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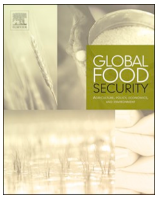

The second green revolution: Innovative urban agriculture's contribution to food security and sustainability – A review

Dian T. Armanda[a,b,*], Jeroen B. Guinée[a], Arnold Tukker[a,c]

[a] *Department of Industrial Ecology, Institute of Environmental Sciences (CML), Leiden University, Van Steenisgebouw, Einsteinweg 2, 2333, CC Leiden, the Netherlands*
[b] *Department of Biology, Faculty of Science and Technology, Walisongo State Islamic University, Jl. Prof. Dr. Hamka, Ngaliyan, Semarang, Indonesia*
[c] *Netherlands Organisation for Applied Scientific Research, Anna van Buerenplein 1, 2595, DA Den Haag, the Netherlands*

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ABSTRACT

Since 2010, advances in scientific knowledge and innovative agricultural technology have revitalized urban agriculture (UA) into innovative urban agriculture (IUA). The continuous intensification of IUA could lead to a Second Green Revolution, which aims to meet the current and future food demand. Here, we review the emerging IUA practices and estimate the contribution of IUA to food security and environmental sustainability by limitedly comparing scientific literature and actual data of eighteen practitioners worldwide. The currently most productive IUA practice can produce up to 140 kg vegetables per m^2/year. Various scales of IUA potentially contribute to global food security by supporting local food supply, strengthening the food value chain, and applying more sustainable practices than conventional agriculture. Further comprehensive life cycle assessments of IUA are needed, especially in developing countries, to prevent an increase of the environmental burden and to balance the interests of people, planet, and profit.

1. Introduction

The period of the Green Revolution (GR) (1960–2000) marked an extraordinary era of increased global food security. The period was characterized by a tremendous increase in world food production and distribution, especially of grains such as wheat, rice, and maize, due to intensification of rural agriculture. Intensification was achieved by means of a combination of high crop research investment rates, agricultural expansion, mechanization, and massive use of synthetic fertilizers, pesticides, and genetically improved high-yielding varieties (HYV) of crops (Pingali, 2012; Shiva, 1993). Although the population had doubled, the production of cereal had tripled with only 30% increase in farm area (Wik et al., 2008). While the GR benefited consumers in general thanks to lower food prices, several agrarian developing countries experienced adverse side effects through the decrease in ecosystem quality due to environmental degradation and biodiversity loss (Shiva, 1993; Tyagi, 2016).

Complementary to rural agriculture (RA), the concept of urban agriculture (UA) as a food security solution evolved over centuries along with the growing global population and increasing urbanization. Urban agriculture is defined as the production, process, and distribution of food and other products by plant and/or livestock raised in and around cities to meet local needs (Game and Primus, 2015). In 2050, approximately 68% of the world's population is expected to live in cities, and by then, agriculture will need to produce almost 50% more food than in 2012 to meet the needs of around 9.73 billion people (ESA UN, 2018a; FAO, 2017).[1] Consequently, UA is increasingly considered to also become an important contributor to future urban food security.

UA's contribution to food security is currently provided by 100–200 million urban farmers worldwide who produce and market fresh agricultural products (Orsini et al., 2013). UA initiatives claim to contribute to food resilience (Barthel and Isendahl, 2013), reduce food miles and reduce economic pressure among the poorest due to self-sufficiency (Orsini et al., 2013; Poulsen et al., 2015) and creates job (Golden, 2013). UA practices claim to support education (Duncan et al., 2016), community health (Armstrong, 2000; Dennis and James, 2017), empowerment of women (Poulsen et al., 2015), and urban beautification (Lindemann-Matthies and Brieger, 2016).

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[*] Corresponding author. Department of Industrial Ecology, Institute of Environmental Sciences (CML), Leiden University, Van Steenisgebouw, Einsteinweg 2, 2333, CC Leiden, the Netherlands.

E-mail address: d.dian.triastari.armanda@cml.leidenuniv.nl (D.T. Armanda).

[1] These cities' population estimations are based on the U.N. statistics, compiled from the proportion of the population living in urban areas reported by its 233 member countries (ESA UN, 2018b). However, there is no universal definition of urban, and thus every country defines urban differently and collects data according to its own definition.

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Nevertheless, UA continuously faces land insecurity issues due to competitive land use (FAO, 2007), pollution risks from the urban ecosystem to agriculture and the other way around (Mok et al., 2014), contamination of food products by heavy metals and organic chemicals (Russo et al., 2017), and increasing health issues due to sanitation (Cofie et al., 2005) and vector diseases (Hamilton et al., 2014).

Attempts to resolve these challenges have led to advances in scientific knowledge and innovative agricultural technology, which allowed the common UA practices to evolve into the present innovative urban agriculture. UA has been categorized into two spheres: Uncontrolled Environment Agriculture (UEA) and Controlled Environment Agriculture (CEA) (Game and Primus, 2015). UEA comprises open space vegetable gardens, rooftop gardens, and community gardens, which are commonly stated to play a role in food security in cities worldwide. In contrast, CEA includes agriculture practices that apply environmental optimization, commonly in conjunction with surrounding urban structures. Examples are greenhouses, indoor farming, vertical farming, and building-integrated agriculture (BIA) (Al-Kodmany, 2018; Game and Primus, 2015). For this article, we defined innovative urban agriculture as urban agriculture that optimizes food production (minimizing maintenance and resources whilst maximizing yield) by involving at least one of the recent technological innovations in their methods, irrespective of whether it concerns an open or closed system (Al-Kodmany, 2018; Benis and Ferrão, 2018; Game and Primus, 2015; Gwynn-Jones et al., 2018). These innovations include indoor agriculture, remote sensing, vertical agriculture, hydroponic, aeroponic, aquaponic and soilless agriculture, precision agriculture, and other novel technologies.

We found a rapid increase in the number of publications related to urban agriculture and innovations since 2010 (we provide an extensive historical overview of the Green Revolution and the emergence of innovative urban agriculture in Supplementary Information 1.1). This suggests that innovative urban agriculture has developed rapidly since 2010, which could be related to the global economic and food price crises of 2008. Therefore, we propose using the term “innovative urban agriculture” (abbreviated as IUA) to distinguish this modernized type of UA from conventional UA.

Despite the continuous debates about the sustainability of the current UA practice, the potential intensification of IUA is worth more attention in view of lessons learned from the Green Revolution (GR 1.0) and the increasingly complex food security challenges (FAO, 2017; Pingali, 2012). The potential intensification of IUA is similar to the intensification of RA during GR 1.0 and history may potentially repeat itself as the Second Green Revolution (GR 2.0). GR 1.0 was also characterized by the introduction of novel technologies and new desired food species, but also by massive commercialization of agricultural goods (not only food) and services, requiring more resources, leading to a higher energy dependency and requiring higher capital investments than before with related increased environmental impacts (see SI 1). IUA may potentially constitute a GR2.0 with similar characteristics. We should thus deliberately consider the environmental sustainability of IUA practices, keeping in mind the drawbacks of GR 1.0 (Tyagi, 2016).

2. Methods

Although many historical reviews claimed the positive contribution of UA to food security throughout several centuries (Hamilton et al., 2014; Lawson, 2016; Mok et al., 2014) and even millennia (Barthel and Isendahl, 2013), the potential contribution of IUA to food security is still questioned. Since around 2010, some IUA companies have attempted to capture vast, untapped market opportunities with more sustainable production of healthier and fresher food (Al-Kodmany, 2018). Some scientific systematic reviews and scoping studies were published on the contribution of IUA food production systems to sustainability used IUA-related terms: commercial UA, vertical UA, or edible green infrastructure (Al-Kodmany, 2018; Benis and Ferrão, 2018; Russo et al., 2017). So far, however, no publication has summarized and compared realistic production scales of IUA to common UA and drafted recommendations for preventing adverse environmental claims and impacts of IUA.

This systematic review aims to do so by clarifying the potential contributions of IUA as a complement of UA in their complex variability concerning food security and environmental sustainability. The main research question was whether the current IUA as a food production system can complement UA and contribute significantly to food security and environmental sustainability. We broke this main question down into three sub-questions:

1. What are realistic production scales for the current IUA practices?
2. To what extent can IUA contribute to global food security?
3. What is known about the environmental sustainability of the current IUA practices?

We try to answer these sub-questions by 1) providing a summary of actual food production information from some IUA practitioners worldwide; 2) reviewing (comparing and contrasting, validating, and concluding) food production functions of IUA and UA (and RA) from a food security and an environmental perspective.

Although the term “innovative urban agriculture” (IUA) has not been used in common references, we found updates on recent developments of IUA projects in various forms, including scientific publications, news articles, reports, websites and blogs. This article combines all these materials to answer the above-mentioned questions. We adopted a qualitative informative approach, studying more than 100 sources, mainly from scientific articles, books, and websites to conduct this review. We examined recent scientific literatures from Google Scholar and Web of Science Databases, dating 2010–2018 (the Boolean search information is available in Supplementary Information 1.2). We included every IUA publication that provided actual production information. For the actual production information, we selected eighteen of all the IUA practitioners worldwide that: (1) apply innovation in their UA, (2) have a significant scale to represent IUA development (commercial scale, preferably), (3) are still operating, or have operated in the past, and (4) provide production information that is accessible and written in English. We adapted PRISMA guideline to ensure the transparent reporting of this review (see Supplementary Information 2) (PRISMA, 2015).

Without denying the importance of other functions of UA, our discussion here is limited to IUA's food production potential on a global scale. Amongst all dimensions of food security, IUA as a food production system is mostly related to food availability. Therefore, estimations of the global IUA (and UA) production potential was reviewed based on relevant indicators for food availability: global production amount, coverage of the food basket, agricultural area, and number of practitioners. Information regarding the current global food status and the trends and challenges of four food security dimensions is provided in Supplementary Information 1.1.

Regarding the environmental sustainability of current IUA practices, we reviewed their use of technology and related environmental aspects. While the FAO distinguishes four important sub-sectors of agriculture (crop farming, fisheries and aquaculture, livestock, and forestry), our discussion and case study focus on food crop production only.

3. Potential contribution of IUA to food security

This section addresses the realistic production scales of IUA and to what extent it can contribute to food security. We present a summary of the actual food production information of IUA practitioners that independently extracted from various sources, discuss IUA's and UA's realistic production scales, and determine their position in the global food production system.

Table 1
Recent food production of innovative urban agriculture practitioners worldwide.

	Farm	Location	Starting year/status	Food product	Production capacity	Agricultural area	Consumer
1	Farm 360	Indianapolis, Indiana, The US [1.1]	n/a/in operation	35 types of greens (mint, kale, lettuce, spinach, chard, arugula, etc.)	82,000 plants/month	use abandoned warehouse Growing area: 5667.08 m^2	restaurants, schools, grocery store
2	80 Acres Farms	The US (5 farms)	n/a/in operation	herbs, vine crops, microgreens, leafy greens, fruits	90,718.4 kg/year (in Cincinnati) [2.2]	uses abandoned warehouse and 2 shipping containers (Cincinnati) Growing area: 1114.8 m^2 [2.2]	grocery store and restaurants
3	Gotham Greens	The US, 4 farms: 2 in Brooklyn New York, 1 in Queens New York, 1 in Chicago [3.1]	2011/in operation	various leafy vegetables, tomatoes, herbs	136 tons of leafy greens from 2 Brooklyn farms + 15 million heads of leafy greens and herbs from 2 other farms	Growing space: 15,793.5 m^2 (total of the four farms)	retailers, restaurants
4	Green Girls Produce	Memphis, Tennessee, The US [4.1]	2012/in operation	microgreens	22.67 kg/week [4.1] 45.3 kg/day [4.2]	Uses the fourth floor of a 5574 m^2 building Growing space: 232 m^2 [4.2]	local restaurants
5	Aerofarms	The US, 9 farms, centered in Newark, New Jersey. The largest farm in Newark, New Jersey [5.1], expansion to Saudi Arabia [5.2]	2004, the largest farm in Newark started in 2015/in operation	leafy greens, has grown over 700 different crops to date	907,184 kg/year (the largest farm), 390 times higher/m^2 than conventional farming [5.3]	Underground, Growing space: 6503.21 m^2 (the largest farm) [5.3]	grocery stores, restaurants
6	FarmedHere	The US, 3 farms in Chicago, Illinois: Englewood, Flanagan, Bedford Park [6.1]	2011/no longer operated since 2017 [6.2]	fish (Tilapia) and leafy vegetables: basil, arugula, mints, watercress, microgreens, etc. Received the USDA Organic Certification	136,078 kg of leafy greens/year (Bedford Park)	71 m^2 in Englewood, 929 m^2 in Flanagan, 8361 m^2 in Bedford Park Total growing space: 13,935 m^2 [6.3]	100 grocery stores in Chicago [6.4]
7	The Plant	Chicago, Illinois, The US [7.1]	2016/in operation	greens, mushrooms, bread, and Kombucha tea	226.7 kg oyster mushroom/week [7.2]	Horizontal area: 8686 m^2 (eks-meatpacking facility) Vertical area: four-story building	"The Plant" farmstand
8	Brooklyn Grange	The US, 2 farms: Brooklyn and Queens [8.1]	2010/in operation	40 varieties of organic produce: microgreens, tomatoes, peppers, fennel, salad greens,kale, Swiss chard, beans, beets, carrots, and radishes, herbs. Also produce hot sauce and honey	22,679.6 kg/year	Growing space: 8093 m^2 (total of the two farms)	farmer markets [8.2]
9	Green Spirit Farms	The US, 2 farms: New Buffalo, Michigan & East Benton, Pennsylvania [9.1]	2013 (commercial start)/in operation	lettuce, basil, spinach, kale, arugula, peppers, tomatoes, stevia, strawberries, and Brussel sprouts (New Buffalo), herbs, leafy vegetables, tomato, peppers (East Benton)	3175 kg/month (New Buffalo) [9.2]	3716 m^2 (New Buffalo). 1715 vertical growing stations that produce same amounts of food as 81 ha of conventional farmland (East Benton)	grocery store, restaurants, direct selling from farm (New Buffalo), market with maximum 75 miles away from the farm (East Benton)
10	Growing Underground	London, The UK [10.1]	2012/in operation	microgreens, salad leaves, herbs	700 boxes of microgreens/day	uses two vast former air-raid shelters (semicircular bunker) - underground Growing area: 550 m^2	local markets
11	La Caverne	Paris, France [11.1]	2017/in operation	organic certified product, mushrooms, microgreens, chicory [11.2]	300 kg chicory/month [11.3]	Underground, uses two level parking lot Growing area: 3600 m^2 [11.2]	markets, restaurants, home delivery service
12	UrbanFarmers AG	De Schilde, Den Haag, The Netherlands [12.1]	May 2016/no longer operated since July 2018 [12.2]	tomatoes, vegetables, microgreens, fish (tilapia)	50,000 kg of vegetables, 20,000 kg of fish/year	Uses 3 floor of the 7 story abandoned factory building Growing area: 1200 m^2 greenhouse, 900m^2 fish tank [12.3]	restaurants and wholesale
13	PlantLab	Den Bosch, The Netherlands [13.1]	2006 (R&D start); 2010 (commercial start)/in operation	vegetables, tomatoes, herbs [13.2]	produce three times of the best greenhouse production, or up to 40 times of the open field production	Horizontal area: 18,580 m^2 underground	supermarkets, restaurants
14	Badia Farms	Dubai, UAE [14.1]	2017/in operation	18 varieties of microgreens	n/a	Growing space: 789.6 m^2	over 30 clients including hotels and restaurants

(*continued on next page*)

Table 1 (*continued*)

	Farm	Location	Starting year/status	Food product	Production capacity	Agricultural area	Consumer
15	Nuvege	Kyoto, Japan [15.1]	n/a/in operation	lettuce [15.2]	6 million lettuces/year [15.2]	Horizontal: 2787 m^2 Vertical: 5295 m^2 [15.3]	restaurants, tourist destinations [15.2]
16	Sky Greens	Singapore [16.1]	2009 (R&D start); 2012 (commercial start)/in operation	tropical vegetables: Chinese cabbage, Spinach, Lettuce, Nai Bai, Cai Xin, Xiao Bai Cai, Mao Bai, Bayam, Kai Lan, Kang Kong	1000 kg/day produce ten times of the conventional farming production [16.2]	A-frame occupies 5.6 m^2 horizontal area, 9 m vertical area (including 38 tiers of growing troughs)	exclusively sold at Fairprice Finest Store
17	Pasona O2	Tokyo, Japan [17.1]	2010/no longer operated since 2017	200 species: fruits (oranges, tomatoes), vegetables (leafy greens, broccoli), rice (model farm/not for commercial use) [17.2]	n/a	19,974 m^2, 9 story office building Growing area: 3994.8 m^2 [17.2], 929 m^2 [17.3]	own cafeterias
18	iFarm	Taoyuan's Luchu, Taiwan [18.1]	n/a/in operation	30 varieties of vegetables, including arugula, ice plant, and mustard leaf	produces over 100 times what a traditional farm could with only a tenth of the water.	Horizontal area: 2645 m^2 Vertical area: 14 story vertical farm	n/a

3.1. *The actual food production of IUA practitioners worldwide*

In this sub-section, a compilation of actual food production data of eighteen IUA practitioners worldwide is presented in two tables: food production (Table 1) and technology use (Table 2). Table 1 shows the names of practitioners, location, food product, actual production capacity, farming area, and consumers, while Table 2 shows the technology applied and related environmental efforts. We gathered these data from more than 40 news media and websites and often identified inconsistencies in the available information, particularly in quantitative information.

In summary, all the eighteen practitioners apply indoor vertical farming, and no information from Australia and Africa is available. Nine practitioners are from the US, and all together operate at least 28 farms throughout the country; four practitioners are from Europe, and five from Asia. Although some practitioners started their R&D before 2010, most of them started the commercialization around 2010. At least four farms were built underground, four farms reutilized an abandoned building, a parking lot, or a bunker, and four farms utilized rooftop areas. Their main food products were leafy vegetables and microgreens, followed by herbs, fruits, mushrooms, chicory, fish, and honey. Some practitioners also produced processed food, such as bread, kombucha tea, sauce, or salad mix. The highest actual annual food productivity is estimated to be achieved by Aerofarms, which applied aeroponics with a production capacity of up to almost 140 kg/m^2 (data from the largest farm). Other productive farms include the '80 Acre Farm' with about 81 kg/m^2/year, 'UrbanFarmers AG' with 41 kg/m^2/year, and 'FarmedHere; with 16 kg/m^2/year. However, the two latter farms, which both applied aquaponics, were no longer operational. Ten practitioners applied hydroponics, three applied aquaponics, two farms applied aeroponics, and two farms preserved soil-based farming. Most of the practitioners mentioned the advantage of this hydroponics, namely 90–95% less water use than conventional farming, and less or no use of pesticides, insecticides, and fungicides. Thirteen farms used LED growlight to optimize their production, and at least two farms used 100% renewable energy.

3.2. *Realistic production scale of IUA and position of UA and IUA in the global food production system*

This sub-section discusses the realistic production scale of IUA and UA in relation to the global food demand. At the national scale, the potential of IUA as food production function in developed and developing countries are different. Table 3 shows that UA in developing and developed economies is practiced for different reasons. Urban farmers in emerging economies tend to rely on UA to meet personal and local market needs, while the primary mission of many UA farmers in developed economies is to achieve social goals rather than supplying food (Poulsen et al., 2015; Rogus and Dimitri, 2015). Therefore, as the future population growth is expected to be higher in developing economies (particularly in Africa and Asia), UA may still have significant potential to contribute to local food security in these countries, mainly by contributing to food access of the poor. This expectation aligns with the fact that the poor in these countries spend up to 85% of their revenues on food (Orsini et al., 2013).

3.2.1. *Potential global production amount*

To date, there is no publication on actual global UA production rates. A previous estimation showed that UA provided 15–20% of the world's food in 1993, complementary to RA (Armar-Klemesu, 2001). UA production rates in developing countries are difficult to estimate since most of these farms and markets are small-scale and informal (Orsini et al., 2013) and most of the traditional horticultural food crops are poorly considered in national statistics (FAO, 2003). Nevertheless, in 2010, Zezza and Tascioti made the first estimation by gathering representative data from 15 developing countries and found that the

Table 2
Technology use and environmental efforts of the recent innovative urban agriculture practitioners worldwide.

	Farm	Location	Applied technology								Other technology	Environmental aspects
			Soil based	Hydroponic	Aeroponic	Aquaponic	Greenhouse/ Indoor farming	Vertical farming	Rooftop farming	Precision, automation		
1	Farm 360	The US		●			●	●		●	LED grow light [1.1]	
2	80 Acres Farms	The US (5 locations)		●			●	●		●	LED-driven vertical farm [2.2]	no GMO seeds, no pesticides, 100% renewable energy, 90% less water than traditional farming
3	Gotham Greens	The US (4 locations)		●			●	●	●	●	LED grow light application increased production and shortened grow cycle, energy saving innovations [3.1]	Using 95% less water than field farming and 40% less than common hydroponics. Grows 390 times more produce than field farming, 80% less fertilizer than field farming, no harmful pesticides, herbicides or fungicides
4	Green Girls Produce	The US		●			●	●		●	LED grow light [4.1]	
5	Aerofarms	The US (9 locations)			●		●	●			organic seeds, LED growlight, patented reusable cloth medium from recycled plastics, smart farming technology [5.1] [5.4]	produces over 100 times what a traditional farm could with only a tenth of the water
6	FarmedHere	The US (3 locations)			●	●	●	●				Electricity and heat generation using anaerobic digester [6.1]
7	The Plant	The US				●	●	●			A large anaerobic digester captures the methane from 11,000 tons of food waste/year and generateselectricity and heat. [7.1]	90% less water than conventional farming techniques
8	Brooklyn Grange	The US (2 locations) [8.1]	●				●	●	●			
9	Green Spirit Farms	The US (2 locations)					●	●			LED grow light application increased production and shortened grow cycle. Uses the Volksgarden Rotary Garden unit, referred to as a Rotary Vertical Growing Station (RVGS), and a multi-level tray system, referred to as a Vertical Growing Station (VGS) [9.1]	LED use lower energy for growlight.
10	Growing Underground	The UK		●			●	●		●	LED growlight [10.1]	
11	La Caverne	France		●			●	●			Cycloponics [11.1]	no pesticides
12	UrbanFarmers AG	the Netherlands				●	●	●	●	●	LED and hydroponics allows crops to grow 30–50% faster than conventional farming [12.1]	no pesticide use
13	PlantLab	the Netherlands					●	●		●	LED growlight, Plant Production Unit (PPU) [13.1] [13.3]	90% less water than traditional agriculture
14	Badia Farms	Dubai, UAE		●			●	●		●	LED, use pure drinking water for irrigation [14.1]	use 97% less water than traditional farms, grown with 100% renewable energy, use 10x less land, yields 100x more/acre than outdoor farming
15	Nuvege	Japan		●			●	●			LED growlight [15.2]	
16	Sky Greens	Singapore	●	●			●	●			Hydraulic technology for the rotation of planting systems, rotating tiers [16.1]	Low energy: rotation of planting system using hydraulic technology, only 0.5 L of water is needed to rotate 1.7 ton vertical tower. 40 W of electricity is needed to power 9 m tall growing tower
17	Pasona O2	Japan		●			●	●	●		Building Integrated Agriculture (BIA), HEFL, fluorescent, LED growlight [17.2] [17.4]	non-GMO seeds, use compost, no pesticides, insecticides, herbicides. Use 90% less water than open-field growing

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Table 2 (*continued*)

	Farm	Location	Applied technology								Other technology	Environmental aspects
			Soil based	Hydroponic	Aeroponic	Aquaponic	Greenhouse/ Indoor farming	Vertical farming	Rooftop farming	Precision, automation		
18	iFarm	Taiwan					●	●			LED growlight, fertilizers from organic soybeans [18.1]	“4 zeroes 2 lows” standards: zero pesticide residue, zero toxic heavy metals, zero E.coli, zero parasites, low nitrates, and low bacteria count.

Sources of Tables 1 and 2 (Accessed in mid-January 2019).
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proportion of UA yields to total agricultural yields ranged from 3 to 27% (Zezza and Tasciotti, 2010). Innovative urban horticulture in developing countries could potentially produce up to 50 kg/m^2 of food (depending on the species and the technologies applied) and can complement the regular rural perishable food production in the local market (Orsini et al., 2013).

Some researchers compared the agricultural productivity of innovative agriculture and conventional agriculture. For instance, Barbosa et al. (2015) indicated the potential of hydroponic systems to produce 11 times more lettuce per acre; while Khoshnevisan et al. (2013) and Martinez-Blanco et al. (2011) indicated the potential of greenhouse systems to produce 13 times more strawberries and 1.5 times more tomatoes per acre, than conventional agriculture. A rooftop garden in Bologna is estimated to provide 12,000 t/year of vegetables, meeting the needs of 77% urbanites (Orsini et al., 2014). Most of these studies were highly context-dependent (location, specific technology, requirement, and crop type); thus, we cannot generalize the results. Nevertheless, the actual food production data summary in Table 1 indicates a high potential of IUA, specifically for the indoor vertical aeroponics system, showing a production capacity of up to 139.46 kg/m^2/year (the case of Aerofarms).

3.2.2. Coverage of the food basket

Current UA and IUA mostly focus on quite specific types of food, such as horticultural products, due to their relatively light weight, short season, simplicity and practicality of cultivation (Farrell et al., 2012). Urban farmers tend to choose for these high value food crops to balance the high cost of labor and farmland (Angotti, 2015). Most of these horticultural products are fresh and perishable vegetables. Other common UA crops are fruit, rice, and tuber (FAO, 2007; Mok et al., 2014; Moustier and Danso, 2006). Asian vegetables, strawberries, and potatoes are among the favorite crops in UA in developed countries today (Mok et al., 2014). This means that most UA food products today provide vitamins, minerals, fiber, and (relatively small percentages of) carbohydrate and protein sources. de Bon et al. (2015) encouraged urban horticulture in developing countries, where the daily consumption of vegetables is generally lower than the FAO recommendation (205 g/capita, or 75 kg/year/capita). Although improvement of nutritional status by UA engagement is still debatable, UA engagement positively supports dietary diversity in many countries (Warren et al., 2015).

The FAO noted that UA meets 10–100% of the urban demand for vegetables (depending on the season and the country) (Table 4). We further analyzed the UA food provision table of the FAO (FAO, 2007) and found these UA contributions to be relatively higher in developing countries than in developed countries. This difference in contribution could perhaps be due to differences in the development of the food value chain between these countries (FAO, 2014a).

The summary of the actual food production of IUA systems (Table 1) confirmed that they mostly grow vegetables. However, recent innovations provide opportunities for diversifying urban food types and enriching nutritional supply for urbanites. Aquaponic systems could provide fish as protein sources. Aeroponic technology has rarely been studied so far (see Supplementary information 1.1) but it has the potential for tuber production (Battaglia, 2017). Moreover, Battaglia (2017) showed aeroponic to be the most productive technique for commercial IUA. Some practitioners also add value to their products by processing them into salad mix, sauce, bread, or tea, which eventually diversifies the urban food supply. Some IUA practitioners, for example PlantLab in the Netherlands, optimize their production based on computer models, creating specific growing recipes for a specific taste of selected vegetables (Besten, 2019). Thus, the production process can be customized based on the demand. This example shows that agricultural technologies are continuously developing, providing opportunities for a wider coverage of the food basket via IUA in the future.

3.2.3. Potential agricultural area

In terms of available horizontal area, cities worldwide are incomparable to the global agricultural area today. Global agriculture occupies an area of 48 million km^2, 6.8 million km^2 of which is cereal production area. Cities worldwide occupy only about 300–700 thousand km^2. The annual global harvests of vegetables and fruits each cover an area approximately equivalent to that of cities (respectively 546 and 552 thousand km^2) (Hamilton et al., 2014). Therefore, if only the potential horizontal area is considered, UA production can only be a marginal addition to RA production.

The proportion of UA area in developed countries can be relatively larger than in developing countries, due to the earlier development of UA in developed countries. For instance, in 2010, a case study of a metropolitan city in Germany by Pölling et al. (2016) revealed that urban farmland occupied around 33% of the total area of the city. The proportion of urban farmland varied from 19% in the city center up to 42% in the peri-urban area (Pölling et al., 2016). Another study confirmed that regarding urban land availability, UA is more feasible for growing basic daily vegetables for the urban poor in developed countries than in developing countries (Badami and Ramankutty, 2015). Using visual interpretation on vacant land, McClintock estimated that the most conservative farming scenario could contribute 2.9–7.3% of the vegetable needs of Oakland, California (McClintock et al., 2013).

Vertical area optimization is promising to enable space-efficient food production (Al-Kodmany, 2018). The actual food production data in Table 1 confirms this statement. Preliminary estimations of the potential production capacity of vertical IUA showed a significant increase of agricultural output compared to conventional agriculture. For instance, Germer et al. (2011) estimated the production capacity of a “Skyfarm”, a vertical aeroponic greenhouse with 1 ha ground area, 20 floors, and 90% useable area, to annually produce 200 times more rice grain (almost 900 Mg) than the current most productive regular rice cultivation practice in Egypt (about 8 Mg). Optimization of urban areas also has the potential to improve food production. Integration of hydroponic systems on industrial rooftops may produce up to 277% of Montreal's total vegetable demand with lower production cost. Combination of hydroponic systems on industrial rooftops, residential gardens, and vacant space may potentially increase vegetable production up to 446% (Haberman et al., 2014). Our findings on eighteen practitioners also show IUA's potential to optimize urban area use by reutilizing abandoned buildings and underground space.

3.2.4. Potential number of IUA practitioners

Regular global statistics on the number of UA practitioners are lacking. Armar-Klemesu (2001) estimated that of a global total of 800 million urban farmers, around 100 to 200 million were producing fresh agricultural products for the market in 2000. Although the validity of this estimation was questioned, these numbers are still cited (Orsini et al., 2013). The total of UA participation in 15 developing countries varied (depending on the country) from 11 to 69%, while the total of RA participation in these countries was relatively higher, ranging from 64 to 99% (Zezza and Tasciotti, 2010). In the US and Canada, the number of urban community-supported agriculture practices increased significantly from around 1700 in 2005 to over 12,500 in 2007 (Mok et al., 2014).

Due to a lack of available studies, the precise number of IUA practitioners is still unknown. Previous studies on this topic were mostly limited to specific techniques and not limited to an urban context. Aquaponic, for example, is a technique that has been frequently studied. An international survey of aquaponic practitioners in 2013 involved 1084 responses (81% from the US and the remaining 19% from 22 other countries). This study also showed the dominance of small-scale aquaponics farms over bigger ones (Love et al., 2014). The number of commercial aquaponic facilities in the US more than doubled between 2013 and 2014 (Love et al., 2015). These studies focused on aquaponics as one type of IUA technology, without distinguishing

Table 3
Comparison of urban agriculture (UA) in developing and developed countries.

Aspect	UA in developing countries	UA in developed countries
UA development	UA is highly complementary to rural agriculture (RA). Most UA farms use a soil-based system (Zezza and Tasciotti, 2010). Increasing food demand in cities in developing countries gradually is transforming subsistence farming to commercial agriculture (Dossa et al., 2011)	In USA, UK, Australia, and Japan, the development of urban agricultural practices was strongly influenced by wars and economic crises, government policies and urban environmental risks (Mok et al., 2014) UA for commercial purposes developed earlier and in a more advanced way in developed countries than in developing countries (Lawson, 2016; Mok et al., 2014)
UA motivation/intention	More for subsistence than for commercial purposes (Poulsen et al., 2015) Most of the food from UA in 15 developing countries was for self-consumption, and the rest (around 7–45%, depending on the country) was sold (Zezza and Tasciotti, 2010)	More as a social goal than for subsistence (Rogus and Dimitri, 2015) Metropolis Ruhr (Germany) case study: urban farms that offer other services (example: agrotourism) are more abundant than urban farms that only focus on direct food marketing (Pölling et al., 2016) Survey of aquaponic practitioners in Europe: respondents reported the following intentions: for education (98%), to improve the sustainability of food production (96%), to aid in development (68.6%), to reduce climate change effects (68%), for food subsistence and to improve health (25%) (Villarroel et al., 2016)[a] An international survey of aquaponic practitioners (81% respondents from the US): 84% as a hobby, 57% for education purposes, 32% for commercial reasons (selling fish, vegetables, and aquaponic services and materials) (Love et al., 2014)
UA participation	Representative national data from 15 developing countries: UA participation (urban sample) varied from 11% (in Indonesia, 2000) to 69% (in Vietnam, 1998). UA participation in 11 of the 15 countries was over 30%. In these countries, rural agriculture participation (rural sample) was relatively higher, varying from 64% (in Indonesia, 2000) to 99% (in Vietnam, 1998). UA is mostly practiced by the poor (Zezza and Tasciotti, 2010)	The USA and Canada: The number of urban community-supported agriculture practices increased from around 1700 in 2005 to over 12,500 in 2007 (Mok et al., 2014) The American Community Gardening Association estimation (2010): at least 18,000 community gardens in the US and Canada (Kortright and Wakefield, 2011) Commercial urban farms in the US (2007): 316 farms (average size was around 174 acres, in total they occupied around 6% of the total commercial farmland in the US) (Rogus and Dimitri, 2015) An international survey of aquaponic practitioners in 2013 included 1084 responses (81% from the US and the remaining 19% from 22 other countries) and showed the dominance of small-scale aquaponic farms over bigger ones (Love et al., 2014)[a] The number of commercial aquaponic facilities in the US more than doubled between 2013 and 2014, increasing from 71 to 145 systems (Love et al., 2015)[a]
Share in total agricultural production	UA production is complementary to the rural agriculture production (De Zeeuw et al., 2011) Representative national data from 15 developing countries: UA production: 3% (in Malawi, 2004) to 27% (in Madagascar, 2001) of the total agricultural production (Zezza and Tasciotti, 2010).	Metropolis Ruhr (Germany) case study: The share of urban horticultural production is positively correlated with population density (Pölling et al., 2016).
Contribution to economy	Representative national data from 15 developing countries: UA contributed between 1 and 27% of the households' incomes (Zezza and Tasciotti, 2010). The net daily income from vegetable peri-UA in Vietnam was twice as high as the income from rice agriculture and created five times more employment (Jansen et al., 1996)	In an aquaponic survey in Europe, 80.4% of respondents stated that aquaponics is not their source of income (Villarroel et al., 2016)[a] Commercial aquaponic farmers who sold aquaponic materials and services besides aquaponic products (fish and vegetable) were likely to have aquaponics as a primary income source (Love et al., 2015)[a]

[a] Studies positively include aquaponics as innovative farming technique; however, they did not specify location (urban, peri-urban, or rural area).

between urban or non-urban context, while clearly showing the emerging trend of aquaponic systems.

Increasing food and nutrition demands in cities along with increasing GDPs in developing countries are gradually transforming subsistence farming to commercial agriculture (Dossa et al., 2011). This resulted in upscaling and professionalization of UA in these countries, as well as in transfer of IUA technology from developed countries to developing countries. Such scaling up of IUA may even lead to farming practices that are so very intensive that they have to move back to less densely populated areas (see Supplementary Information 3). Therefore, we need further studies on food productivity of IUA, mainly from developing countries.

The application of multiple scales of IUA could in future support the three dimensions of food security: food availability, food access, and food utilization. Small-scale and medium-scale IUA can produce sizable amounts of vegetables for the local market. Medium and commercial scales of IUA could be developed to meet wider ranges of food consumers, adopting a national and global market orientation. These commercial IUA practices could be technologically developed further to complement RA and produce the world's major carbohydrate or protein source crops (cereals, sugar cane, maize, roots and tubers, rice and wheat) (FAO, 2014b). IUA can contribute to food stability (including food safety) by reducing the dependency of food supply on long, poorly developed food value chains (poor post-harvest processing and storage technologies) from rural areas to cities (FAO, 2014a). Nevertheless, as the environmental sustainability remains the most significant critical aspect of IUA in the future, the most challenging and debatable issue will be the contribution of IUA to food stability.

4. The environmental sustainability of innovative urban food agriculture

4.1. Sustainability challenges for agriculture and urban agriculture

The world's agricultural capacity is continuously threatened by a combination of human and natural factors: climate change, pollution, depletion of natural resources, and worldwide loss of biodiversity due to massive land conversion to agricultural areas. The continuing

Table 4
Food provision by urban and peri-UA in several cities.

Category	City	Source	Percentage of food demand met by urban and peri-UA				
			Leafy vegetables	All vegetables	Fruit	Rice	Tuber
Developing countries	Havana	Gonzalez Novo and Murphy, 2000		58	39 (non-citrus)	64	13
	La Paz	Kreinecker, 2000		30			
	Dakar	Mbaye and Moustier, 2000		70–80			
	Dar es Salaam	Jacobi et al., 2000		90			
	Accra	Cofie et al., 2003		90			
	Brazzaville	Moustier, 1999	80				
	Bangui	David, 1992	80				
	Yaounde	Dongmo, 1990	80				
	Bissau	David and Moustier, 1993	90				
	Nouakshott	Laurent, 1999	90				
	Jakarta	Purnomohadi, 2000		10	16	2	
	Shanghai	Cai and Zhang, 2000		60			
	Hanoi	GTZ, 2000; Phuong Anh et al., 2004	70–80	0-75 (seasonal variation)			
	Vientiane	Kethongsa et al., 2004	100	20-100 (seasonal variation)			
	Sofia	Yoveva, 2000		50			53 (potato)
Developed countries	Hong Kong	Smit et al., 1996		45			
	Singapore	Smit et al., 1996		25			
	Sydney	(Mok et al., 2014)*	56 (lettuce)	24 (Asian vegetables = 99)	6 (Strawberry = 56)		5 (potato)
	Melbourne	(Mok et al., 2014)*	73 (lettuce)	33 (Asian vegetables = 89)	7 (Strawberry = 97)		18 (potato)

Main sources (FAO, 2007; Moustier and Danso, 2006): expanded with a category column and additional sources (*).

deforestation for agricultural land conversion since the Green Revolution era until 2005 contributed significantly to forest loss in 41 tropical countries (DeFries et al., 2010). FAO-UN (2017) reports that agriculture uses around 70% of the fresh water in the world, and the percentage increased to 90% in low rainfall areas, due to water exploitation from rivers and aquifers. Agriculture, forestry, and other land use also have resulted in around 21% of total global GHG emission. Therefore, we need to reduce water use and GHG emission per unit of food. Two top challenges of food security are the sustainable improvement of agricultural productivity and ensuring a sustainable natural resource base (FAO-UN, 2017) (see SI 1), and both demand attention from rural as well as urban agriculture.

Commercial UA is facing the risk of mutual pollution between agriculture and the urban ecosystem (Mok et al., 2014). Urban food products are more vulnerable to contamination by chemicals (particularly heavy metals) (Russo et al., 2017), biological pollution and soil pollution produced by other urban activities (Déportes et al., 1995). Although the use of wastewater for fertilization and irrigation in UA is regarded as beneficial wastewater treatment (Lydecker and Drechsel, 2010), it has been reported to increase health issues (Cofie et al., 2005). The heavy use of pesticides in UA in tropical countries increased malaria-vectoring mosquito resistance (Hamilton et al., 2014). However, these studies on UA mostly examined open agricultural systems, whereas IUA offers more semi-closed or closed systems; which may reduce the risk of IUA pollution. Hamilton et al. (2014) and Mok et al. (2014) also argued that sustainability assessments of UA nowadays are mostly conducted from economic and social viewpoints rather than from an environmental viewpoint and that we need proper methods to comprehensively assess the environmental aspects.

4.2. The relevance of including a life cycle perspective

While UA is claimed to play a positive role for various urban ecosystem functions (see Introduction)., the environmental claims have not yet been supported by convincing evidence. Most environmental studies of IUA conducted so far focused on single processes or aspects and did not include systematic analyses of all activities that are required for IUA practice. For instance, a study revealed that an urban hydroponic system required 82 times more energy per acre to produce 11 times more lettuce than regular agriculture (Barbosa et al., 2015). On the other hand, drainage water reuse for greenhouse hydroponic cucumber production has increased water efficiency up to 33% and reused 566 kg/ha N, 25 kg/ha P and 703 kg/ha K at the farm (Grewal et al., 2011). However, since these studies focused on individual parts of an IUA system, no robust conclusions could be drawn regarding the full life cycle environmental performance of such a system (Guineé et al., 2017; Hellweg and Milà i Canals, 2014).

In view of the high variety of IUA practices, requires the adoption of proper methods for assessing the comprehensive environmental sustainability of IUA. A suitable method for this assessment is environmental Life Cycle Assessment (LCA). LCA is a widely applied method that assesses the environmental impact associated with all the stages of a product. The principle and framework of LCA have been standardized in ISO 14040-14044:2006 (ISO 14040, 2006; ISO 14044, 2006). The handbook of LCA by Guinée contains a useful operational guide for complying with these standards (Guinée et al., 2002). For the life cycle of a food product, three attributes of IUA should be considered in an environmental assessment: technological complexity, farm scale, and crop types.

4.2.1. Technological complexity

Although IUA farms seem to use less water and soil for food production than regular farms (Rothwell et al., 2016), they may require more material and energy than conventional UA to properly function as a complete food production system. Every farming system requires agricultural input such as water, media, fertilizers, and pesticides. However, IUA, which typically is a closed or semi-closed system, often requires more sophisticated constructions, solid substrates as soil substitution, equipment, and automation. All of these imply the use of more raw materials and energy, resulting in more activities and a more complex life cycle (Fig. 1).

Some experimental studies claimed that IUA might support increased resource efficiency, particularly regarding the use of water and fertilizers. For instance, in an experimental setup, the application of a double recirculating aquaponic system (DRAPS) for 1 m^3 water increased fertilizer efficiency up to 23.6% compared to a conventional hydroponic system, while producing the same quantity and quality of tomatoes per m^3 water, and even providing 1.5 kg of tilapia as an additional product (Suhl et al., 2016). Nevertheless, this efficiency claim is limited to an individual production process, excluding upstream and downstream processes of the whole life cycle of the food product.

Practitioners of IUA might also use significantly higher amounts of synthetic materials and chemicals, such as plastics, processed metals, or specific synthetic fertilizers, which eventually may contribute to a higher carbon footprint than RA (Sanyé-Mengual et al., 2015). Studies showed that the environmental impact of precision agriculture was significantly affected by product packaging and transportation (Rothwell et al., 2016), environmental conditioning (Llorach-Massana et al., 2016), and preservation (Abeliotis et al., 2016). To conclude, from a comprehensive life cycle perspective, the total system of IUA food production may need relatively more material and energy than UA and RA. Therefore, a comprehensive LCA is needed before making any claims on the environmental performance of IUA systems.

4.2.2. *Farm scale: commercial vs. amateur*

Global markets often demand compliance with food quality standards and environmental standards, resulting in the need of precision management to optimize resource use. Compared with commercial urban farmers, amateur urban farmers could potentially create a more significant environmental impact. If the popularity of IUA increases further, the farmer's environmental awareness may at a certain point be overruled by the profit orientation, or by the pleasure derived from IUA practice as a hobby. Also, the growing popularity of IUA tends to promote the emergence of new small-scale urban farms run by inexperienced practioners, which creates a cumulative trial-and-error practice while they gain experience in IUA. This tendency has occurred globally since around 2010.

Our finding that two of the three included commercial aquaponic farms are no longer operational supports the need for discussion on global aquaponic experience (see Table 1). An aquaponic infrastructure can be overly complicated and expensive and may require more resources than regular aquaculture (Forchino et al., 2017; Somerville et al., 2014). An international survey reported that aquaponic UA is mostly practiced for hobby and education purposes, and 90% of the respondents had less than five years of aquaponic experience (Love et al., 2014). Most commercial aquaponic farmers in 2013 exploited farms that were relatively small in size and revenues, most started their business in 2010, less than 10% of them had 10 or more years of experience, and less than one-third of the farms were profitable (Love et al., 2015). An aquaponic survey in Europe also showed that 75% of the facilities were relatively new (built in or after 2010), 47% of the practitioners were working at universities, 35.5% of the systems were funded via government grants, 19% were commercial producers, and only 12% had sold fish or plants over the past 12 month (Villarroel et al., 2016). These studies indicate the collective lack of experience among aquaponic practitioners and show that aquaponics has the characteristics of a hype. Consequently, the collective lack of experience combined with little awareness of environmental impacts could result in a high cumulative environmental burden.

4.2.3. *Crop types*

Crop selection may influence the environmental performance of IUA production systems. Typical food plants produced by IUA around the world are horticultural plants such as tomato, lettuce, and basil (Barbosa et al., 2015; Love et al., 2015; Somerville et al., 2014; Suhl et al., 2016). High-yield urban horticulture is the most competitive branch of UA due to the high cost of urban agricultural areas and the need for resources (water and fertilizer) (Orsini et al., 2013). Fertilizer factories intentionally produce and distribute specific fertilizers for optimal growth of specific horticultural varieties, resulting in the increased use of synthetic fertilizers in IUA systems. Moreover, these species or varieties are often non-native; thus the seeds need to be imported from distant places. For instance, the cherry tomato, originating from South America (Wexler, 2016), has probably become the most widely cultivated horticultural species in urban farms worldwide today. The introduction of cherry tomatoes in Asia altered Asian urbanites' preferences in food production and consumption. Importing new varieties also implies the use of energy for long-distance transportation, which adds to the environmental burden of IUA.

Hamilton et al. (2014) and Mok et al. (2014) emphasized the need of proper environmental impact assessment by applying life cycle approaches to UA systems, both in developing and developed countries. Compared with developing countries, developed countries potentially contribute more to the increased use of technology in UA that requires more natural resources and capital. The FAO highlighted that developed countries require four units of capital to generate one unit of value added, compared to around 1.5 unit of capital in developing countries (FAO, 2017). Since developing countries contribute more to the increase of future urban food demand than developed countries, particular attention should be paid to LCA studies of IUA systems in these countries.

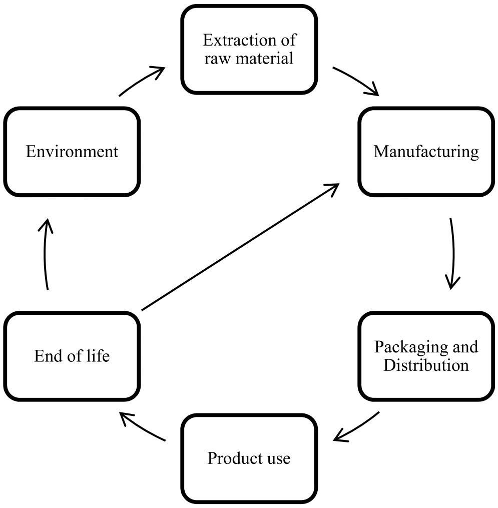

Fig. 1. The simplified life cycle of a product.

5. Conclusions

In this section, we will provide conclusions and recommendations referring to our initial research questions. We will first answer our subquestions:

1. What are realistic production scales for the current IUA practices and to what extent can IUA contribute to global food security?
2. What is known about the environmental sustainability of the current IUA practices?

Next, we will answer our main question whether IUA as a food production system can complement UA and contribute significantly to food security and environmental sustainability. Before we do so, we emphasize that our review only includes 18 studies. This may limit the validity of our conclusions and recommendations, which will have to be evaluated by future studies on IUA.

We defined innovative urban agriculture (IUA) as urban agriculture that optimizes food production (minimizing maintenance and resources whilst maximizing yield) by involving at least one of the recent technological innovations in an open or closed system. These innovations may include indoor agriculture, remote sensing, vertical agriculture, hydroponic, aeroponic, aquaponic, and soilless agriculture, precision agriculture, as well as other novel technologies.

Global IUA has developed rapidly since around 2010. Our findings reveal that among IUA technologies, aeroponics is the least studied technique, yet it has huge potential for food production (various types and significant amounts), with Aerofarms as an example of a successful case study. Aquaponics gained the most attention of researchers and urban growers, yet the feasibility and the economic sustainability of its commercial scale still need to be studied further.

Regarding the realistic production scale, IUA in its various scales provides a potential contribution to food security by supporting local food supply (particularly of perishable horticultural products) and by reducing dependency on the rural-urban food value chain. The commercialization and modernization of UA tend to develop faster and to be more advanced in developed countries than in developing countries. Nevertheless, the global number of IUA practitioners is still unclear and needs further research. To date, the US leads IUA industry and keeps expanding and transferring their technology to other regions worldwide. The current gradual transformation of subsistence farming to commercial farming in developing countries will likely occur as well in the case of IUA. In the future, commercial IUA might be technologically developed to produce world's major carbohydrate or protein source crops (cereals, sugar cane, maize, roots and tubers, rice and wheat) to balance nutritional needs of the current IUA and complement RA. Optimization of the indoor and vertical urban areas for IUA may contribute to solving the problem of limited areas available for agriculture in cities, yet further study is required on the associated environmental impacts. Summarizing, we find that basic rigorous research data are lacking as yet for various indicators of IUA's potential production scales and its contribution to food security.

Concerning the environmental sustainability of IUA, we conclude that this is the most challenging and questionable dimension of IUA. To make a positive contribution to food stability, IUA needs to employ sustainable practices more than ever. IUA potentially can support specific elements of the food basket and make food provision more resilient. However, this may not be a change at the scale of the GR 1.0, and it is crucial to avoid the negative environmental side effects GR 1.0 has caused. We should be careful not to make the same mistakes again as were made in GR 1.0, when tremendous increases in food production resulted in high environmental and ecosystem impacts (see SI 1).

To comprehensively evaluate the environmental impact of the existing UA and the emerging IUA technologies, studies should consider the whole life cycle of urban food production system. Unfortunately, most environmental assessments today only consider individual processes of UA and IUA, and consequently present biased results, and do not provide proper insight into the environmental performance of IUA versus UA.

We conclude that three attributes of IUA should be considered in an environmental assessment: technological complexity, farm scale, and crop types. Based on our review, we expect that IUA will likely require more resources, infrastructure and energy than UA and RA, with associated environmental impacts. To test this hypothesis, environmental life cycle assessment (LCA) studies are required for each specific regional or local implementation and variation of IUA practices. Special attention should be paid to LCA studies of IUA systems in developing countries, because the main future population growth, with associated increased urban food demands, will take place in these countries. Increasing food demands will most likely drive these countries towards commercializing the existing UA and IUA practices and modernizing current RA practices. Commercial urban farmers targeting the global market might face product standardization, including environmental standards that necessitate LCA, for the more sustainable practices of IUA.

Finally, referring back to our main question - whether IUA as a food production system can complement UA and contribute significantly to food security and environmental sustainability?– we conclude that IUA is worth being continued in the future as long as it respects all three sustainability pillars: people, planet, and profit. We propose to first assess the environmental sustainability of IUA practices and, based on the assessment results, to encourage (even) more sustainable practices of IUA. We expect that such LCA studies will bring more realism to the expectations of UA and contribute to more fact-based sustainable IUA in the future.

Conflicts of interest

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere. All authors have approved the manuscript and agreed to this submission and its future publication. We have no competing interests to declare.

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Abbreviations

RA	Rural (Regular) Agriculture
UA	Urban Agriculture
IUA	Innovative Urban Agriculture
GR	The Green Revolution
HYV	High Yielding Varieties
CEA	Controlled Environment Agriculture
UEA	Uncontrolled Environment Agriculture
BIA	Building Integrated Agriculture
GHG	Greenhouse Gas
LCA	Life Cycle Assessment

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2019.08.002.

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