than urban living quality and social and  
431 educational farms, in which investment costs were probably limited due to unpredictable economic  
432 returns. For instance, commercial cases such as *Comcrop* in Singapore or *Gotham Greens* in  
433 Chicago showed an average installation cost of approximately 1000 € m<sup>-2</sup>, while that of urban living  
434 quality cases such as *Garden City Farmers* in Bengaluru or *Risc's Roof Garden* in Reading was  
435 approximately 300 € m<sup>-2</sup>.

436 The running costs and net incomes could be evaluated only for 9 cases, showing 80 € m<sup>-2</sup> year<sup>-1</sup> and  
437 26 € m<sup>-2</sup> year<sup>-1</sup>, respectively, on average. In this case, empirical observations showed that the  
438 economic impact could widely vary among the same farming purposes. For instance, the case study  
439 of *Ortoalto Ozanam* in Turin, an open-air rooftop garden with social and educational aims, had a  
440 running cost of 50 € m<sup>-2</sup> year<sup>-1</sup> and an income of 20 € m<sup>-2</sup> year<sup>-1</sup>. On the other hand, another  
441 example of a social-educational open-air farm at *NIST International School* in Bangkok presented a  
442 sixth of the running costs along with a tenth of the income. Although this large difference may be  
443 imputed to countries purchasing powers and diverging material and labor costs, variations can also  
444 be determined by different management conditions (e.g., composting of organic wastes for  
445 fertilization, collection of rainwater for watering) impacting running costs, as well as incomes  
446 coming not only from crop selling but also from the offer of services such as workshops or renting  
447 for events. Cost and incomes may also vary depending on necessary working hours, by human  
448 resources employed (volunteers or salaried workers) and relative employment contract typology, as  
449 in some experiences wage subsidies for professional integration had a strong impact on offsetting  
450 hiring costs (CRETAU, 2020). Unfortunately, drawing further conclusions on the economic  
451 performance of rooftop farming cases may be difficult due to the limited sample size that reported  
452 economic data.

453

### 454 **3.8 INVOLVING STAKEHOLDERS AND THE PUBLIC**

455 The societal impact of RA was also examined based on the number of people engaged in RA not  
456 only as consumers but also as volunteers, trainees or recreational users. A notable case of  
457 community involvement was *Schieblock DakAkker* in Rotterdam, which reaches approximately  
458 15000 consumers and 20000 visitors per year. In the Global South, particularly in the Africa-Middle  
459 East and South America, the feasibility of applying RA to projects involving government and  
460 nongovernmental bodies that address poverty and food insecurity has been demonstrated. The  
461 potential to involve women in RA was also observed, as in the case of small hydroponic systems in

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

470

#### 471 **4. The overall picture of rooftop agriculture**

472 The analysis of worldwide practices over time and geographical distribution confirmed the trends of  
473 increasing RA around the world and the predominance of certain RA types. In our sample, we  
474 detected an emphasis on RA cases in countries in the Global North and in the form of open-air  
475 rooftop farms/gardens. Although Thomaier et al. (2015) revealed greater interest in social-  
476 educational and image-oriented farming purposes, the current investigation showed a wider number  
477 of cases intended to improve urban living conditions. However, this study outlined the  
478 multifunctionality of RA, as most cases presented a secondary farming purpose, usually combining  
479 urban living quality with social education or image improvement. At the continent and country  
480 levels, the presence and distribution of RA cases showed strong variations. In North America,  
481 rooftop farming projects are mainly found in larger cities where innovation in urban agriculture is  
482 promoted through specific policies, such as New York and Toronto. The presence of a high number  
483 of cases can be explained by the substantial importance that municipalities in North America place  
484 on developing food system strategies and plans to overcome food insecurity in the urban context  
485 (Sonnino, 2016). The main farming objectives are often related to urban dwellers' quality of life or  
486 social and educational actions connected to school projects or community integration initiatives.  
487 These kinds of projects are usually developed as open-air farming systems, although a few

488 examples, such as the *Manhattan School for Children* in New York or *Concordia Greenhouse* in  
489 Montreal, use rooftop greenhouses. For-profit companies, including those with commercial and  
490 image-oriented farming purposes, are also common in North America, where these RA types  
491 occurred at a higher frequency than in other world regions. In terms of commercial farms, North  
492 America is also the location of some of the best-known RA food businesses in the world, such as  
493 *Gotham Greens* in the US and *Lufa Farms* in Canada. These types of farms are usually rooftop  
494 greenhouses, although open-air commercial rooftop farms may also occur, as in the case of  
495 *Brooklyn Grange* in New York or *McCormick Place* in Chicago. Although North America showed  
496 a higher occurrence in RA than other regions, cases of RA with purely innovation-oriented purposes  
497 were lacking. In contrast, Europe was the continent promoting innovation in RA at both the  
498 academic and private for-profit levels. *AgroParisTech* in Paris and *RTG-Lab* in Barcelona are two  
499 examples of European research centers investing in rooftop farming development, while companies  
500 such as *UrbanFarmers* in Switzerland and *ECF Systems* in Germany have already developed  
501 innovative rooftop aquaponic systems for commercial food production.

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

512 The difference in the number of rooftop farming cases in Europe and North America was still  
513 notable; there were approximately twice as many North American cases as European cases. This

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

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

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

534 Oceania had a very low number of cases compared to those on other continents of the Global North,  
535 which some authors attribute to local restrictions on the productive use of rooftops (De Zeeuw et al.,  
536 2017).

537 As previously anticipated, the absence of statistical correlations between the geographical  
538 distribution of RA and the size, population and density of cities or HDI suggests that RA is widely  
539 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



566 than that presented in this study, especially in the case of low-technology projects that do not have a  
567 website presence or any links with academia. The large amount of data collected per case study in  
568 the database led to missing information in specific fields, such as activities performed or  
569 organization type, due to incomplete websites or vague information. Moreover, the data were too  
570 limited to perform a full social and economic evaluation, and a deeper investigation would be  
571 required to obtain a full picture.

572

## 573 **5. Guidelines for future development**

574 RA represents a complementary solution to ground-based and indoor UA, ensuring similar  
575 multifunctional benefits while avoiding competition and conflicts over land access. Despite the  
576 already established roles that RA could play to improve environmental, social and economic  
577 sustainability in urban contexts, some potential benefits of RA are still underrated. In fact, while RA  
578 projects designed for social and recreational purposes seem to have a broad range of applications,  
579 the intensive food production capacity of RA is still limited, highlighting its inability to meet  
580 current food and nutritional needs in cities at a larger scale. Regulating RA practices, including the  
581 agreements between building owners and rooftop farmers, may represent a fundamental step in  
582 resolving eventual conflicts and setting the ground for the implementation of RA projects.  
583 Moreover, the recognition of a certification program to ensure product quality and safety, such as  
584 certification for chemical-free production or the absence of heavy metals, may also be a key factor  
585 in enhancing consumer acceptance and preventing health risks. Similarly, environmental benefits  
586 and sustainable practices used in RA could also be included in certification schemes, such as  
587 sustainable urban resource use (e.g., rainwater harvesting), building byproduct reuse, urban  
588 environmental management (e.g., heavy rain management) or carbon footprint reduction. To enable  
589 future RA implementation, the regulatory framework from both the building and farming  
590 standpoints should specifically be addressed and customized. This will require efforts from policy

591 makers to fill legislative gaps and fully develop specific policies that target the promotion and  
592 support of UA. Legislators should consider local conditions and constraints and adapt norms  
593 through casuistry to address specific issues. In addition to the need for specific regulations, RA is  
594 already shaped by municipal planning codes. Zoning and historical constraints may limit building  
595 height and floor number, while safety codes may hinder rooftop accessibility and structural loads. In  
596 the latter cases, existing buildings could overcome limitations by adapting the farm design to the  
597 circumstances, e.g., using soilless systems to reduce roof loads or installing safety barriers. Because  
598 rooftop retrofitting for RA bears some limitations, RA should be considered for integration from the  
599 beginning into the design of new buildings. This would help to include food production spaces in  
600 the urban fabric to more effectively plan urban food supplies in the future.

601 Although it is difficult to precisely predict its future development, RA may certainly play a  
602 fundamental role in future cities. Building on its multiple functions, RA may become a strategy for  
603 targeting urban issues at different levels, including heat island mitigation, stormwater management,  
604 biodiversity improvement, social inclusion, food desert and urban poverty reduction, and health and  
605 nutrition advancement. Accordingly, future research should focus more on how to improve the  
606 integration of sustainable practices into RA, such as by investigating the social impacts of RA,  
607 developing a functional metabolism between the building and the farmed surface (particularly for  
608 water, energy and CO<sub>2</sub> cycles), and how to improve cropping practices by building on existing  
609 advances in modern agriculture. However, given the need to optimize resource use efficiency and  
610 define economically and environmentally sustainable systems, planning and legislation will need to  
611 go hand in hand with applied research and innovation.

612

## 613 **6. Conclusions**

614 In conclusion, this study revealed an increase in global interest in RA in recent years, with more  
615 projects developing throughout the world in different climatic areas and independent of city size or  
616 demography. Most RA projects have a noncommercial farming purpose, especially those

617 established as open-air and soil-based systems. On the other hand, commercial rooftop farms are  
618 still scarce despite their high food production capacity (based on integrating greenhouse  
619 technologies and soilless systems).

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

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

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670 **Figures**

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



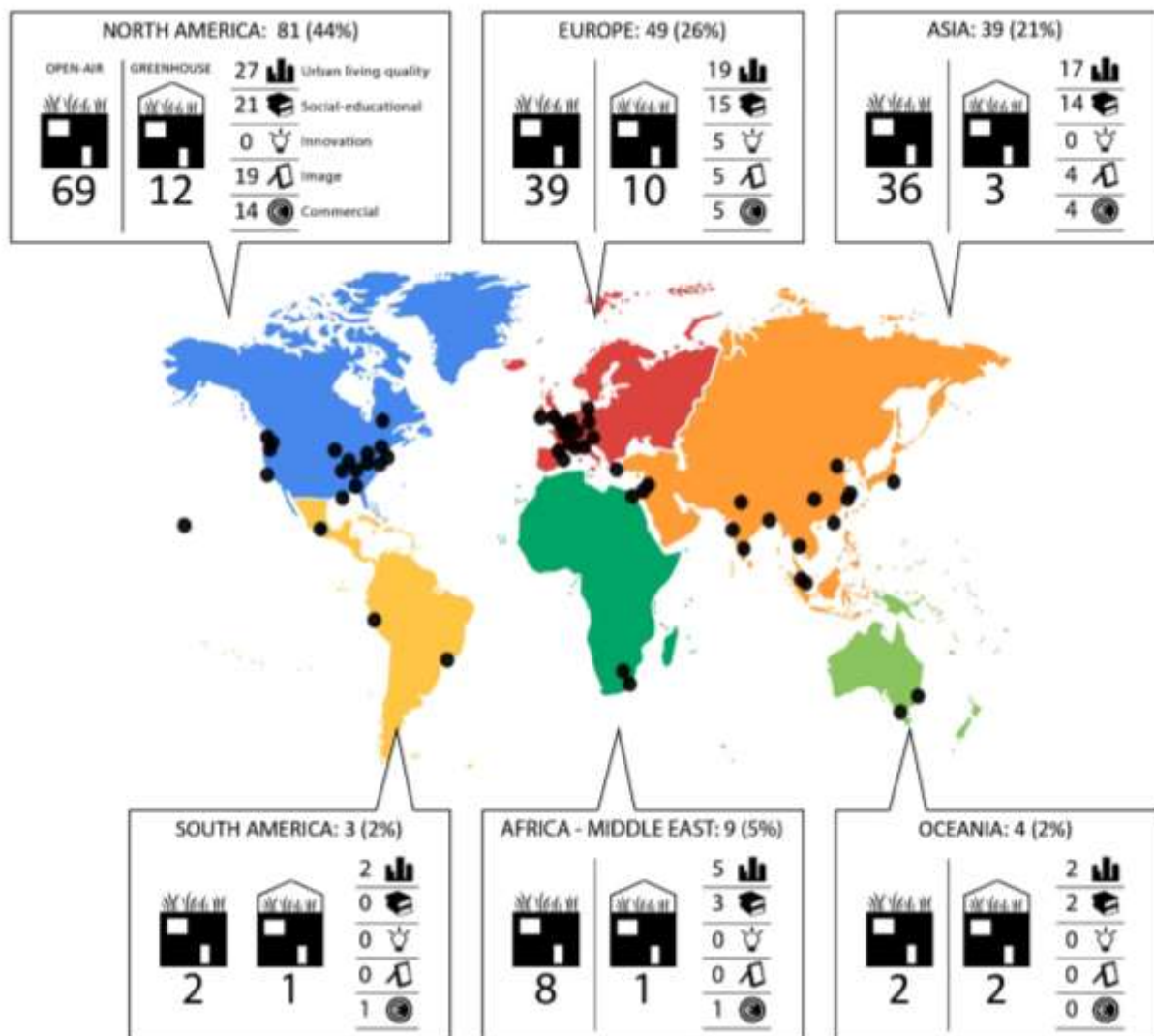
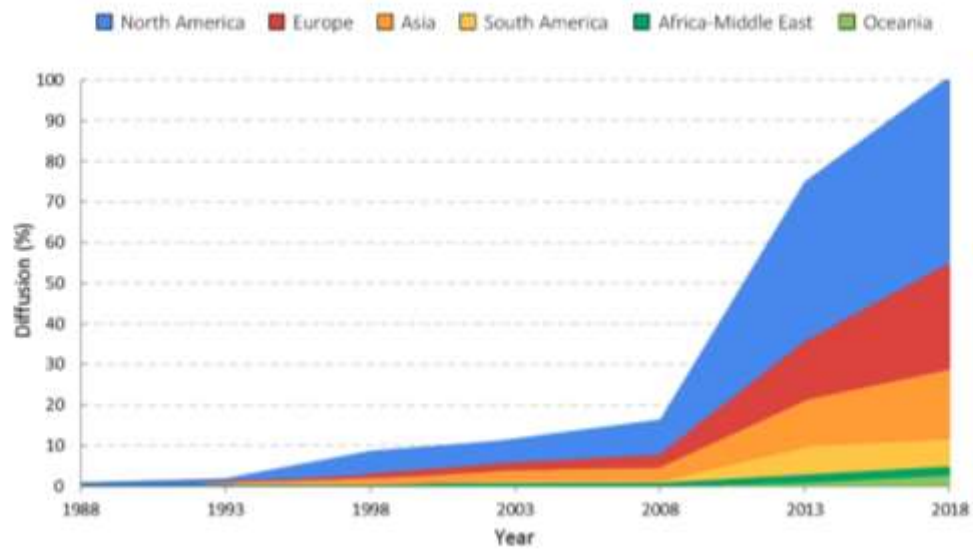
672

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

677

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679



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

682

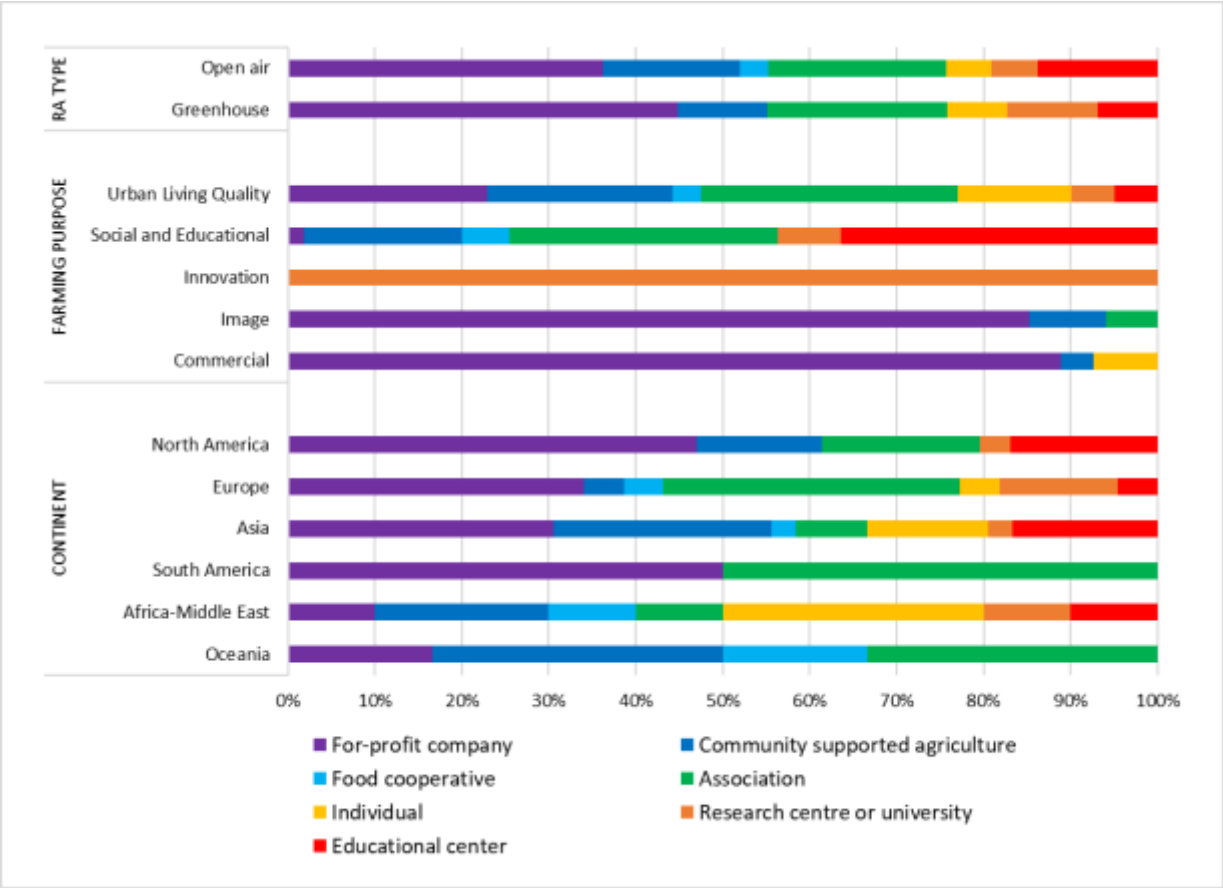
RA TYPE		BUILDING TYPE		FARMING PURPOSE				
OPEN-AIR	GREENHOUSE			URBAN LIVING QUALITY	SOCIAL- EDUCATIONAL	INNOVATION	IMAGE	COMMERCIAL
								
1	3		FARMING / FOOD BUSINESS	0	0	0	0	4
28	4		HOUSING	28	3	0	1	0
7	5		WAREHOUSE / MANUFACTURING	4	2	1	2	3
28	6		RESEARCH/EDUCATION	1	30	3	0	0
9	4		RETAIL	5	2	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

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684

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

687  
688



689



## 690 Tables

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

694

	Subcategory	Description
<b>RA type</b>	<i>Rooftop Farm/Garden</i>	Open-air rooftop agriculture
	<i>Rooftop Greenhouse</i>	Protected rooftop agriculture
<b>Building type</b>	<i>Farming/Food Business</i>	Farming-oriented building, possibly integrated with a grocery store or a wholesale shop
	<i>Housing</i>	Residential building
	<i>Warehouse/Manufacturing</i>	Industrial or storage structure
	<i>Research/Education</i>	University, school, research center, educational center, etc.
	<i>Retail</i>	Retail shop, mall, supermarket, etc.
	<i>Hotel/Restaurant</i>	Hotel, restaurant, cafe, etc.
	<i>Transportation Facility</i>	Train station, bus station, parking lot, etc.
	<i>Office</i>	Bank, post office, company building, etc.
	<i>Community Services</i>	Church, reception or social center, government building, etc.
	<i>Health</i>	Hospital, clinic, retirement home, gym, etc.
	<i>Mixed-use</i>	Building with different uses
<b>Farming purpose</b>	<i>Urban Living Quality</i>	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
	<i>Social-Educational</i>	Cases often located at schools, hospitals or social centers with educational, social and integration purposes
	<i>Innovation</i>	Research cases or innovative production systems
	<i>Image</i>	Cases with an image or marketing aim, especially cultivated for the production of food to use in hotel, restaurant and cafeteria kitchens
	<i>Commercial</i>	Food production businesses

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

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

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698

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

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

700

701    **ADDITIONAL MATERIALS**

702    Of the 185 analyzed case studies, 165 reported valid addresses used for the creation of a prototype  
703    map. The map was inspired by existing examples (e.g., the *Toronto Urban Growers Map*) and was  
704    created to easily locate RA cases worldwide. As this map is a prototype, it should be improved and  
705    implemented to become a useful tool for potential users. The map can be found at the following  
706    link:

707    [https://www.google.com/maps/d/u/0/viewer?mid=1apMREBaATUTldxyRx7JNg0gasbD-](https://www.google.com/maps/d/u/0/viewer?mid=1apMREBaATUTldxyRx7JNg0gasbD-tu1U&ll=2.5756014516108294%2C-125.98531144999993&z=1)  
708    [tu1U&ll=2.5756014516108294%2C-125.98531144999993&z=1](https://www.google.com/maps/d/u/0/viewer?mid=1apMREBaATUTldxyRx7JNg0gasbD-tu1U&ll=2.5756014516108294%2C-125.98531144999993&z=1).

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