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Review

Global Trends and Current Status of Commercial Urban Rooftop Farming

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Abstract: The aim of this study was to analyze current practices in commercial urban rooftop farming (URF). In recent years, URF has been experiencing increasing popularity. It is a practice that is well-suited to enhancing food security in cities and reducing the environmental impact that results from long transportation distances that are common in conventional agriculture. To date, most URF initiatives have been motivated by social and educational factors rather than the aim of creating large sustainable food production systems in cities. The commercial operation of urban rooftop farms, should they become profitable, is likely to attract notable private investment, allowing a significant level of high quality urban food production to be achieved. There is a reasonable amount of literature available on urban farming that deals with its potential, and its limitations. However, it does not focus on commercial operations. In contrast to other surveys and theoretical papers, this study of URF focuses on large and commercial operations. The analysis showed that commercial URFs can be grouped into two main types: Firstly, hydroponic systems in greenhouses where mostly leafy greens, tomatoes, and herbs are grown; secondly, soil-based open-air farms that grow a large variety of vegetables. Hydroponics is frequently seen as the key technology for commercial urban food production. While the technology is not in and of itself sustainable, hydroponic farms often make an effort to implement environmentally friendly technologies and methods. However, there is still untapped potential to systemically integrate farms into buildings. The findings of this study identified where future research is needed in order to make URF a widespread sustainable solution.

Keywords: urban rooftop farming; Building-Integrated Agriculture; Building-Integrated Farming; Zero-Acreage Farming; hydroponics; commercialization; trends

1. Introduction

In a globalized and urbanized world, the food supply chain stretches over long distances. The production location is decoupled from the location where products are consumed, thus resulting in long transportation distances and an associated environmental impact [1]. Moreover, the increasing global population means there is an increasing demand for food, which puts more pressure on food security in cities [2].

In recent years, urban agriculture has become a popular countermovement, which aims to reduce the environmental impact of conventional agriculture, increase food security, and enhance social cohesion in cities. Urban agricultural activities that do not use farmland or open space can be summarized under the term Zero-Acreage Farming (ZFarming). These activities include private backyard gardens, the development of community gardens on vacant land as well as agriculture in and on buildings [3–5].

The building-based forms have been conceptualized as Building-Integrated Agriculture (BIA) [2,6]. Figure 1 illustrates how these concepts can be further categorized into vertical farming (sky farming), edible walls, indoor farming, and rooftop farming, with the latter also classified into open-air rooftop farming and rooftop greenhouses [2].

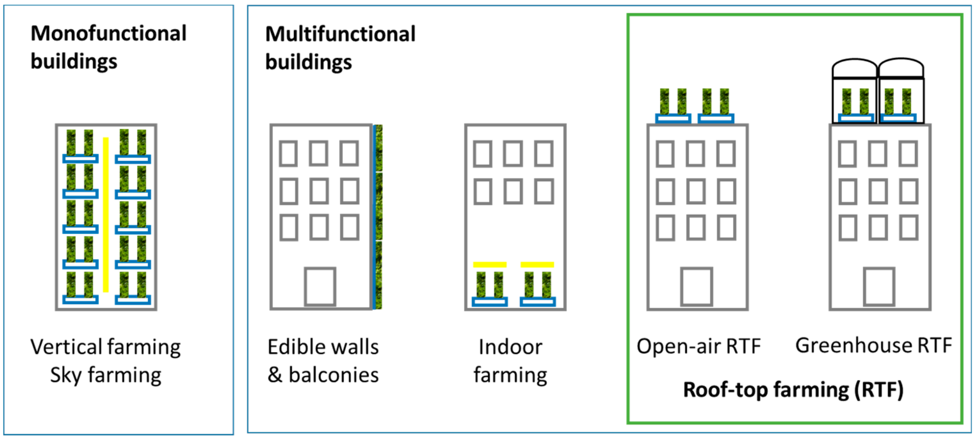

Figure 1. Typologies and nomenclatures for Building-Integrated Agriculture (modified after [2]).

Like urban agriculture in general, interest in urban rooftop farming (URF) has also been increasing. The main advantage of URF is that it does not compete with other land uses or uses of a building's interior, and it does not require fertile farmland [6].

The Berlin research group led by Rosmarie Sieber [7] conducted comprehensive reviews of papers connected to the topic of ZFarming [6,8]. By applying their conceptual framework they identified core topics connected to ZFarming as well as opportunities and obstacles [6]. It has been noted that URF has a lot of potential in environmental, social, and economic fields [6]. In a further paper [8], they systematically analyzed ZFarming case studies and presented empirical evidence supporting current practices and innovations. A total of 73 projects were analyzed in terms of specific criteria, such as typology, farming methods, and spatial diversification. Other practical studies assessed and tested the environmental performance of URF and potential techniques for improvement [9–12]. A number of studies have calculated that cities can achieve significant levels of local self-reliance in terms of food production [1,13–15]. However, URF is a very new concept for food production, which is in an early stage of development, and, as a result faces different obstacles [6]. It competes with alternative uses of urban rooftops, such as solar energy generation [6], albeit prototypes combining URF and solar energy generation have already been implemented [16].

The paper of Thomaier et al. [8] discusses the question of financing, which is a key challenge for new URFs [8]. Most projects are motivated by social, educational, and quality-of-living issues. Many of them are financed through crowdfunding or governmental and private grants [8], since the costs are often higher than the (financial) benefits. The main value of such projects is more social than environmental. However, in order to mitigate the environmental impact of conventional food supply systems, it is essential to achieve a substantial level of food production within a city. A high level of production, coupled with good quality produce, requires a great amount of horticultural knowledge that includes, but is not limited to, selecting the right varieties, creating seasonal planting plans, identifying and controlling pests and treating diseases. Therefore, most URFs have to be operated by professionals, which in most cases, will also require them to be commercial operations. A well-executed commercial operation has the potential to attract private investment and is therefore likely to overcome the key challenge of obtaining financing. This would allow URFs to spread rapidly and provide fresh products to a significant portion of the citizens of a city. While hydroponics is often seen as the key technology for commercial and large-scale URF operations [6], it is also stated that hydroponics is not by nature sustainable if not managed properly [6].

To date, there has been no study that has analyzed current practices of commercial URF. The purpose of this study is to close this gap and identify patterns in terms of potential and limitations in existing commercial URF operations the review of Thomaier et al. [8] is concerned with ZFarming in general and also includes smaller farms, whereas this survey focuses on farms that are larger than 100 m^2 and on commercial URF. The results of this study will highlight the areas where future research is needed in order to make URF a widespread and sustainable agricultural production method.

2. Materials and Methods

Based on the most important findings of the ZFarm-Group regarding commercialization of URF outlined in [6,8], guiding questions to direct the analysis of the case studies were formulated (Table 1).

Table 1. Guiding questions for the research of case studies based on findings in the literature.

Core Findings from the Literature	Guiding Questions for Research
Functions: "(. . .) the real challenge is to design urban landscapes for a wide range of functions. Agriculture could provide enormous benefits if it is not only production-oriented but designed to meet multiple societal and ecological functions [17]."	What functions do current URFs have? How far has the development of commercial URFs progressed?
Global trend: ZFarming is part of a trend in urban lifestyles in western cities. There is a worldwide growing interest in becoming closer to the production of food again [6].	In which countries is the movement the strongest?
Scale of implementation: "The real impact on sustainability will depend on the scale on which ZFarming will be applied in the future [6]."	How is the surface area of URFs changing in quantitative terms?
Growing method: "Many studies share the view that ZFarming in urban areas on a larger scale can only be realized by growing food using soil-less techniques such as aeroponics or hydroponics [15,18–20]."	Which growing methods do commercial farms use for cultivation purposes?
Sustainability of hydroponics: "It is important to recognize that the different types of ZFarming are not in and of themselves sustainable. ZFarming practices can be as unsustainable as conventional agribusiness if not managed properly." Special attention should be paid to energy efficiency, building-integrated production of renewable energy, use of rainwater, focusing on local resources and involving the social dimension [6].	Do hydroponic farms implement further technologies that increase their environmental sustainability?
Cultivated products: For open-air farms, the range of products is limited to tolerant species [17]. Hydroponics is best suited for leafy crops (spinach, lettuce, salad greens), vine crops (tomato, cucumber, pepper, squash, beans, courgette), or culinary herbs (basil, parsley, chives, coriander) [21]. Combining hydroponics with fish farms is recommended [22]. Indoor farms are limited in terms of their sustainability for the production of cereals, feeds, root vegetables, and tree borne fruit. Cattle, horses, sheep, goats, and other large farm animals also seem to fall outside the paradigm of commercial urban agriculture [23].	What products do hydroponic and soil-based farms grow?

An extensive web and literature survey was undertaken to compile a comprehensive list of URF operations. The research into case studies was limited to information that has been published and is available online in English, German, and Dutch. The main sources for the information on the case studies were websites that list various case studies such as *Carrot City* for green roofs. Furthermore, information was found in scientific publications, on URF company and organisation homepages, as well as urban farming news portals.

To gain a broad overview of current practices, commercial URFs as well as farms with other functions were included in the case studies examined. While the list of contemporary commercial

URF cases studies can be seen as complete, the list of case studies that includes all functions is instead a sample of worldwide projects. The URF case studies had to fulfil a minimum set of criteria to be included in the further research. These criteria were: (i) the farm must have a minimum area of 100 m^2; (ii) it should be located on a rooftop; (iii) it should grow vegetables over more than 50% of its area; and (iv) it must currently (2015) be in operation.

The parameters in Table 2 were assessed for every case study. A detailed description of the classification of the parameter «Function» is shown in Table 3. The classification method is based on ZFarm [24] and Thomaier et al. [8].

Table 2. Parameters and values for to the case studies.

Parameter	Value
Location	Name of City, Country, Continent
Size of URF	Area in m^2
Commissioning	Year
Type	Open-air/Greenhouse
Function	Commercial/Life Quality/Image/Innovation/Education and Social

Table 3. Classification framework for functions of urban rooftop farms, according to ZFarm [24].

Parameter "Function"	Description
Commercial	- Main objective is selling produce to costumers - Farm is mainly run by paid workers
Life Quality	- Experience gardens for social activities and education - Farm is mainly run by volunteers - Produce is sold or consumed by the operators/volunteers
Image	- Produce for in-house hotel and restaurant kitchens - Commercial objectives: Image, marketing
Innovation	- Research into URF or other scientific fields of agriculture - Educational activities
Education and Social	- Farm is built on institution: school, hospital, retirement home - Objectives: food production, recreation and education

In order to illustrate the trends, visualizations were made using the R statistical software tool.

Next, the trends in commercial URFs were investigated in more detail. The literature stated that it has only been possible to realize URFs on a larger scale using soil-less techniques, such as hydroponics or aquaponics [15,18–20]. Therefore, it was of interest to find out which cultivation method is predominantly being used in practice, hydroponic or soil-based.

Given that hydroponic farms are not by nature environmentally sustainable [6], it was of interest to find out if, and to what extent environmentally friendly methods and technology are used to operate hydroponic farms. Firstly, a list of the considered methods/technologies was compiled (Table 4). Secondly, the frequency with which a method/technology was named (absolute frequency) was counted. One farm was able to implement several methods and technologies since they are not mutually exclusive.

Finally, the products produced and the methods used were investigated, since the product is what is sold at market and consequently generates revenue. It is essential for an operator that there is a buyer for the products and if not, that the systems allows for flexibility to produce products that meet the market's demands. For every commercial case study, the absolute frequencies of vegetable varieties and other products were determined by counting how often a type of product had been named. The products that were named more than once were illustrated in a bar plot that showed the most common URF products.

Table 4. Environmentally sustainable methods and technologies that can be applied in hydroponics.

Method/Technology	Description
Chemical Free Production	The cultivation process is free of chemical containing pesticides, fertilizers etc.
Energy Efficiency	The farm implements technologies and materials to increase energy efficiency such as LED lighting, highly insulating glass etc.
Renewable Energy	The farm uses renewable energy sources such as solar thermal, photovoltaic, wind etc.
Waste Heat	The farm uses waste heat from the building
Water Re-Use	Irrigation water is re-used, usually in a circulating system
Rainwater Collection	Rainwater is collected and used for irrigation
Greywater	Greywater from the building is used for irrigation
Recycling of Nutrients	Recycled nutrients are used instead of fertilizers
Exchange of Gases	The farm exchanges O_2 for CO_2 with the building

3. Results

The search for case studies resulted in 57 cases that fulfilled the criteria described in Section 2. Table 5 shows an overview of these. The complete list can be found in the Appendix A (Table A1).

Table 5. Summary of case studies for urban rooftop farms.

City	*N*	Country	*N*	Continent	*N*
New York	15	USA	30	North America	40
Chicago	7	Canada	10	Europe	11
Montreal	4	Netherlands	3	Asia	6
Toronto	3	Germany	2		
Boston	2	Switzerland	2		
Mumbai	2	Singapore	2		
Other	24	Other	8		
Area	**m^2**	**Year**			
Min.	121	Min.	1988		
1st Quartile	280	1st Quartile	2009		
Median	650	Median	2011		
Mean	3008	Mean	2009		
3rd Quartile	1800	3rd Quartile	2013		
Max.	60,000	Max.	2015		
Function	***N***	**Type**	***N***		
Commercial	15	Greenhouse	17		
Education/Social	11	Open-air	40		
Image	5				
Innovation	4				
Life Quality	22				

3.1. Overall Trends

New York is the city with the most URFs (15 rooftop farms and an installed area of 11.61 hectares), followed by Chicago (7 URFs, 1.06 ha) and Montreal (4 URFs, 0.82 ha). The trend is clearly coming from North America where 70% of the projects are currently located. 70% of the farms (40 farms) are open-air farms. The greatest percentage (39%, 22 farms) were built with the purpose of increasing quality of life. Interestingly, commercial operation is the second most frequent purpose of farms (26%, 15 farms). Commercial farms will be examined in more detail in Section 3.2.

Figure 2 shows a scatterplot with four variables. It illustrates how the number, sizes and types of URFs in each function category have developed over the years. The first farm started operations in 1988 in Asia. However, the trend has really only recently started to spread. Half of the farms started operation after 2011 (median = 2011). Commercial URFs have only been operating since 2010 and are generally larger than the URFs in the other categories. From the plot it can be seen that some functions favor either open-air or greenhouses. URFs in the Life Quality, Education/Social, and Image category are typically open-air farms. Innovation in the form of research is typically done in greenhouses, while commercial farms have both open-air and greenhouses.

Figure 3 shows the cumulative area over time of established URFs by continent. The graphic illustrates that North America does not only have the highest number of URFs, but also the largest installed area. However, Europe and Asia have also been installing new farms in the past years. URFs seem to be turning into a global trend.

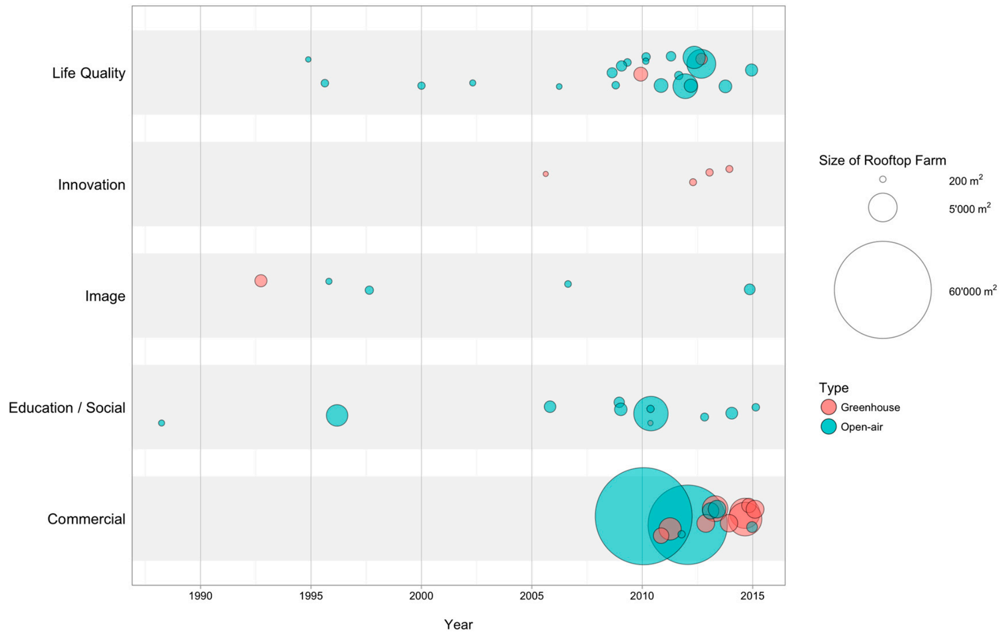

Figure 2. Development of size, type, and function of urban rooftop farms over time.

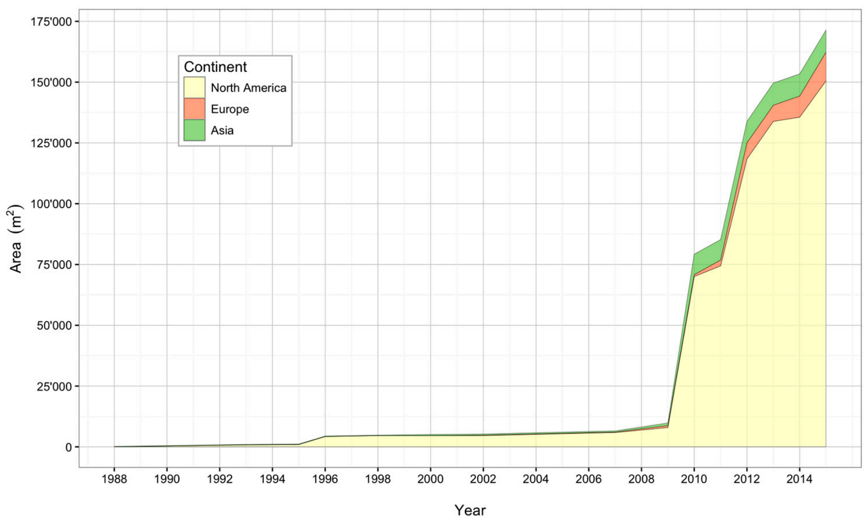

Figure 3. Total globally installed area of urban rooftop farms over time and by continent.

3.2. Commercial Rooftop Farms

From the total of 57 case studies, 15 were commercially operated. The complete table with further descriptive parameters for commercial URFs can be found in the Appendix A (Table A2).

Figure 4 shows the development of the cumulative area of URFs since 2010 when the first commercial farm (Brooklyn Grange [25]) started operations. Despite the fact that the graphic seems to suggest that there are more open-air farms than greenhouses, it is in fact just the opposite: there were only six open-air farms and nine greenhouse farms. Two very large open-air farms (Brooklyn Grange [25]), made up 96% of the open-air farm area that existed in 2015. The actual trend is moving towards greenhouses with hydroponic systems, with nine farms in operation in 2015. This is the type of farm that has grown the fastest since 2012. All commercial greenhouses are run using hydroponics, while all open-air farms are soil-based.

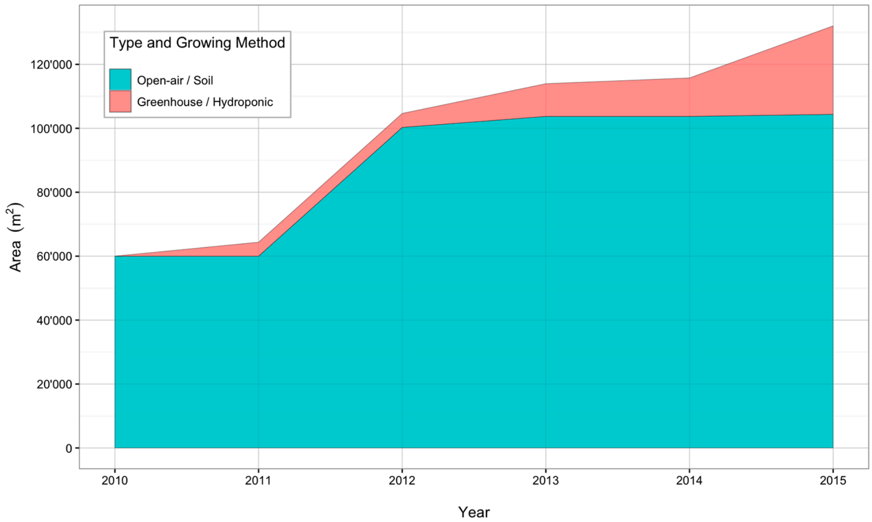

Figure 4. Development of cumulative area of commercial urban rooftop farms by type and method.

When looking at the development of the size of new hydroponic greenhouse farms, it can be seen that there has been a steady increase in the average size (Figure 5). The overall average size of a hydroponic farm is 3075 m^2.

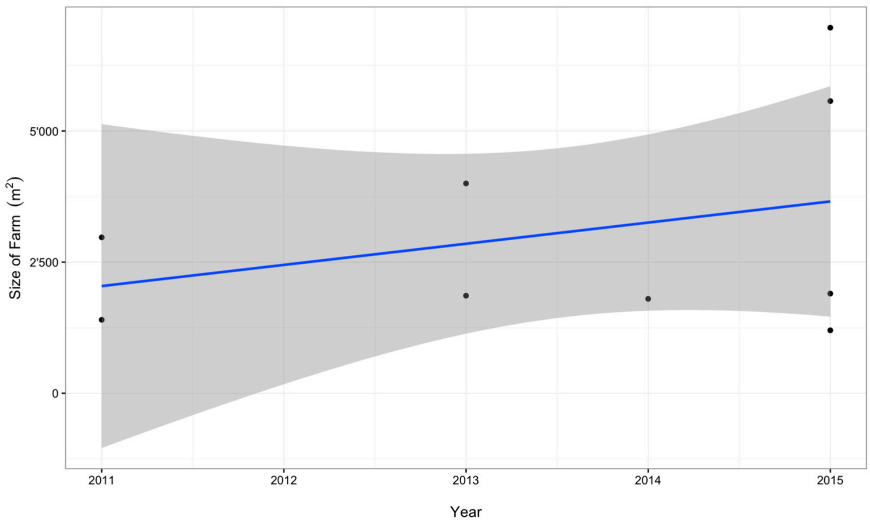

Figure 5. Sizes of new commercial hydroponic greenhouse farms over time, with regression line (blue) and confidence region (grey).

Given the increasing implementation of hydroponics, it is of interest to investigate whether further environmental sustainable technologies and methods have also been implemented in rooftop farms. Table 6 lists the absolute frequencies in the nine case studies of each technology/method. It can be seen that the case studies perform very well in terms of chemical free production, implementation of energy efficient measures and re-use of water in the hydroponic systems. Some farms implemented renewable energy production, rainwater collection, and recycling of nutrients in the form of aquaponics, however, there is still room for improvement. There is still untapped potential in terms of the exploitation of synergies between the building and the farm, such as the use of waste heat, the use of greywater and the exchange of gases (CO_2/O_2). None of the commercial hydroponic farms have applied any of these technologies.

Table 6. Application of environmentally sustainable technologies/methods in commercial hydroponic URF.

Technology/Method	Absolute Frequency (*n* = 9)	Share (%)
Chemical Free Production	9	100
Energy Efficiency	9	100
Renewable Energy	4	44
Waste Heat	0	0
Water Re-Use	9	100
Rainwater Collection	3	30
Use of Greywater	0	0
Recycling of Nutrients	3	33
Exchange of Gases	0	0

The search for the most common products resulted in a list of 13 products in total that were named more than once (Figure 6). Leafy greens, such as lettuce, chard, or pak choi are at the top of the list with 15 counts, followed by tomatoes (12 counts) and herbs (11 counts). Generally, the variety of products in open-air farms is larger than in hydroponic greenhouses. On average, an open-air farm cultivates 7.8 different products while a hydroponic greenhouse produces 4.6 different products. The combination of vegetable and fish production (aquaponics) has been implemented in three commercial farms, which are all located in Europe [26,27].

Figure 6. Most commonly produced products in commercial urban rooftop farms by growing method (hydroponic/soil).

4. Discussion

Many of the outcomes of the assessment of the case studies are in line with concepts and trends hypothesized in the literature. The analysis confirmed the trend towards commercialization of URFs with implementation of hydroponic farms in greenhouses that mainly grow leafy greens, tomatoes, and herbs, as was outlined in the literature [15,18–21]. In some cases, aquaponics (combination of fish and vegetable production in one water cycle) is also already being implemented on a commercial scale [26–28]. However, an interesting fact, not often mentioned in the literature, is that there are also a number of soil-based open-air farms that operate commercially. Yields from open-air farms are typically lower than those from hydroponics [13]. However, they have other advantages that they can exploit. They can grow larger varieties of products, such as root vegetables, fruits, cereals, and can even produce eggs and honey, which can attract other types of costumers. Furthermore, their production is more flexible, allowing them to adapt to the demands of the market. The fact that open-air farms are outside in the fresh air and that people can work with the soil, like on a "real farm", also attracts volunteers who are willing to work for free. In such cases, revenue might be lower, but there is still the possibility to realize a profit due to lower labor costs. These two models for operating commercial farms were also identified in general ZFarming by Thomaier et al. [8].

In terms of the environmental sustainability of hydroponics, the fact is that hydroponics is not unconditionally sustainable [6]. The review showed that nearly all operators of hydroponic farms have designed their farms with further environmentally friendly technologies and techniques. These improve the environmental sustainability of the farm, and also contribute towards a reduction in operational costs. However, there is a lot of room for improvement in terms of rainwater collection, renewable energy supplies, use of waste heat, use of greywater, recycling of nutrients, and exchange of gases. In particular, technologies that exploit synergies between buildings and farms have not been implemented in any commercial farms. Some non-commercial farms, however, do implement techniques for the use of waste heat from the building [29] or use greywater for irrigation [8,30]. To date, there has been very limited research within this new field of "synergetic BIA", where agriculture is not only physically but also systemically integrated into the building. There is a need for future research into the technical, conceptual, and financial feasibility of synergetic BIA.

All farms state that their crop cultivation is free of chemicals contained in pesticides, herbicides, etc. However, apart from these statements, there is very little published data about the implementation of plant protection in URF [31]. In most countries, hydroponics is not eligible for organic certification. These countries include Canada, Mexico, Japan, New Zealand, and 24 European countries, such as the Netherlands, the United Kingdom, Germany, Italy, France, Spain, and Switzerland. Currently, the United States is one of the few countries that allow hydroponics for organic certification [32]. The explanation for this is that some nutrients are mined and therefore not renewable. However, these nutrients have to be added into hydroponic solution because they appear naturally in soil and thus are not present in normal soil-fertilizers [33]. Nevertheless, the case studies demonstrate that even though they cannot be certified as organic, they still strive to implement the most sustainable cultivation methods possible. The issue of nutrient recovery is an important advantage for soil-based cultivation processes that can re-use organic waste for composting [10], even though there are also options for hydroponics to use recycled nutrients. The system can be extended to include aquaponics, where the waste from the fish production can be used as a fertilizer for the plants. Furthermore, effluents from anaerobic digestion of biomass can also be used as a fertilizer in hydroponic systems. This technology, however, is still at the pilot stage [34,35].

In terms of general trends in URFs of all functions, most of the case studies examined were located in large cities in North America, where the trend has been the strongest since 2009. New York is the leader in the development of URF. Caplow [13] calculated in 2009 that 5000 hectares of unshaped rooftop space in New York City is capable of cultivating vegetables for more than 30 million people, though only 0.23% of this area is currently used for cultivation.

In recent years, the trend in URF has become more global and is also spreading to Europe and Asia. However, the URF area in Europe and Asia is still small when compared to North America. This result may be explained by the fact that North American cities like New York are much larger than European cities. In large cities, it takes longer to reach the countryside from the city and therefore it is even more important to have outdoor activities in the city. In this case, rooftop farms provide a good opportunity and space for social and educational activities. Moreover, New York is an innovative city, which is home to many contemporary trends that spread from there to the rest of the world.

In the search for case studies, several urban farming projects in European cities were found that did not fit the basic criteria outlined in Section 2, and were therefore excluded from further analysis. Many European initiatives are urban farming or ZFarming projects, but are not located on a roof or do not grow vegetables on a substantial part of the roof [36,37]. Despite the fact that they could not be included in the list, they demonstrate that there are also many activities happening in this field in Europe.

In Asia, rooftop gardens have had a long tradition. Therefore, it was expected that more Asian case studies would have been found. However, it turned out to be very difficult to find online information in English about these projects. Most of the information was either in the local language or not published. Moreover, these traditional rooftop gardens are typically small-scale and therefore, for the most part, would not meet the minimum size of 100 m^2 necessary to be included in the list [38]. For further research on this topic, it is suggested that either the location of case studies be limited to North America and Europe or that people who know the local language undertake the research.

The application of certain criteria for the research on case studies has advantages and disadvantages. Due to the criterion that the URFs have a minimum area of 100 m^2, many small-scale projects were not included in the list. Thus, the presence of small-scale projects is not shown in this study. However, the choice of 100 m^2 appeared to be a good limit for distinguishing between "serious" URF and informal gardening on a rooftop.

Finally, it should be noted that all the information on case studies in this study was limited to what has been either published or is available online. Sometimes the available information was very vague. For example, when a farm listed what vegetables they grow; it was not always clear whether the list included all the vegetables or only the most important ones. Furthermore, the cultivated products can change over time and might not be updated on their website. The same holds true for the implementation of technologies (e.g., photovoltaic). If no information was found, it was assumed that the technology had not been implemented.

In conclusion, this study has been able to provide some quantitative evidence of common assumptions made in the literature. Theory predicted that hydroponic farms will be most suitable for commercial operations. However, practice shows that not only hydroponic farms but also soil-based farms can be run for-profit, due to certain advantages soil-based cultivation has over hydroponics. The numbers and figures underline that there is a strongly increasing trend in URF around the globe, especially in North America. The analysis showed that there is more research needed in order to improve the operation of hydroponic farms, by systemically integrating them into buildings and connecting the material and energy flows of the URF with the building they are located on. This will foster further innovation in terms of combined energy and food production, use of waste heat in buildings, combined greywater treatment, and food production. In addition, future research is needed to deepen on technical and economic aspects of commercial URF. These findings highlight the great potential for URF and show in which direction future developments might lead.

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Author Contributions: Devi Buehler and Ranka Junge conceived and designed the research. Devi Buehler performed the research, analyzed the data, and wrote the paper, with inputs from Ranka Junge. Both authors read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Complete list of case studies with the evaluated parameters.

No.	Name	City	Country	Continent	Area	Year	Type	Function	Ref.
1	Brooklyn Grange Flagship Farm	New York	US	North America	40,000	2012	Open-air	commercial	[25]
2	Brooklyn Grange Navy Yard Farm	New York	US	North America	60,000	2010	Open-air	commercial	[25]
3	Hell's Kitchen	New York	US	North America	380	2010	Open-air	life quality	[39]
4	Eagle Street Rooftop farm	New York	US	North America	560	2009	Open-air	life quality	[40]
5	Higher Ground Farm	Boston	US	North America	5110	2013	Open-air	life quality	[41]
6	HK Farm	Hong Kong	China	Asia	370	2012	Open-air	life quality	[42]
7	Lufa Farms Ahuntsic	Montreal	Canada	North America	2972	2011	Greenhouse	commercial	[33]
8	Lufa Farms Laval	Montreal	Canada	North America	4000	2013	Greenhouse	commercial	[33]
9	Gotham Greens Greenpoint	New York	US	North America	1400	2011	Greenhouse	commercial	[43]
10	Gotham Greens Gowanus	New York	US	North America	1860	2013	Greenhouse	commercial	[43]
11	Gotham Greens Hollis	New York	US	North America	5570	2015	Greenhouse	commercial	[43]
12	Gotham Greens Pullman	Chicago	US	North America	6970	2015	Greenhouse	commercial	[43]
13	Rooftop Greenhouse Lab (RTG-Lab)	Bellaterra	Spain	Europe	250	2014	Greenhouse	innovation	[2]
14	Community Rooftop Garden	Bologna	Italy	Europe	500	2011	Open-air	life quality	[2,44]
15	The Vinegar Factory	New York	US	North America	830	1993	Greenhouse	image	[29,45]
16	Arbor House at Forest Houses	New York	US	North America	740	2013	Greenhouse	life quality	[2,45]
17	Rye's Homegrown	Toronto	Canada	North America	930	2014	Open-air	life quality	[46]
18	ECF Farmer's Market	Berlin	Germany	Europe	1800	2014	Greenhouse	commercial	[28,47]
19	Rooftop Farm Ecco Jäger	Bad Ragaz	Switzerland	Europe	1200	2015	Greenhouse	commercial	[26]
20	The Science Barge	New York	US	North America	121	2006	Greenhouse	innovation	[13]
21	School Sustainability Laboratory	New York	US	North America	130	2010	Greenhouse	education and social	[13]
22	UF001 LokDepot	Basel	Switzerland	Europe	250	2012	Greenhouse	innovation	[27]
23	UF002 De Schilde	The Hague	Netherlands	Europe	1900	2015	Greenhouse	commercial	[27]
24	The Urban Canopy	Chicago	US	North America	280	2012	Open-air	commercial	[48]
25	Fairmont Royal York Hotel	Toronto	Canada	North America	370	1998	Open-air	image	[49]
26	Fairmont Waterfront Hotel	Vancouver	Canada	North America	195	1996	Open-air	image	[50]
27	Fenway Farms	Boston	US	North America	650	2015	Open-air	image	[51]
28	Whole Foods Market	Lynnfield	US	North America	1580	2013	Open-air	commercial	[49]
29	Rothenberg Rooftop Garden	Cincinnati	US	North America	790	2014	Open-air	education and social	[49]
30	The Visionaire Penthouse Green Roof	New York	US	North America	204	2010	Open-air	life quality	[49]
31	Khoo Teck Puat Hospital (KTPH)	Singapore	Singapore	Asia	7340	2010	Open-air	education and social	[49]
32	Gary Comer Youth Center Green Roof	Chicago	US	North America	760	2006	Open-air	education and social	[49]
33	Trent University Vegetable Garden	Peterborough	Canada	North America	2790	1996	Open-air	education and social	[49]

Table A1. *Cont.*

No.	Name	City	Country	Continent	Area	Year	Type	Function	Ref.
34	Changi General Hospital	Singapore	Singapore	Asia	185	1988	Open-air	education and social	[49]
35	Zuidpark	Amsterdam	Netherlands	Europe	3000	2012	Open-air	life quality	[52]
36	Bronxscape	New York	US	North America	300	2009	Open-air	life quality	[45]
37	Carrot Common Green Roof	Toronto	Canada	North America	300	1996	Open-air	life quality	[45]
38	Uncommon Ground restaurant	Chicago	US	North America	230	2007	Open-air	image	[45,53]
39	True Nature Foods' Victory Garden	Chicago	US	North America	160	2006	Open-air	life quality	[45]
40	Le Jardin sur le Toît	Paris	France	Europe	600	2009	Open-air	education and social	[45]
41	5th Street Farm Project	New York	US	North America	280	2010	Open-air	education and social	[45]
42	RISC Rooftop Forest "Forest Garden"	Reading	UK	Europe	190	2002	Open-air	life quality	[45]
43	Santropol Roulant	Montreal	Canada	North America	140	1995	Open-air	life quality	[45]
44	Gartendeck	Hamburg	Germany	Europe	1100	2011	Open-air	life quality	[54]
45	Via Verde	New York	US	North America	3720	2012	Open-air	life quality	[55]
46	Maison Productive	Montreal	Canada	North America	1110	2010	Greenhouse	life quality	[30]
47	Dakkaker	Rotterdam	Netherlands	Europe	1000	2012	Open-air	life quality	[56]
48	Florida State University	Tallahassee	US	North America	278	2013	Greenhouse	innovation	[57]
49	Hôtel du Vieux-Québec	Québec	Canada	North America	300	2009	Open-air	life quality	[58]
50	Up Top Acres at Elm and Woodmont	Bethesda	US	North America	650	2015	Open-air	commercial	[59]
51	Shagara at School	Cairo	Egypt	Middle East	340	2013	Open-air	education and social	[60]
52	Mumbai Port Trust Terrace Urban Leaves	Mumbai	India	Asia	280	2000	Open-air	life quality	[61]
53	Urban Leaves	Mumbai	India	Asia	600	2009	Open-air	life quality	[62]
54	Food Roof Farm	St. Louis	US	North America	840	2015	Open-air	life quality	[63]
55	Metro Atlanta Task Force Rooftop Garden	Atlanta	US	North America	900	2009	Open-air	education and social	[64]
56	McCormick Palace	Chicago	US	North America	1860	2013	Open-air	commercial	[65]
57	Roosevelt University	Chicago	US	North America	300	2015	Open-air	education and social	[66]

Table A2. Parameters for commercial farms.

No.	Growing Method	Products	Environmentally Sustainable Technologies/Methods
1	Soil	Leafy Greens, Pepper, Tomato, Kale, Chicory, Ground Cherries, Eggplant	-
2	Soil	Leafy Greens, Herbs, Carrot, Turnip, Radish, Beans, Honey, Eggs	-
7	Hydroponic	Leafy Greens, Microgreens, Tomato, Cucumber, Pepper, Eggplant, Herbs	Chemical Free Production, Energy Efficiency, Water re-use, Rainwater Collection
8	Hydroponic	Leafy Greens, Microgreens, Tomato, Cucumber, Pepper, Eggplant, Herbs	Chemical Free Production, Energy Efficiency, Water re-use, Rainwater Collection
9	Hydroponic	Leafy Greens, Tomato, Herbs	Chemical Free Production, Energy Efficiency, Water re-use, Renewable Energy
10	Hydroponic	Leafy Greens, Tomato, Herbs	Chemical Free Production, Energy Efficiency, Water re-use, Renewable Energy, Rainwater Collection
11	Hydroponic	Leafy Greens, Tomato, Herbs	Chemical Free Production, Energy Efficiency, Water re-use, Renewable Energy
12	Hydroponic	Leafy Greens	Chemical Free Production, Energy Efficiency, Water re-use, Renewable Energy
18	Hydroponic	Fish, Leafy Greens, Tomato, Cucumber, Pepper, Microgreens, Cabbage, Herbs	Chemical Free Production, Energy Efficiency, Water re-use, Recycling of Nutrients
19	Hydroponic	Fish, Leafy Greens, Herbs	Chemical Free Production, Energy Efficiency, Water re-use, Recycling of Nutrients
23	Hydroponic	Fish, Leafy Greens, Tomato, Pepper, Herbs, Microgreens	Chemical Free Production, Energy Efficiency, Water re-use, Recycling of Nutrients
24	Soil	Leafy Greens, Pepper, Tomato, Squash, Cucumber, Zucchini, Corn, Onions, Beet	-
28	Soil	Leafy Greens, Herbs, Tomato, Turnip, Eggplant, Carrot, Cucumber, Radish, Pepper, Zucchini, Fruits	-
50	Soil	Leafy Greens, Radish, Beet, Tomato, Microgreens, Carrot, Herbs	-
56	Soil	Leafy Greens, Pepper, Eggplant, Tomato, Radish, Carrot, Kale	-

References

1. Grewal, S.S.; Grewal, P.S. Can cities become self-reliant in food? *J. Cities* **2011**, *29*, 1–11. [CrossRef]
2. Sanyé Mengual, E. Sustainability Assessment of Rooftop Farming Using an Interdisciplinary Approach. Ph.D. Thesis, Autonomous University of Barcelona, Barcelona, Spain, 2015.
3. Cohen, N.; Reynolds, K.; Sanghvi, R. *Five Borough Farm: Seeding the Future of Orban Agriculture in New York City*; Design Trust for Public Space: New York, NY, USA, 2012.
4. Gardiner, M.; Prajzner, S.P.; Burkman, C.E.; Abro, S.; Grewal, P.S. Vacant land conversion to community gardens: Influences on generalist arthropod predators and biocontrol services in urban greenspaces. *Urban Ecosyst.* **2013**, *17*, 101–122. [CrossRef]
5. McClinton, N.; Cooper, J.; Khandeshi, S. Assessing the potential contribution of vacant lands to urban vegetable production and consumption in Oakland, California. *Landsc. Urban Plan.* **2013**, *111*, 46–58. [CrossRef]
6. Specht, K.; Siebert, R.; Hartmann, I.; Freisinger, U.B.; Sawicka, M.; Werner, A.; Thomaier, S.; Henckel, D.; Walk, H.; Dietrich, A. Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. *Agric. Hum. Values* **2014**, *31*, 33–51. [CrossRef]
7. Siebert, R. ZFarm—Zero Acreage Farming—Urban Agruculture of the Future. Available online: http://www.zalf.de/htmlsites/zfarm/Seiten/zfarmenglish/index.html (accessed on 27 September 2016).
8. Thomaier, S.; Specht, K.; Henckel, D.; Dierich, A.; Siebert, R.; Freisinger, U.B.; Sawicka, M. Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). *Renew. Agric. Food Syst.* **2015**, *30*, 43–54. [CrossRef]
9. Goldstein, B.; Hauschild, M.; Fernández, J.; Birkved, M. Testing the environmental performance of urban agriculture as a food supply in northern climates. *J. Clean. Prod.* **2016**, *135*, 984–994. [CrossRef]
10. Grard, B.J. Recycling urban waste as possible use for rooftop vegetable garden. *Future Food J. Food Agric. Soc.* **2015**, *3*, 21–34.
11. Sanyé-Mengual, E.; Oliver-Solà, J.; Montero, J.; Rieradevall, J. An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. *Int. J. Life Cycle Assess.* **2015**, *20*, 350–366. [CrossRef]
12. Sanyé-Mengual, E.; Orsini, F.; Oliver-Solà, J.; Rieradevall, J.; Montero, J.; Gianquinto, G. Techniques and crops for efficient rooftop gardens in Bologna, Italy. *Agron. Sustain. Dev.* **2015**, *35*, 1477–1488. [CrossRef]
13. Caplow, T. Building integrated agriculture: Philosophy and practice. In *Urban Futures 2030: Urban Development and Urban Lifestyles of the Future*; Heinrich Böll Foundation, Ed.; Heinrich Böll Foundation: Berlin, Germany, 2009; pp. 54–58.
14. Ackerman, K. *The Potential for Urban Agriculture in New York City: Growing Capacity, Food Security, and Green Infrastructure*; Urban Design Lab, Earth Institute, Columbia University: New York, NY, USA, 2011.
15. Astee, L.Y.; Kishnani, N.T. Building integrated agriculture: Utilising rooftops for sustainable food crop cultivation in Singapore. *J. Green Build.* **2010**, *5*, 105–113. [CrossRef]
16. ZinCo. Green Roof and Solar Energy Projects. Available online: http://www.zinco-greenroof.com/EN/references/green_roofs_solar_energy.php (accessed on 14 July 2016).
17. Lovell, S.T. Multifunctional urban agriculture for sustainable land use planning in the United States. *Sustainability* **2010**, *2*, 2499–2522. [CrossRef]
18. Despommier, D. *The Vertical Farm: Feeding the World in the 21st Century*; Thomas Dunne Books: New York, NY, USA, 2010.
19. Nowak, M. Urban Agriculture on the Rooftop. Master's Thesis, Cornell University, Ithaca, NY, USA, 2004.
20. Rodriguez, O. London Rooftop Agriculture: A Preliminary Estimate of Productive Potential. Master's Thesis, Welsh School of Architecture, Cardiff, UK, 2009.
21. Puri, V.; Caplow, T. How to Grow Food in the 100% Renewable City: Building-Integrated Agriculture. In *100% Renewable: Energy Autonomy in Action*; Earthscan: London, UK, 2009; pp. 229–241.
22. Graber, A.; Schoenborn, A.; Junge, R. Closing water, nutrient and energy cycles within cities by urban farms for fish and vegetable Production. *Int. Water Assoc. Newsl.* **2011**, *37*, 37–41.
23. Ellingsen, E.C.; Despommier, D. The vertical farm—The origin of a 21st century architectural typology. *CTBUH J.* **2008**, *2008*, 26–34.

24. Siebert, R.; Freisinger, U.B. *Es Wächst Etwas auf dem Dach*; Guidebook; Leibniz-Zentrum für Agrarlandschaftsforschung: Müncheberg, Germany, 2013.
25. Brooklyn Grange. Available online: http://www.brooklyngrangefarm.com (accessed on 30 March 2016).
26. Ecco-jäger, Früchte und Gemüse AG. Available online: http://www.ecco-jaeger.ch (accessed on 30 March 2016).
27. Urban Farmers—Projects. Available online: http://urbanfarmers.com/projects (accessed on 30 March 2016).
28. ECF Farmsystems GmbH. Available online: http://www.ecf-farmsystems.com/en/ (accessed on 30 March 2016).
29. Eli Zabar. Available online: http://www.elizabar.com (accessed on 30 March 2016).
30. Maison Productive House. Available online: http://www.produktif.com/designs-developments/maison-productive-house-mph/ (accessed on 30 March 2016).
31. Bittsánszky, A.; Gyulai, G.; Junge, R.; Schmautz, Z.; Komives, T. Plant protection in ecocycle-based agricultural systems: Aquaponics as an example. In Proceedings of the International Plant Protection Congress (IPPC), Berlin, Germany, 24–27 August 2015.
32. Dixon, L. Is Hydroponics Organic? Cornucopia Institute. Available online: http://www.cornucopia.org/2015/03/hydroponics-organic/ (accessed on 14 July 2016).
33. Lufa Farms. About the Farm. Available online: https://montreal.lufa.com/en/about-the-farm (accessed on 30 March 2016).
34. Davis, S.; Kauneckis, D.; Kruse, N.; Miller, K.; Zimmer, M.; Dabelko, G. Closing the loop: Integrative systems management of waste in food, energy, and water systems. *J. Environ. Stud. Sci.* **2016**, *6*, 11–24. [CrossRef]
35. Goddek, S.; Schmautz, Z.; Scott, B.; Delaide, B.; Keesman, K.; Wuertz, S.; Junge, R. The effect of anaerobic and aerobic fish sludge supernatant on hydroponic lettuce. *Agronomy* **2016**, *6*, 37. [CrossRef]
36. Lauer, A. 10 Urban Agriculture Projects in Berlin. Available online: http://foodtank.com/news/2014/03/ten-urban-agriculture-projects-in-berlin-germany (accessed on 14 July 2016).
37. Hamburg.de. Urban Gardening in Hamburg. Available online: http://www.hamburg.de/stadtleben/4127050/urban-gardening/ (accessed on 14 July 2016).
38. Bryld, E. Potentials, problems, and policy implications for urban agriculture in developing countries. *Agric. Hum. Values* **2003**, *20*, 79–86. [CrossRef]
39. Hell's Kitchen Farm Project. Available online: http://www.hkfp.org (accessed on 30 March 2016).
40. Eagle Street Rooftop Farm. Available online: http://www.rooftopfarms.org (accessed on 30 March 2016).
41. Higher Ground Farm. Available online: http://www.highergroundrooftopfarm.com (accessed on 30 March 2016).
42. HK Farm. Available online: http://www.hkfarm.org (accessed on 30 March 2016).
43. Gotham Greens. Available online: http://www.gothamgreens.com/our-farms (accessed on 30 March 2016).
44. Greenhousing. A Community Garden on the Rooftops of Bologna. Available online: http://www.rescue-ab.unibo.it/website/en/project-Greenhousing.php (accessed on 30 March 2016).
45. Carrot City. Rooftops. Available online: http://www.ryerson.ca/carrotcity/rooftops.html (accessed on 30 March 2016).
46. Rye's Homegrown. Available online: http://www.ryeshomegrown.wordpress.com/about/ (accessed on 30 March 2006).
47. Uhlmann, S. Frisch vom Dach. 2014. Available online: http://www.sueddeutsche.de/wirtschaft/bauer-sein-in-der-stadt-frisch-vom-dach-1.1878095 (accessed on 30 March 2016).
48. The Urban Canopy. Available online: http://www.theurbancanopy.org/vision (accessed on 30 March 2016).
49. The Greenroof and Greenwall Projects Database. Available online: http://www.greenroofs.com/projects/ (accessed on 30 March 2016).
50. Fairmont Waterfront Eco Hotel. Available online: http://www.fairmont.com/waterfront-vancouver/dining/herbgardenhoneybees/ (accessed on 30 March 2016).
51. Green City Growers. Available online: http://www.greencitygrowers.com/fenway-farms/ (accessed on 30 March 2016).
52. Biotope City. URBAN FARMING & BUREAUS: "Zuidpark" in Amsterdam. Available online: http://www.biotope-city.net/gallery/urban-farming-bureaus-zuidpark-amsterdam (accessed on 30 March 2016).
53. Uncommon Ground. Roof Top Farm. Available online: http://www.uncommonground.com/roof-top-farm (accessed on 30 March 2016).
54. Gartendeck. Available online: http://www.gartendeck.de (accessed on 30 March 2016).

55. Philipps Houses & Jonathan Rose Companies. Via Verde—The Green Way. 2012. Available online: http://libweb1.lib.buffalo.edu/bruner/year/2013/ViaVerde/Application/ViaVerde.pdf (accessed on 30 March 2016).
56. Luchtsingel. Roof Garden. Available online: http://www.luchtsingel.org/en/locaties/roofgarden/ (accessed on 30 March 2016).
57. Indiana University Bloomington. BioNews: Winter 2013–14. Available online: http://www.bio.indiana.edu/alumni/newsletters/13Winter/jh_renovation.shtml (accessed on 30 March 2016).
58. Les Urbainculteurs. Hôtel du Vieux-Québec. Available online: http://www.urbainculteurs.org/en/hvq (accessed on 30 March 2016).
59. Clabaugh, J. Forget Gardens. This Bethesda Rood Is a Farm. *Wash. Bus. J.* **2015**. Available online: http://www.bizjournals.com/washington/news/2015/09/17/forget-gardens-this-bethesda-roof-is-a-farm.html (accessed on 30 March 2016).
60. Laylin, T. Rooftop Farm in Egypt Finally Trumps Red Tape. 2013. Available online: http://www.greenprophet.com/2013/02/shagara-rooftop-farm-egypt-red-tape/ (accessed on 30 March 2016).
61. Zeller, K. Urban Leaves Blossoming on a Concrete Backdrop. RESET—Smart Approaches to Sustainability. 2013. Available online: http://www.en.reset.org/blog/urban-leaves-blossoming-concrete-backdrop (accessed on 30 March 2016).
62. Sriram, J. Rooftop Farmers Reap Rich Harvest. 2015. Available online: http://www.thehindu.com/news/cities/mumbai/news/rooftop-farmers-reap-rich-harvests/article7954312.ece (accessed on 30 March 2016).
63. Food Roof Farm. Available online: http://www.urbanharveststl.org/food-roof-farm/ (accessed on 30 March 2016).
64. Our Rooftop Garden! Available online: http://www.atlantataskforceforhomeless.org/roof-top-garden-watch-us-grow/ (accessed on 30 March 2016).
65. Firozi, P. Rooftop Farms Appealing, but Will They Catch on? 2015. Available online: http://www.chicagotribune.com/news/local/breaking/ct-rooftop-farms-met-20150610-story.html (accessed on 30 March 2016).
66. Hustad, K. Want to Check out Roosevelt's Sustainability Innovation? Look up. 2015. Available online: http://www.chicagoinno.streetwise.co/2015/07/20/urban-farming-roosevelt-university-utilizes-vertical-space/ (accessed on 30 March 2016).