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Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings

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Abstract Innovative forms of green urban architecture aim to combine food, production, and design to produce food on a larger scale in and on buildings in urban areas. It includes rooftop gardens, rooftop greenhouses, indoor farms, and other building-related forms (defined as "ZFarming"). This study uses the framework of sustainability to understand the role of ZFarming in future urban food production and to review the major benefits and limitations. The results are based on an analysis of 96 documents published in accessible international resources. The analysis shows that ZFarming has multiple functions and produces a range of non-food and non-market goods that may have positive impacts on the urban setting. It promises environmental benefits resulting from the saving and recycling of resources and reduced food miles. Social advantages include improving community food security, the provision of educational facilities, linking consumers to food production, and serving as a design inspiration. In economic terms it provides potential public benefits and commodity outputs. However, managing ZFarming faces several challenges. For some applications, the required technologies are known but have not been used or combined in that way before; others will need entirely new materials or cultivation techniques. Further critical aspects are the problem of high investment costs, exclusionary effects, and a lack of acceptance. In conclusion, ZFarming is seen as an outside-the-box solution which has some potential in generating win–win scenarios in cities. Nevertheless, ZFarming practices are not in and of themselves sustainable and need to be managed properly.

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Abbreviations

BIA	Building-integrated agriculture
CEA	Controlled environment agriculture
CPUL	Continuous productive urban landscape
ZFarming	Zero-acreage farming

Introduction

Urban growth dynamics and development have posed serious questions of food production and processing, transport, and consumption. Sustainable urban food production has recently become a subject of interest across a range of professional and academic disciplines (Caplow 2009). Driven by global imperatives such as climate change mitigation, more equitable economic models, and health concerns, urban agriculture has in the past few years moved from an issue at the edge of public discourse to one at its center (Bohn and Viljoen 2011). As increasing urbanization is seen as unavoidable (United Nations 2004), new approaches should contribute to delivering fresh, local food for cities (Brock 2008).

Innovative forms of green urban architecture aim to combine food, architecture, production, and design to produce food on a larger scale in and on buildings in urban areas. The major motivation for this new type of food production (subsequently known as "ZFarming") is based on opportunities resulting from the use and recycling of resources, especially those derived from synergies between agriculture and buildings. The idea behind ZFarming is to create entities linking food production and buildings with multiple uses of residential or industrial waste resources (e.g., waste water, waste heat, organic waste) to establish a small-scale resource saving system. Some of the practices are therefore characterized by demanding high standards of technology, maintenance, operation, and investment that are necessary in the early stages of development. In addition, the free space for conventional, ground-based agricultural production is very limited in many cities. All this explains why ZFarming is often investigated separately from other urban agriculture practices.

On the global level, the development of building-integrated forms of urban food production is driven by the challenges that cities currently face. The world population is projected to pass the 9 billion mark by 2050 (United Nations 2004). For the first time in human history, more than half of the world's population lives in cities, and by 2030, this figure will increase to more than 60 % (United Nations 2004). Today, cities consume more than two-thirds of the world's energy and account for more than 70 % of global CO_2 emissions (UNFCCC 2010). As a result, they can play a leading role in decarbonization by decreasing CO_2 emissions. Sustainable solutions for food, water, energy, and transport of food or waste are needed as integrated components of a city's climate change adaptation. Urban agriculture is currently considered one of the solutions to climate change adaptation as it can play a significant role in greening the city and improving the urban climate, while stimulating the productive reuse of urban organic waste and reducing the urban energy footprint (De Zeeuw 2011). Rather than growing food in remote areas and spending large amounts of resources on transportation, growing food within the city itself may provide several advantages.

In addition to climate change and urbanization, our food production will be confronted with another mega-trend: the rising demand for food against the background of a decrease in productive agricultural land. Currently, 13.4 billion hectares of land worldwide are used for crop production (arable land and land under permanent crops) (FAO 2011), but intensive forms of agriculture can cause severe environmental damage. Besides the limitation in productive land, food crops are now competing for land, water, and other resources in many parts of the world as other types of land use emerge (e.g., bioenergy, urbanization, nature conservation areas) (FAO 2012). Large-scale urban food production could provide new landscape opportunities and take pressure off agricultural land. Consequently, researchers and practitioners aim to find solutions to decouple arable land from production and produce food on a larger scale in and on buildings in high-density urban areas.

Against the background of population growth and urbanization, planners and practitioners all over the world share the vision of cities as food production spaces, meeting a range of societal and ecological needs. Because urbanization is unavoidable, ZFarming is treated as a role model for sustainable cities and the question is what food production areas could look like in the cities of the future (Woetzel 2011). According to Lovell (2010), the real challenge is to design urban landscapes for a wide range of functions. Zande (2006) states that cities need cooperating functions, not competition. Bohn and Viljoen (2011) envision the "edible city" and introduced the concept of Continuous Productive Urban Landscape (CPUL), advocating the coherent introduction of interlinked productive landscapes into cities as an essential element of sustainable urban infrastructure. According to Lovell (2010), urban areas often require the greatest effort but also offer the greatest potential reward in the integration of local food systems in planning. This is primarily due to the high densities of consumers and the large proportion of poor people who have limited access to fresh food (Bryld 2003) or agricultural land.

One major challenge to the viability of urban food production is land availability and access. For some cities (or neighborhoods), which are less densely populated or have experienced population loss in the past (e.g., shrinking cities), space availability is not a limiting factor. Principally, there might be large resources of land or brownfields set aside for development that could be made accessible for agricultural purposes, though this is often linked with high decontamination costs. But for many other cities, open spaces are scarce. In densely built-up areas and where availability of space often limits the size of the production unit, no-space or low-space technologies offer tremendous opportunities for space-confined growing (Dubbeling 2011).

During the last two decades definitions of urban agriculture showed some development. The most commonly used definition of urban agriculture is that of Smit et al. (1996), which was adopted by the United Nations Development Programme. It defines urban agriculture as an industry that produces, processes, and markets food, largely in response to the daily demand of consumers within a town, city, or metropolis, on land and water dispersed throughout urban and peri-urban areas. Mougeot (2000) submitted a revised definition, wherein urban agriculture is defined as an industry located within (intraurban) or on the fringe (periurban) of a town, city or metropolis, which grows or raises, processes, and distributes a diversity of food and non-food products, (re-)using largely human and material resources, products, and services found in and around that urban area, and in turn supplying human and material resources, products and services largely to that urban area. The already existing definitions referring to urban agriculture in and on buildings are very narrow and do not include all possible types.

Vertical farming is defined as the concept of cultivating plants or animal life within skyscrapers or on vertically inclined surfaces (Despommier 2010), whereas building-integrated agriculture (BIA) is the practice of locating high-performance hydroponic greenhouse systems on and in mixed-use buildings to exploit the synergies between the building environment and agriculture-like energy and nutrient flows (Caplow 2009).

We introduce the term "Zero-acreage farming" (ZFarming) to describe all types of urban agriculture characterized by the non-use of farmland or open space, thereby differentiating building-related forms of urban agriculture from those in parks, gardens, urban wastelands, and so on. Such production types might include the installation of rooftop gardens, rooftop greenhouses, edible green walls as well as further innovative forms such as indoor farms or vertical greenhouses. We use the term ZFarming to include all possible types of urban agriculture in and on buildings, including those mentioned above. The term is an operational tool that helps us to include all forms of food production related to buildings while avoiding conflicts with existing definitions.

We define ZFarming as a subtype and specification of general urban agriculture and understand it therefore as a complementary rather than competing practice. While ZFarming does overlap with some ground-based practices of the new and emerging urban food movements, some distinctions can be identified. The main difference is based on opportunities resulting from the use and recycling of resources, especially those derived from synergies between agriculture and buildings (e.g., residential or industrial waste water, waste heat, organic waste). ZFarming is often investigated separately from other urban agriculture practices, as it raises new questions regarding technical solutions for water, energy, or waste recycling which are not relevant for ground-based agriculture. Practitioners in the field of ZFarming work on technologies to combine the requirements of architecture with those of food production and are confronted with more technological challenges than other forms of urban agriculture. In terms of policy and planning, urban agriculture in open spaces and brownfields is often confronted with planning insecurities, rising from the fact that those spaces are often earmarked for development. In this context, the integration of food production into buildings or the installation of gardens on rooftops has different implications as it offers new certainty for long-term planning.

It is obvious that future food infrastructure will have to be more productive than today's food infrastructure, but it will also have to be more sustainable. Sustainable urban food production needs to address all the dimensions of sustainability at the same time. It needs to address environmental challenges, to tackle and improve social issues, and provide economic welfare. To contribute to the ongoing debate, we reviewed the potential benefits and limitations of ZFarming in all three dimensions of sustainability to determine whether it could serve as an element of sustainable urban infrastructure in cities of the future. Until now, a systematic overview has not been available in publically accessible literature on forms of urban agriculture related to buildings. The aim of this study is to fill this gap and provide a systematic overview of the current state of the debate on urban agriculture in and on buildings as presented in the available literature. We investigate and discuss how ZFarming can contribute to sustainable urban food production including resource efficiency and climate mitigation.

Research method and analytical framework

Overview of ZFarming types

In this study we consider three main type of ZFarming: rooftop gardens/rooftop farms, rooftop greenhouses, and indoor farms. Further types include *edible green walls* as an outdoor application and *vertical greenhouses,* which are stacked greenhouses or *vertical farms* constructed as multistory greenhouses. The latter have not yet been realized, as they currently only exist as concept studies.

Rooftop gardens or *rooftop farms* have the longest tradition. Examples of medium- or large-scale rooftop gardens can be found all over the world. Figure 1 illustrates one rooftop farm, in Brooklyn, New York (USA). According to Gorgolewski et al. (2011), contemporary urban roofs are largely wasted spaces. Even if planted, the vast majority of green roof installations to date and new green roof technologies have focused on non-productive green roofs. Rooftop gardening is a subset of urban agriculture with its own set of particular characteristics and challenges (e.g., weather and wind conditions, rainwater collection, load, access).

Rooftop greenhouses refer to the use of greenhouse methods adapted for use on top of buildings (see Fig. 2 for an example). Rooftop greenhouses already exist, but they are mainly prototype facilities or for public demonstration. The leading project groups are "New York Sun Works" and "BrightFarms" in New York.[1] Hydroponic techniques are best suited economically and logistically to a range of vegetables that include leaf crops (spinach, lettuce, salad greens), vine crops (tomato, cucumber, pepper, squash, beans, zucchini), and culinary herbs (basil, parsley, chives, coriander) (Puri and Caplow 2009). Supermarkets, hotels, convention centers, hospitals, schools, apartment blocks, prisons, warehouses, and shopping malls may provide ideal settings for rooftop greenhouses (Caplow 2009).

Indoor farms employ the practice of locating high-performance agriculture in buildings to exploit the synergies between the building environment and agriculture. Indoor farms can be distinguished as (a) leveled indoor farms and (b) storefront glasshouses. The latter often combine a double-skin building façade with a greenhouse in the skin. Indoor farms mainly exist as prototypes. Lighting is one of the limiting factors. Brock (2008) suggests shade-tolerant species for leveled indoor farms, including edible fungi or invertebrates (e.g., mussels, snail culture or vermiculture). Figure 3 demonstrates an indoor farm located within a former meat packing plant in Chicago, Illinois (USA).

[1] See http://www.nysunworks.org and http://www.brightfarms.com, respectively.

Selection of articles

Scientific and public electronic databases were accessed from January to June 2011 to gather publications in the analyzed field. In the first stage, only peer-reviewed articles were selected. In a second step, further documents, including conference papers, theses, project reports, and magazine articles were added for further analysis. The following databases were used to identify the relevant documents: ISI Web of Science, AGRIS, GREENPILOT, National Agricultural Library (AGRICOLA), Google Scholar (beta), International Bibliography of Social Sciences (IBSS), Oxford Journals, science.gov, wordwide-science.org, KOBV, and Primo-FU Berlin.

We found the majority of the publications directly by defining a list of 51 keywords in the context of ZFarming (e.g., building-integrated agriculture, rooftop farming). To ensure that the whole set of keywords was entered into all databases; we used a Microsoft Excel spreadsheet as a keyword-database matrix. In addition, we also collected relevant articles by scanning the reference lists of documents already identified.

Analytical framework and advanced analysis

A conceptual framework was used to systematically review the collected literature. Using the framework helped us to structure the complexity of topics for the review. However, we are aware that the assignment of themes is not as clear as it may appear. The framework is based on the concept of sustainability as introduced by the Brundtland Report in 1987 (United Nations 1987). We have followed IUCN (2006) in their interpretation of sustainability, where the "three pillars" (environmental, social, economic) are overlapping, and sustainable development stands at the confluence of the three constituent parts.

To assess the empirical basis, each document was linked to a questionnaire that allowed us to check each article matching the different ZFarming types, the key disciplines of authors involved, the year of publication, and the location of authors and project groups. For advanced analysis of the content, we developed a grid, in which we grouped 41 subtopics and categories (adapted from Bohn and Viljoen 2011) under the three general themes (i.e., social, environmental and economic), and compiled an accompanying file for each analyzed document. If an analyzed article addressed a theme relevant to ZFarming, we included that theme as a topic in the file. We used the absolute frequencies of the entries as a means of statistical analysis and comparability.

We used the framework as an operational tool for orientation, and by assigning a topic to one of these dimensions of sustainability, we acknowledge that interrelationships and overlaps exist between the dimensions as well.

Fig. 1 Rooftop garden: active rooftop gardening at Eagle Street Rooftop farm, an organic vegetable farm located on the roof of a three-story industrial warehouse in Brooklyn, New York (USA) overlooking the East River (Picture by Regine Berges)

Fig. 2 Rooftop greenhouse: herbs and vegetables grown in a rooftop greenhouse on top of a bakery at Eli Zabar's Vinegar Factory, New York, USA (Picture by Thomaier/Dierich)

Empirical basis

Characteristics of the empirical basis

We identified 96 articles that were considered for further analysis. We classified 19 of the articles as being of "high academic quality," which includes only papers published in peer-reviewed journals. The second category consists of 37 documents and was labeled of "medium academic quality," which includes conference papers, book chapters, articles in scientific (but not peer-reviewed) journals, theses, project reports, and conference presentations. Another 40 articles published in magazines, newspapers, on websites, and other documents are classified as "non-academic." The last type of publication was only used in the quantitative part, while the major findings were principally extracted from publications with high or medium academic value. Limiting the study to peer-reviewed papers was not suitable due to the low number of papers available. Many authors who published in the field of ZFarming are affiliated with research institutions in the USA (38 %), Germany (16 %), or Canada (13 %).

The investigation of involved disciplines shows a large variance. By combining agricultural sciences and urban planning, ZFarming intersects the disciplines of ecology and landscape planning, design and architecture, and economics and social sciences. It is mainly addressed by authors and groups with an interdisciplinary perspective who are aware of the interrelated nature of these issues. For the quantitative analysis of the considered documents, we classified more than 60 % as "interdisciplinary" (e.g., environmental economics, ecological design, socioeconomics). The quantitative and

Fig. 3 Indoor farming at "The Plant," a former meat packing plant and slaughterhouse in Chicago, Illinois, USA (Picture by Ina Hartmann)

qualitative analysis of the existing literature shows that ZFarming is a very new area of study. The low number of peer-reviewed publications shows that ZFarming is still at an early stage of research, conception, and application.

Empirical evidence of sustainability dimensions

In order to identify the core topics of ZFarming, we quantify the results of the advanced analysis. In doing so we find that the three dimensions of sustainability are relatively well balanced. The consistent distribution demonstrates the interrelated nature of ZFarming and shows that it cuts across many areas (e.g., environmental problems, new business structures, town-city relationships). As shown in Fig. 4, the vast majority of articles (90) investigated at least one topic that was attributed to the environmental dimension, while 74 out of 96 referred to topics within the social dimension and 70 dealt with topics in the field of economics. The majority of articles address aspects of all three dimensions.

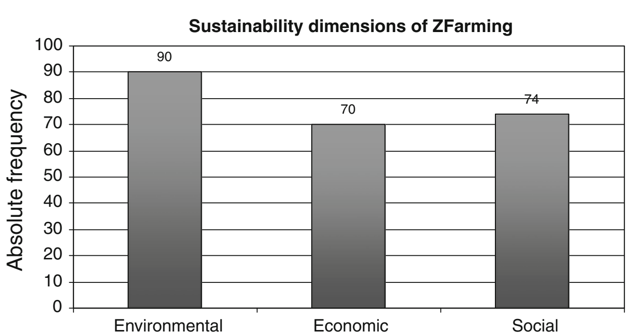

Fig. 4 Empirical evidence (absolute frequencies) of sustainability dimensions in the surveyed literature (n = 96; multiple entries possible)

Environmental dimension

In the context of environment and ecology, the most prominent issue is how to identify and technically develop environmentally sustainable solutions for urban food production. As shown in Fig. 5, the majority of publications investigate the question of sustainable resource management, describing building-integrated production systems, and how those systems can contribute to saving water resources (n = 55) and energy (n = 49) by exploiting synergies with the building. Because a range of practitioners recommend soil-less growing techniques for ZFarming applications, another key issue is the use or replacement of soil by artificial substrates or hydroponics techniques (n = 40). The literature furthermore reflects how ZFarming can stimulate the productive recycling of (mainly organic) waste (n = 28) and which role ZFarming practices can play as a strategy for climate change adaptation and mitigation (n = 25) by reducing CO_2 and other emissions (n = 25) and food miles (n = 24). Against the background of increasing farmland degradation, several studies discuss the potential of ZFarming as a means of farmland preservation (n = 20).

Social dimension

With regard to the social dimension of ZFarming, Fig. 6 shows that in the literature, the most dominant topics are

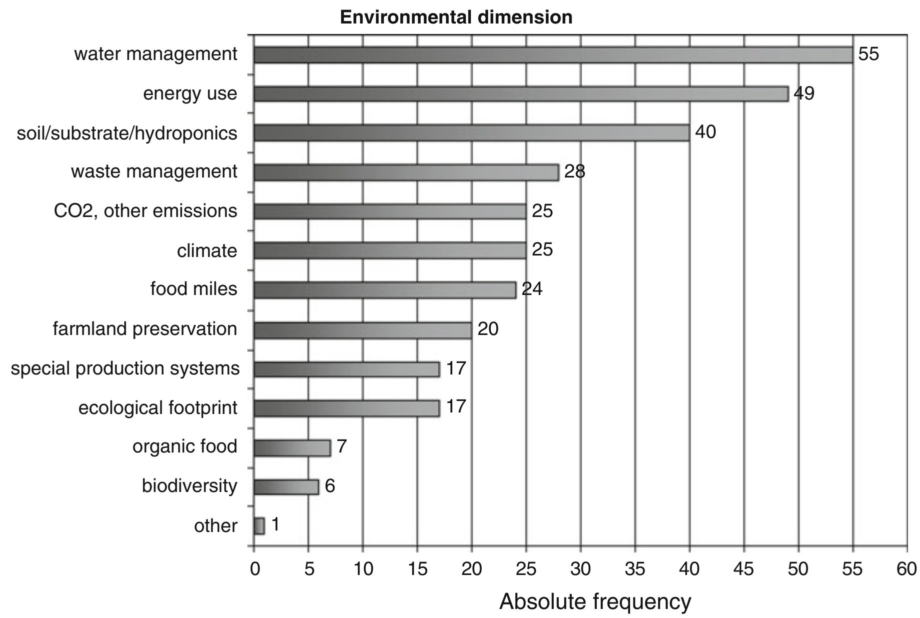

Fig. 5 Quantitative evidence (absolute frequencies) of topics in surveyed literature related to the environmental dimension of sustainability (n = 96; multiple entries possible)

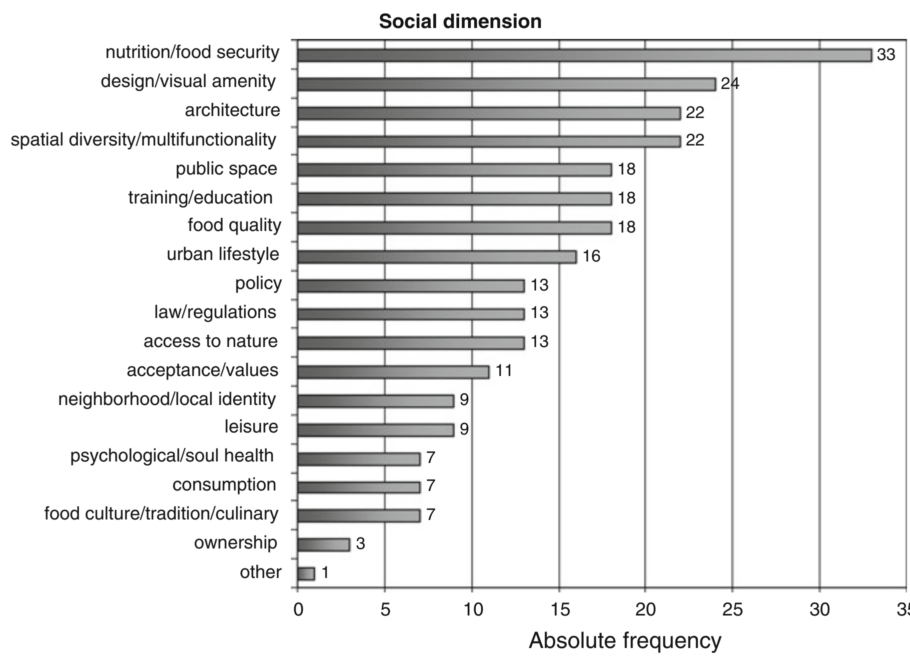

Fig. 6 Quantitative evidence of topics (absolute frequencies) in surveyed literature related to the social dimension of sustainability (n = 96; multiple entries possible)

nutrition and food security. Many publications address the issue of whether building-integrated approaches can contribute to improving community food security and to what extent (n = 33). From an architectural and design perspective, ZFarming is challenged with how to improve design and visual amenity (n = 24) by integrating productive elements and how to relate food with architecture (n = 22). Another key topic is multifunctionality and spatial diversity and how ZFarming can serve as an element of infrastructure fulfilling multiple societal functions (n = 22). Besides the production of marketable commodities, many ZFarming projects are concerned with education and training issues which is also investigated in the literature (n = 18). These topics are followed by publications posing questions about food quality (n = 18) and reflections on changing consumption patterns and urban lifestyles (n = 16).

Economic dimension

In examining the economic dimensions of ZFarming, we found the key topics within the investigated studies were questions of resource usage or costs of construction and engineering (see Fig. 7). These mainly referred to how

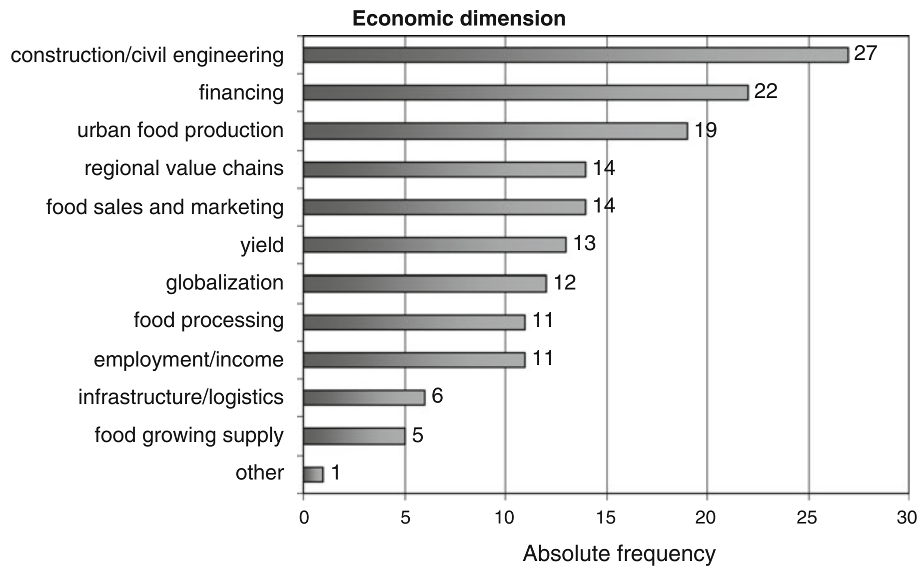

Fig. 7 Quantitative evidence of topics (absolute frequencies) in surveyed literature related to the economic dimension of sustainability (n = 96; multiple entries possible)

ZFarming can be integrated into existing buildings through construction and retrofitting (n = 27). There are also publications that discuss the feasibility of projects and the issues of investment cost and financing (n = 22). From the perspective of urban food production and planning, studies deal with the issue of whether urban food production can bring economic advantages for the cities' inhabitants (n = 19), how it could strengthen the local economy and the regional value chains (n = 14), and what opportunities it offers for sales and marketing (n = 14). As the value chain is highly influenced by expected yields, a range of studies investigate which products are feasible for the different production systems and are promising in terms of their yields (n = 13).

Results and discussion

In the following we outline the main potentials and limitations faced by ZFarming as derived from the literature. The results are presented and discussed based on the three dimensions of sustainability.

Environmental dimension: potentials

ZFarming is expected to provide several potential benefits for enhancing issues surrounding climate change, resource saving, and resource efficiency. Major potentials are assumed in reducing the environmental impact of buildings, reducing transport emissions, improving the recycling of resources, and taking pressure off agricultural land.

Eco-effective architecture and urban landscapes

The disciplines of sustainable architecture, design, and planning are leading the debate on the integration of green architecture and urban food production. The connection of aesthetic, ecological, and productive principles and the development of houses that are productive and eco-effective is seen as a challenge (Komisar et al. 2009), wherein the overall interest is to reduce the environmental impact of architecture (Bohn and Viljoen 2011).

The idea is to transform increasingly dense cities, build forms, and habitually design future cities around a sustainable food infrastructure (Gorgolewski et al. 2011). According to Lovell (2010), 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. Designers, planners, and architects reflect the vision of eco-effective architecture (Zande 2006) which could be embedded into a "Sustainable Eco City" (Sartoux and Rosenstiehl 2008) or even an "arable city" (Sartoux 2008). They share the overall vision to reintroduce food systems in urban space.

Reducing food miles and transport emissions

It is likely that ZFarming contributes to sustainable development of a city by creating a proximity of consumers and producers that lowers transportation distance and thereby reduces harmful environmental emissions as well as costs of transportation (Bosschaert 2008). It represents a worldwide trend that promotes "local for local" (Schans 2010) to shorten the distance between food production and consumers. As less energy is used for transport, cooling, storage, and packaging, strengthening the local food system is one cornerstone to climate change adaptation and mitigation for future cities (De Zeeuw 2011). This applies to all the applications of ZFarming, from the urban rooftop garden to the indoor farm which Vogel (2008, p. 752) calls the "high tech answer to local food movements."

Literature on transport emissions mainly refers to the U.S., where the problem of "food miles" is an emerging issue. Weber and Matthews (2008) analyzed the average final delivery of food in the U.S. to be 1,640 km (1,020 miles), and the total supply chain requires movement of 6,760 km (4,200 miles). Food groups vary in these average distances from a low of beverages (330 km delivery, 1,200 km total) to a high of red meat (1,800 km delivery, 20,400 km total). Many publications see urban food production as a strategy to reduce food miles and combat the problem of "food deserts" which is a metaphor used to describe neighborhoods with limited (fresh) food retail (Raja et al. 2008).

As the American Planning Association (2007) explains, the separation of cities from their food sources is directly linked to many urgent problems the U.S. is facing today (e.g., climate change, pollution). One initial step to counteract them was to raise awareness that the food Americans eat takes a considerable amount of fossil fuel energy to produce, process, transport, and dispose of. They adopted a Policy Guide on Community and Regional Food Planning in 2007 (APA 2007), which focuses on "food system planning." Food system planning is a relatively new concept that has emerged from American society's increasing concern for what it eats, where and how its food is produced, and the inequities that exist in the distribution of food resources. ZFarming can provide answers to that, especially in highly densely populated cities where transportation of food would otherwise be indispensable.

The potential benefits of reduced transport distances and emissions differ geographically. The argument for reduced impact of transport emissions is not as important for cities that are surrounded by productive agricultural land and already have a strong regional food chain. There are a lack of studies linking food miles to greenhouse gas emissions, resource efficiency (land, nutrients, water, energy), and other indicators of sustainable development integrating the whole value-added chain of food production.

Use and recycling of water resources

One potential benefit of ZFarming would be to use systems that can contribute to saving water resources. The idea is to develop ZFarming systems that exploit the synergies of agricultural production with buildings and create closed entities within the protected environment of a building. Water-saving and recycling systems differ for open forms (rooftop gardens) and closed forms (greenhouses, indoor farms).

Studies of rooftop garden projects across the U.S. concluded that rain water collection is a key consideration for rooftop food production (Engelhard 2010; Hill 2009). While the technical ability to capture significant amounts of water from direct rain and runoff effectively exists, the added cost, weight onto the statics of the roof of the building, and required permits are given as limiting factors.

For rooftop gardens, Astee and Kishnani (2010) described the use of four times less water than conventional farming for the same yield of vegetables utilizing hydroponics instead of soil. They also promote the harvesting of rainwater. Caplow (2009) states that each hectare of a recirculating hydroponic greenhouse has the potential to replace 10 hectares of rural land and save 75,000 tons of fresh water per year. This could be achieved by recycling water that transpires from crops (Sauerborn 2011); evaporated water is regained from the greenhouse atmosphere via cooling traps and fed back into the system. Another solution is the conversion of 'gray water' with appropriate conditioning into irrigation water (Despommier 2008).

Energy consumption and production

With regards to energy use, researchers and practitioners view "building-integrated" as a synonym for "energy-integrated." Studies in this field outlined the potentials of buildings with greenhouses to act as cooling, heating, and energy recycling entities and documented the energy-saving effects. In their "Science Barge" Nelkin and Caplow (2007) successfully operate a 120 m^2 greenhouse that grows mixed crops in New York City. The greenhouse works independently of the city's power and water resources. Delor (2011) found that a combined building/greenhouse structure could save up to 41 % in heating compared to standalone greenhouses and buildings. Rooftop greenhouses add an insulating layer to the building, reducing heat loss, and it is possible to use waste heat from the building to heat the greenhouse. Model results showed that a prototype hydroponic vertical garden on the building's storefront had the potential to reduce the energy consumption of a multistory building by 23 % for cooling and by 20 % for air circulation (Bass and Baskaran 2001). The installation of a rooftop garden could result in a saving of 1–15 % of a building's annual energy consumption (Wong et al. 2003a, b).

Recycling of organic waste

There are different ways of improving a city's environment by recycling resources. One of the most efficient ways is by recycling organic waste. The general approach is to create a low or even "no-input system" (Ellingsen and Despommier 2008) that creates a closed loop entity in terms of waste recycling to minimize pollution. Organic matter can be sourced from animal waste, plant residues, or waste from food industry or households (Altieri et al. 1999). Several concepts for waste management in ZFarming are presented in the literature, the aim of which is to optimize or even close nutrient cycles, whether in a small entity (e.g., building) or on a larger scale (e.g., city or region). The use of organic waste as compost is already quite widespread in urban agriculture. On a smaller scale, "mixed farms" close nutrient cycles, such as aquaponic vegetable combinations (Graber et al. 2011), aquaculture, vermiculture and vegetable systems (Wilson 2004), and urban fisheries fed by sewage and waste water (Ghosh 2004). On a larger scale, De Wilt and Dobbelaar (2005) already demonstrated how huge companies can join forces to make use of each others' by-products in their "agropark" concept.

New landscape opportunities

Intensive farming systems have already caused irreversible damage and farmland degradation, while the potential for further intensification is considered to be limited (FAO 2011). Two common ways of expanding global food production capacity are to create more arable land (via new irrigation methods, new crops, forest degradation) and to increase the output from existing land (through genetic engineering, higher capacity fertilizers, and so on) (Bosschaert 2008). At this early stage of implementation, the relevance of ZFarming in terms of productivity is very low compared to rural production. It would require a wide implementation of ZFarming and other forms of urban agriculture to seriously consider ZFarming as a means of freeing up rural agricultural land. Only in cases of large-scale implementation of urban food production ZFarming and other forms of urban agriculture could potentially provide new landscape opportunities by taking pressure off agricultural land. Given that scenario, urban food production could compensate for the loss of arable land or allow more environmentally friendly methods of cultivation on existing farmland (Astee and Kishnani 2010; Delor 2011). Several studies go even further and talk of released farmland that could serve not only for food production, but also for bioenergy, more extensive agricultural production, and afforestation and nature protection (Sauerborn 2011). At the same time, it is obvious that the problem of damage to existing farmland cannot be tackled through the innovation of ZFarming or other types of urban food production alone, but will also require a shift in farming technologies and consumption patterns (e.g., conservation agriculture, reduced meat consumption, etc.) to take pressure off the land.

Environmental dimension: limitations

As mentioned above, there are several advantages to promoting ZFarming, but as this section will show, managing ZFarming is not unproblematic. For some of the envisaged applications, the technical solutions to recycling water, energy, and waste are known but need to be developed further. Besides technical constraints, we found further weaknesses, such as the lack of experience from case studies or the tendency of food activists and researchers to assume something inherent about the local scale.

Technical constraints

For some applications, the various individual technologies are known, but they have never been used together as required for ZFarming. Other applications require entirely new building materials or cultivation techniques. The integration and exchange of information between the various disciplines involved needs to be further encouraged to solve the remaining theoretical and practical issues. The consumption and production of (renewable) energy and concepts for building-integrated energy use and production can be seen as one of the most difficult issues in ZFarming. For indoor farms and production systems, opponents see the massive amounts of energy required to grow plants indoors as a major disadvantage. Because there is little access to daylight, artificial light must be provided. However, one of the highest efficiency gains in the last decade was in lighting and, consequently, future lighting systems might be substantially less energy demanding.

As has been highlighted before, ZFarming does not seem to be very sustainable if steps are not taken to introduce recycling systems. New systems with innovative technical solutions need to be developed for this to be achieved (Sauerborn 2011). In particular, the integration of rooftop greenhouses in the buildings' infrastructure poses technical challenges. Furthermore, no promising concepts can be found in the literature that allow for the production of effective nutrient solutions for hydroponic systems from organic matter. Existing hydroponic projects mainly use industrial fertilizers to optimize yields.

Lack of experience and bias in food system research

In the context of sustainability, one weakness of the literature is authors' presupposition that ZFarming is a sustainable strategy for the future. This claim mainly concerns environmental sustainability, but matters equally for social and economic issues. In some cases authors refer to proven facts but they often rely on their own "common sense." Frequently, studies state that "ZFarming is sustainable," even though several disadvantages and advantages, as well as primary and secondary costs and benefits, have not yet been scientifically analyzed.

Approximately half of the investigated studies are established on normative statements or analyze potential capacities, whereas the other half are based on experiences from case studies, experiments, analysis of demonstration projects, or feasibility studies. This fact suggests that not all "findings" are predicated on evidence. One example is the potential reduction of CO_2. Many authors logically state that reduced transport miles will save CO_2 emissions. However, the total CO_2 footprint has not yet been quantified. This bias might be explained by Born and Purcell (2006) who describe a widespread problem, the so-called "local trap," in food-system research. The local trap refers to the tendency of food activists and researchers to assume something inherent about the local scale. The local is assumed to be desirable; it is preferred a priori to larger scales. Born and Purcell (2006) argue that "local" is not good per se and underlying goals and objectives need to be considered.

General statements such as "ZFarming is ecologically sustainable" must be assessed with care, as they are not always based on verified research results. Furthermore, even if several benefits have been proven in case studies, they cannot simply be transferred, as they depend too much on specific local characteristics (e.g., potential water savings through utilization of rain water) and different local institutional arrangements. As Born and Purcell (2006) argue, the outcomes produced by a system are contextual and there is nothing inherently good about local production systems that could easily be as unsustainable in conventional agribusiness.

Social dimension: potentials

The main aim and motivation of ZFarming, as pointed out by the literature, is food production. For cities in developing countries or neighborhoods with limited food retail, ZFarming can contribute to improving basic food needs, whereas for cities in developed countries the additional social benefits are of paramount importance. As has been demonstrated in several projects, ZFarming has the potential to provide learning and education facilities for children and adult city-dwellers and help bridge the gap between consumers and producers. Moreover, designers and architects have recently considered the promise of ZFarming as a driver for developing new types of urban buildings.

Improving community food security

As increasing urbanization is seen as unavoidable (United Nations 2004), new approaches should contribute to delivering fresh, healthy food to cities (Brock 2008). As a special practice of urban agriculture, ZFarming brings several potentials for enhancing the situation of urban citizens' access to locally grown food. Many authors share the view that it can contribute to improving the provision of fresh food in future cities (Astee and Kishnani 2010; Bass and Baskaran 2001; Bosschaert 2008; Delor 2011; Despommier 2011; Hui 2011; Mendes 2008; Nelkin and Caplow 2008; Sauerborn 2011; Zande 2006). Its relevance for community food security varies geographically. With very rapid urbanization in many low-income countries, issues of food security differ from the urban food movements seen in developed countries. ZFarming practices range from community-based rooftop farming to commercial flagship projects using high-tech green architecture and are applied differently in different parts of the world.

In general, urban agriculture is an important topic in developing countries, and there is a broad variety of literature on urban rooftop gardens. These projects are not merely focused on commercial production purposes but on small-scale subsistence farming dedicated to family or community nutrition. For developing countries the opportunity to grow and/or acquire food produced locally is seen as a critical component of surviving in the city (Bryld 2003). Urban agriculture offers potential rewards and can contribute to reducing the vulnerability of specific urban groups by diversifying urban food sources (De Zeeuw 2011; Lovell 2010). This is primarily caused by the high densities of consumers in cities and the large proportion of poor people who have limited access to fresh food (Bryld 2003). ZFarming practices such as community rooftop farming or low-space vertical techniques for private usage could contribute to improving the food situation in those areas and contribute to the welfare of poor urban residents in particular.

In the northern hemisphere there is growing interest in improving urban food production, though from a different perspective than in the south. While urban agriculture in general cannot supply an entire city with all its food needs, it can significantly contribute to food security in certain neighborhoods (Ackerman 2011). The issue is equally relevant for neighborhoods with limited (fresh) food retail in developed countries ("food deserts") (Raja et al. 2008). APA (2007) says that access to healthy foods in low-income areas of the U.S. is an increasing problem for which urban food production (including ZFarming) can offer an important solution.

Even if the purpose is not to satisfy the basic hunger of inhabitants of cities in developing countries, it gives people an opportunity to supplement their diet and family income, and to reduce expenditures on food to allow other purchases. Like many scholars, Germer et al. (2011), Islam (2004), and Mendes (2008) see ZFarming as one of the solutions to the expected food crisis in densely populated urban production systems and as supporting food security, public health, and nutrition in urban areas in both developed and developing nations.

Provision of educational facilities

One of the major potentials for cities in developed countries is providing educational facilities through ZFarming concepts which are coupled with the experience of food production and consumption. A number of existing projects demonstrate how ZFarming activities can serve as showcases for education on food production. Famous examples include the Science Barge, an urban greenhouse and educational center that grows vegetables in New York City and is visited by school classes and thousands of visitors throughout the year.[2] Rooftop gardens and greenhouses can even serve as school gardens themselves, as demonstrated by the Manhattan School for Children.[3] A greenhouse on the school's rooftop serves as a hands-on learning facility for teaching about food and nutrition, as well as for empowering children to make educated choices about their impact on the environment. These types of facilities can be experienced as teaching spaces, contribute to environmental education, and provide opportunities for practical learning (Blyth and Menagh 2006). These facilities might serve to re-establish a certain respect and understanding of natural processes in the educational system, as farms and schools can be co-located (Bosschaert 2008).

Further studies performed in the field of training and education focus on the question of how knowledge of agricultural production systems can be produced and diffused in urban areas. De Wilt and Dobbelaar (2005) suggest integrated concepts of agricultural production sites, which are open to the public. They describe the concept of a "rural park" as a special form of an "agropark" that seeks to entertain and educate visitors, including children, by offering a more realistic impression of current food production and high-tech farming. From the social science perspective, Yuen and Hien (2005) and De Wilt and Dobbelaar (2005) address the human factors and reveal that images of traditional agriculture, mediated via education, ultimately determine the relationship of agriculture to the urban core (Brock 2008).

Linking consumers to food production

For decades, urban agriculture has been largely absent from Western cities. Yet, originally food sources were closely tied to urban forms. With the rise of industrialization and agribusiness, cheap transport and food preservation technology, the distance between farm and market has increased steadily, leading to an attrition of those ties in Western cities (Gorgolewski et al. 2011; Steel 2009). The emerging food movement is committed to reintroducing food systems into urban space. Particularly in developed countries, the understanding of "food system" or "food system planning" is associated with more than just food security. It increasingly encompasses individual and societal needs (e.g., trust and transparency, fairness, resilience) (Stierand 2008). ZFarming meets a trend in urban lifestyle, which is reflected by the longing of city inhabitants to become closer to the production of food again. Consumers ask for fresh, local food with low carbon footprints, more transparency, and closer involvement in the food production chain (APA 2007). There is a growing interest worldwide in establishing or re-activating gardens in cities. Bohn and Viljoen (2011) discovered that in northern countries, we are not dealing with integration but rather *re*-integration of production into cities and revealed a historical connection. They assume urban agriculture generally follows the principle of von Thünen, which was first proposed in 1826 by J.H. von Thünen in "The Isolated State."[4] Von Thünen concluded that the cultivation of a crop is only worthwhile within certain distances from the city, and outlined the economic and agricultural logic for locating fruit and vegetable production close to the consumer. As a special form of urban agriculture, ZFarming can be referred to as a "re-integration" (Bohn and Viljoen 2011) and "re-connection" (Schans 2010) of agricultural production back to the city. Within the field of community food security, numerous organizations are driven by the idea of helping city inhabitants re-connect with the production of food and bridging the gap between producer and consumer (De Wilt and Dobbelaar 2005). They have initiated programs to bring fresh, often local food, to 'food desert' areas. As Block et al. (2012) state, many of these projects have involved community gardens, urban agriculture, or farmers' markets and often pair environmental and community development goals through food growing and consumption.

ZFarming as a design inspiration

Architects and designers all over the world use the idea of ZFarming as a source of design inspiration and address the topic on both the functional and the aesthetical level. From the design perspective, ZFarming is challenged by the issue of how to relate food and architecture and thereby improve the visual amenity of future cities. The new idea of connecting food production with the built environment has already created visionary concepts for multifunctional buildings that are productive, eco-effective, and move beyond the primary function of housing (Ellingsen and Despommier 2008; Zande 2006). The architecture's reduction in environmental impact (Bohn and Viljoen

[2] See http://www.nysunworks.org.

[3] See http://www.manhattanschool.org.

[4] See http://www.thuenen.com.

2011) and the connection of aesthetic, ecological, and productive principles is seen as a design challenge (Komisar et al. 2009). Projects such as the "Ecological tower" (Sartoux and Rosenstiehl 2008), "Vertical farm" (Jacobs 2008), "Living skyscraper" (Kurasek 2008), "Center for urban agriculture" (Guenther 2008), "Sky farm" (Graff 2008), "Pyramid form" (Ellingsen 2008), "Coastal fog tower" (Fernandez and Ortega 2008), and "Dragonfly" (Callebaut 2009) can be seen as representative examples, but they only exist as architects' plans. MVRDV architects and the Danish Design Center developed and designed concepts of "pig cities" for commercial indoor pig farming.[5]

Design schools and architects use ZFarming to teach eco-effective design. In 1994, Todd and Todd (1994) described the concept of the "house as a biosphere" with the idea of designing a self-sustainable and functioning system. Further examples can be found at the Design Studio at Ryerson University, where Komisar et al. (2009) tackled agricultural and food issues from a design approach, aiming to connect the functional and symbolic relationships. Exhibitions such as "Carrot City" art projects such as "Waterpod", and "Public farm" were set up to spread the idea and inspire architects to integrate the experience of food production and consumption into housing (Roman 2010).[6]

Social dimension: limitations

The literature reveals some difficulties within the social dimension. One disadvantage lies in the production system itself and the fact that consumers are critical of soil-less growing techniques. Another concern is that if the practices of the local food movement are exclusionary, the food produced by this movement might not be accessible by the general population, thereby creating (further) inequalities in the availability of fresh food. Furthermore, critics point to health risks from food contaminated from air pollution or irrigation with improperly treated wastewater. Critics stress the importance of proper management to avoid the health risks associated with ZFarming practices.

Lack of acceptance of soil-less growing techniques

Many studies share the view that ZFarming in urban areas on a larger scale can only be realized by growing food with soil-less techniques such as aeroponics or hydroponics (Astee and Kishnani 2010; Despommier 2010; Nowak 2004; Rodriguez 2009). A number of suggested techniques originate in the concept of Controlled Environment Agriculture (CEA) (Nelkin and Caplow 2008). The advantages lie in the lightweight system, which can be employed when static loads restrict the use of heavy soil containers and less water is required.

One potential disadvantage in this context could be that there is little acceptance of soil-less growing techniques in society and people are critical of their use. This applies to the production method itself as well as to the products. Many consumers prefer 'naturally' produced food (De Wilt and Dobbelaar 2005) and refuse to buy products grown using hydroponic techniques.

Exclusionary practices and disparities

According to its advocates, ZFarming may contribute to economic, social, and health improvements in communities. These benefits are particularly important in underserved neighborhoods, including many low-income communities. However, analyzing current practices in New York City, Cohen et al. (2012) discovered significant disparities within the urban agriculture system, producing negative impacts for individuals, communities, and the system as a whole. They revealed inequities in access to funding, government grants, and in-kind assistance, as well as to information about these opportunities. Further studies in this context also refer to the U.S. These phenomena have not been investigated at length or discussed in other parts in the world.

According to Ackerman (2011), the stark disparities between neighborhoods, corresponding to socioeconomic inequalities, are the most striking characteristic of the public health environment in New York City. Critics describe a phenomenon experienced in the organic food movement as 'counter-cuisine' (Guthman 2003) to suggest that the success of the organic industry was largely wrapped up with gentrification and the class differentiation that it necessarily entailed. Guthman (2008) describes how the local food movement is tending to locate or distribute to areas of relative wealth and to cater to relatively well-off consumers. She discovered a lack of attention to questions of privilege, which has given rise to some stinging scholarly critiques of the contemporary U.S. alternative food movement of late. This critique may apply to ZFarming projects too, if they claim to deal with community food security issues while the products are only accessible to those who can afford them.

Given the costs associated with commercial ZFarming construction and operation, the commercial viability of rooftop hydroponic greenhouses depends on the production of high-value products, such as micro greens or tomatoes, that can be sold at a premium, especially in the off-season

[5] See MVRDV's example at http://www.mvrdv.nl/#/projects/181pigcity, and the Danish Design Center's example at http://en.ddc.dk/ddd2010-11/winners/pig-city.

[6] See these projects at http://www.ryerson.ca/carrotcity/, http://www.thewaterpod.org/about.html, and http://www.publicfarm1.org.

(Ackerman 2011), which makes them less accessible to the majority of the population. However, according to a study conducted by Cohen et al. (2012), interviewees were confident that urban agriculture could be a mechanism for political and social change to reduce disparities, provided that all farmers and gardeners were able to have a say in policy-making.

Food quality and health risks

Like rural agriculture, ZFarming entails risks to health and the environment if not managed or implemented properly. According to Lock and de Zeeuw (2001), urban agriculture can have both negative and positive effects on the health conditions of the urban population. The positive impacts on health and environment are dealt with in the sections on community food security and environmental benefits. The main health risks include irrigation with improperly treated wastewater and uptake of heavy metals and other pollutants from contaminated soils, water, and air. Another risk to consumers is from food-borne diseases being spread more easily in densely populated areas. Ensuring the quality and disease related healthiness of food would require strict management and control mechanisms.

Critics point to the risk of contamination of food through air pollution, especially in the case of urban rooftop gardens. For ground-based urban agriculture, a minimum distance is recommended between fields and main roads to reduce the contamination of crops by lead and cadmium (Säumel et al. 2012). According to a study by Lee-Smith and Prain (2006), an adequate health impact assessment of urban agriculture is still incomplete. Furthermore, there have been no investigations into the extent rooftops are affected by pollution from roads, and if rooftop greenhouse walls can help prevent contamination. Research questions remain concerning the risk posed by the contamination of urban food from air pollution, as well as from industrial effluents and the health risks of using biological wastes as fertilizer.

For greenhouse food production, proponents state that by applying CEA, the quality of food can be regulated and controlled more easily (Bosschaert 2008) as it allows for the growth medium to be regulated and for controls to be placed on the nutrients (McBride 1994). In general, greenhouse disease management in urban rooftop greenhouses is comparable to rural greenhouse production. Because plant population densities in greenhouses are usually very high and closely confined by the greenhouse walls, some virus diseases, foliar blights, leaf spots, stem and fruit rots, root rots, and other diseases can become severe very quickly. The importance of using sound crop management practices and integrated pest management (IPM) practices must be emphasized (Alberta, Agriculture and Rural Development 2012). Compared to conventional farming, Graff (2009) states that indoor farms would require fewer pesticides and fertilizers and could reduce the human health risks associated with high exposure to agrochemicals. Yet the demand to control pests and diseases in such ZFarming systems is not clear, but could also be high in comparison with regular horticultural practices (integrated as well as organic) in greenhouses. The risks of cross contamination increase when many community people are involved and share production facilities.

Economic dimension: potentials

In terms of potential economic advantages, bringing food production to urban areas is supposed to bring public benefits and commodity outputs. Operators need to consider the feasibility of products for rooftop gardens, rooftop greenhouses, and indoor farms and find the most promising products in terms of the production system and potential yield.

Urban food production as an economic advantage for urban areas

From the perspective of urban food production and planning, bringing the production closer to consumption is supposed to bring enormous public benefits and commodity outputs for urban areas (APA 2007). According to Pothukuchi and Kaufman (1999), food is very much an urban issue affecting the local economy because food sector establishments such as restaurants, fast food outlets, supermarkets, specialty food stores, bars, and food wholesaling are an important part of any city's economy. Consequently, the integration of local food systems in planning is supposed to require the greatest effort but also offers the greatest potential reward for urban areas. Growing food in cities may provide an additional source of agricultural capital (Bosschaert 2008; Lovell 2010). Settings for ZFarming can either be on public buildings (e.g., hospitals, schools, prisons) or private buildings (e.g., supermarkets, hotels, convention centers, apartment blocks, warehouses, shopping malls) (Caplow 2009). According to Rödiger (2009), conventional perceptions of rural and urban role models need to be changed, as does the assumption that there is no space for agriculture within cities. Commercial farms are set up for profit and may be combined with commercial kitchens to create value-added food products to sell at farmers' markets and restaurants (Hui 2011). This implies the creation of new jobs with various qualification levels and in various service sectors along the food chain. Even though urban farming on a large scale relies on a large production volume and is expected to be organized by professional entities, distribution channels can be diversified and dependencies on existing industrial farming economies could be reduced. Potential operators might be private companies, registered societies, or local government employing people to run their facilities (Bosschaert 2008). The establishment of connective producer networks, assisting farmers' markets and other programs that bring urban and rural producers together with urban consumers, is of particular interest (Ackerman 2011).

Potential products and yields

Several studies have tried to determine which products are feasible for the practical implementation of different types of ZFarming and have investigated some advantages and disadvantages in terms of agricultural yields.

For outdoor applications such as rooftop gardens or façades, the range of products would be limited to tolerant species (Lovell 2010). Hydroponic techniques are best suited economically and logistically to a range of vegetables that include leaf crops (spinach, lettuce, salad greens), vine crops (tomato, cucumber, pepper, squash, beans, zucchini) or culinary herbs (basil, parsley, chives, coriander) (Puri and Caplow 2009). For all indoor types of ZFarming, commonly suggested practices include hydroponically grown vegetables in combination with fish farms (Graber et al. 2011) or the coupling of horticulture, vermiculture, and aquaculture (Wilson 2004). For indoor production, spirulina algae (Bosschaert 2008), freshwater fish (e.g., tilapia, trout, stripped bass, carp), a wide range of crustaceans and mollusks (e.g., shrimp, crayfish, mussels) (Despommier 2009), fowl, and pigs have already been commercialized in greenhouses and are recommended for ZFarming (Ellingsen and Despommier 2008). There is also a great deal of potential for year-round production (Despommier 2011). As sunlight is preferable for most vegetables and lighting is one of the limiting factors, Brock (2008) suggests shade-tolerant species, such as mushrooms, edible fungi, or invertebrates (e.g., mussels, snail cultures or vermiculture). The use of "forgotten" or special vegetables is proposed for all types of ZFarming.

Yields are largely dependent on whether the application is an outdoor or indoor system. Possible yields from outdoor applications are affected by the surrounding climate, which differs substantially among the investigated locations.

For indoor farms, the potential yields are not yet validated but can be assumed from existing glasshouse technologies. Despommier (2011) states that secure greenhouses could supply significant amounts of vegetables, herbs, medically valuable plants, and fruits such as strawberries and blueberries. Hidaka et al. (2008) suggests that the yield for strawberries could be four times greater by applying a three-dimensional technique. Sauerborn (2011) states that one indoor hectare is equivalent to 5–7 outdoor hectares or more. Linsley and Caplow (2008) even project 20 times less land use and five times less water for the same yield using hydroponic cultivation techniques compared to conventional farming. According to Caplow (2009), a recirculating hydroponic greenhouse yields between 50 and 100 kg of vegetables per square meter/year.

The limitations of indoor farms are apparent in the production of cereals, feeds, root vegetables, and fruit trees. Cattle, horses, sheep, goats, and other large farm animals also seem to fall outside the paradigm of commercial urban agriculture (Ellingsen and Despommier 2008).

Economic dimension: limitations

One major challenge, which is important for all types of ZFarming, is the potential to integrate ZFarming into existing buildings considering the statics of buildings and the buildings' capacity to cope with add-on structures. There are also unanswered economic questions in the field of investment and financing. At this early stage of development, investment costs are too high and economic feasibility has not been exhaustively investigated, while secondary benefits are difficult to quantify. Moreover, the physical capacities of only a small number of cities have been investigated and the results are not transferable.

Challenges of constructing and retrofitting ZFarming buildings

One emerging issue in construction and engineering, which is important for all types of ZFarming, is the potential to integrate ZFarming into existing buildings. The key idea in this context is "retrofitting" (Castleton et al. 2010). Studies related to construction/civil engineering mainly deal with the statics of buildings and the buildings' capacity to cope with add-on structures. For gardens and greenhouses on existing buildings, the design will be limited to the load carrying capacity of the existing roof unless a higher initial cost is paid to upgrade the structure (Hui 2011). As the case of the "Jardin atlantique" shows, the capacity of buildings for add-on structures is enormous when the static requirements are considered from the beginning of the building project (Schäfer 1996). Rooftop accessibility is another major constraint for gardens or greenhouses on existing buildings (Kortright 2001). In addition to the utilization of rooftops, Yeang and Guerra (2008) developed retrofit designs to grow food on façades and external staircases. As small-scale ZFarming, rooftop gardens or small-scale rooftop greenhouses can adapt proven, low-cost technologies, while high-yield and space-efficient production forms such as vertical farms or large-scale rooftop greenhouses require buildings with high load-bearing capacities. Large-scale ZFarming requires investment in or development of new lightweight materials and techniques.

Competition with other types of use

Another unresolved question in terms of retrofitting is possible competition with other types of use, mainly renewable energy systems. A flat roof is one of the best locations for a solar energy system, given that the solar modules can be adjusted to the correct angle and the most appropriate orientation. For some proponents it is a mistaken belief that one has to decide between a green roof and a solar system. On the contrary, with the right system, significant synergy effects can be achieved when combining both. Prototypes combining both have already been put into practice (ZinCo 2012). Tests have shown that photovoltaic panels work more efficiently when mounted (on fixed frames) over a green roof that cools down the cells through evapotranspiration (Köhler et al. 2007). Meanwhile, the panels shade the plants thus reducing sun exposure and favoring heat-sensitive crops. While photovoltaic systems and ZFarming seem to offer a win–win combination, critics see them as conflicting uses of rooftop space. In some countries, house owners receive tax advantages if they rent their roofs to photovoltaic installers. As a result, it is the higher income and revenues that can result from renting or leasing the roofs for photovoltaic installation rather than the technical difficulties that lead to competition. In this case, food production competes with solar energy production because the average and most commonly used photovoltaic system cannot be combined with food production. There may also be competition for rooftop space from heating system installations or other building services. Another trend in some cities is to retrofit rooftop spaces for housing purposes that might generate higher revenues than ZFarming.

Financing

The economic feasibility of large-scale production on rooftops, in rooftop greenhouses, or in indoor farms has not been investigated fully and there are no long-term studies. Evidence from available studies varies according to the different applications of ZFarming. There are a range of studies on the costs and revenues of rooftop gardens, which have the longest tradition (St. Lawrence 1996). Those small-scale and low-tech applications are profitable in most cases. Nelms et al. (2005) provide an overview of performance categories and measure productive rooftop gardens and conclude that a density bonus would be required to offset the incremental costs and that external benefits, such as waste and water reuse opportunities, emission savings, and social benefits are difficult to quantify in financial terms. Wilson (2002) conducted a feasibility study on a commercial "aquaponic" rooftop microfarm in Australia and concluded that it would be profitable. The viability of a vertical farm enterprise was further investigated at Columbia University under the direction of Dr. Dickson Despommier. Most existing reports are positive but conclude that there are a number of risk factors in installing rooftop greenhouses or large-scale indoor farms and they can only be seen as viable if emphasis is placed on the secondary benefits as well (Bosschaert 2008). Nevertheless, few case studies have been conducted. Because the majority of projects are in the pilot stage, a critical issue is that investment costs are too high.

Production capacities of cities are not transferable

The physical potential of cities for ZFarming varies and studies investigating these capacities are still scarce. Rodriguez (2009) developed a method to estimate the potential area for rooftop food production for the city of London and extrapolated the amount of potential food production to meet food production targets, concluding that the potential roof space could produce 6 % of London's demand for vegetables without retrofitting and up to 60 % of that demand could be achieved through conversion or innovative use of roofs. Caplow (2009) calculated that the 5,000 ha of available unshaded rooftop space in New York is capable of meeting the demand for vegetables of more than 30 million people. This finding is confirmed by Ackerman (2011) who investigated the capacity of New York for urban food production and concluded that rooftops are a vast, under-used resource that could be transformed for food production. Further studies have been conducted on the potential of rooftop gardens in Hong Kong (Hui 2011) and Singapore (Astee and Kishnani 2010). For other cities, the potential production capacity of ZFarming has not yet been studied and can therefore not be transferred from investigated case studies.

Should urban agriculture reach a dimension where it replaces substantial parts of food produced in rural areas, ZFarming would present a serious challenge to the main industry in those areas.

Conclusion

This study used the framework of sustainability to understand the role of ZFarming in future urban food production. Rooftop gardens, rooftop greenhouses, and indoor farms have been set up worldwide and the initial results of their investigations are now available. According to current literature, ZFarming seems to have a high potential in environmental, social, and economic respects and has already found promoters across all disciplines from all over the world. At the same time it is a very new concept for food production, and thus at an early stage of research and development and facing some limitations and difficulties.

This analysis demonstrated that ZFarming has multiple functions and produces a range of non-food and non-market goods that may have positive impacts on the sustainability of the urban setting. It promises environmental advantages such as reducing the environmental impact of architecture, reducing food miles, and improving resource and energy efficiency. Social advantages include improving community food security, providing educational facilities, linking consumers to food production, and serving as a design inspiration. In economic terms, it provides potential public benefits and commodity outputs.

We stress that ZFarming deserves special attention as a food production strategy for very dense cities, where space for ground-based agriculture is a limited resource. This argument is even more relevant in large cities not surrounded by sufficient agricultural land. While the potential benefits vary between the different locations, the basic new ideas and opportunities for resources that come from integrating buildings and food production apply equally to all locations. The idea behind ZFarming is to organize future food production more efficiently by integrating the material and resource cycles. If by-products are not wasted but recycled, and waste-products get reused, potential synergies could be better realized.

Dealing with and managing ZFarming faces several difficult challenges. For some applications, the various individual technologies are known, but they have never been used together as required for ZFarming. Other applications require entirely new building materials or cultivation techniques that have not yet been developed. As well as technical constraints, we found further critical aspects, such as the problem of high investment costs; exclusionary effects due to restricted accessibility, exclusive products, and customers; and a lack of acceptance of soil-less growing techniques.

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. Operators need to use positive potentials meaningfully, by focusing on local resources, energy efficient production, building new market structures, and involving the social dimension.

We therefore want to encourage researchers and practitioners to work hand-in-hand to develop guidelines for the sustainable management of ZFarming practices. The integration and exchange of information among the various disciplines involved should be intensified further to solve unanswered theoretical and practical questions. This should also include assessing the role ZFarming plays in the broader food system (including storage, packaging, processing, sales, marketing, and distribution). To date, sustainability has been largely considered at the project level where the food is produced. Strategies must be developed locally, but they must take into account a broader picture than what is sometimes presented.

ZFarming will continue to play a role, and its relevance could develop from making a small additional contribution with a small share of food production for selected locations to providing a revolutionary alternative to our common understanding of food production for future cities. The real impact on sustainability will depend on the scale on which ZFarming will be applied in the future. The diffusion of ZFarming in terms of surface area will also determine if the identified potentials and limitations will remain relevant on the project level or if they will have an impact on the neighborhood, city, regional, or global level.

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