› Multifunctional rooftop horticulture: a promising strategy for intensifying horticulture production in cities

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In our urbanizing society, urban horticulture is gaining relevance due to its potential to increase resource efficiency, contribute to city food security and enhance associated ecosystem and social services. In cities, however, spaces available for cultivation are limited, thus leading to the need to explore innovative growing solutions, for instance, plant cultivation on building rooftops. While rooftop horticulture experiences are "sprouting" all over the world, scientific evidence on the most suitable growing solutions, policies and potential benefits is growing. The present review will address the main features of rooftop horticulture, providing an interdisciplinary assessment of different approaches for development and the multi-faceted forms that rooftop horticulture may assume in different contexts, bringing together existing experiences as well as suggestions for planning of future sustainable cities.

Rooftop horticulture: status and challenges

With the urban population now surpassing the rural one (Batty, 2015), the relevance of urban food production is today commonly recognised among national and international bodies (Orsini et al., 2013; De Zeeuw and Drechsel, 2015). Given the scarcity and high cost of land in cities, different agricultural and horticultural production and value chain intensification strategies are being explored in a number of cities and towns across the world. These include: (1) Optimising land/space rent of agricultural/horticultural production by intensifying soil-based cropping and animal husbandry, developing non-soil based production systems (hydroponics, containers) and/or switching to above ground, building-borne systems (like rooftop gardening); (2) Optimising income-adding value to horticultural production (including processing and direct producer-consumer relationships); (3) Optimising multiple urban functions of horticultural value chains (including recreation, landscape management and other functions); and (4) Optimising resource utilisation – improving the spatial connectivity of horticultural activities (promoting waste-water re-use in horticultural production; better linking waste management, production, processing and marketing-promoting food hubs) (Mougeot, 2015).

This article will specifically look into the first strategy and the possibility of supporting cultivation over existing paved surfaces, specifically in the form of rooftop horticulture. Rooftop horticulture may convert unused spaces such as building covers into food-producing units, providing a number of benefits for city dwellers (Eigenbrod and Gruda, 2015). Rooftop farming generally differs in the Global North and Global South of the world with regards to the growing systems used, as well as the main functions associated with it (that range from food production to a number of social and ecosystem services) (Viljoen and Howe, 2012). As rooftop farming experiences expand across the world, scientific information and evidence is being collected by a number of research institutions about the ways to integrate current cultivation technologies in urban buildings (recently referred to as "Zero-Acreage Farming", or "ZFarming") and how to maximise benefits associated with the different functions of urban horticulture (Thomaier et al., 2015). In developing countries, rooftop horticulture started to be adopted in the late eighties, mainly through the adoption of simplified low-depth soil and soilless systems (e.g. in wooden containers and using rice hulls or coir as growing substrates) (Marulanda and Izquierdo, 1993). Today, successful income-generating rooftop horticulture experiences have been reported in a number of countries, including Senegal (Saydee and Ujereh, 2002), Peru (Mezzetti et al., 2010), Egypt (Gertel and Samir, 2000), China and India (Doshi et al., 2003). Common features of these experiences are the low technical skills of the farmers involved, the use of low-cost materials and lower water-using production systems; the limited start-up and maintenance costs of the garden, the scarcity of regulatory standards (e.g. both in terms of produce quality and safety, as well as on the building structure/safety/load) and the strong orientation toward informal and community-based marketing options. Nonetheless, more high-tech and commercial rooftop gardens are being promoted on top of supermarkets, restaurants or office buildings in some situations, e.g. in China.

At the same time, the growth of rooftop horticulture in western countries is facing its own challenges. As the food production and marketing sector is strongly regulated, urban actors are required to adhere to standards that were created for rural environments and horticulture. Also, further development and innovations of the required technologies is needed, in order for rooftop farms to become financially sustainable. Furthermore, as the sector emerges, starting costs for such commercial and intensive systems are high, while profit or time for return on the investment are still uncertain. In addition, a main factor limiting the wider uptake and up-scaling of rooftop horticulture turns out to be the lack of coherent interdisciplinary policy frameworks, which should guide practitioners and investors into the sector. These should take into consideration policies for food security, climate change adaptation, comprehensive planning legislation, building regulations and overall the multi-functionality of rooftop horticulture (Specht et al., 2014).

Rooftop crop production

The main distinction amongst different rooftop horticulture projects relates to the technologies applied. Most widely used are the low-level technological systems such as those found on the rooftops of women's associations in Trujillo, Peru (Mezzetti et al., 2010), but also on social housing buildings in the city of Bologna, Italy (Marchetti et al., 2015) (Figure 1). These systems, first developed as a way to promote urban horticulture in the dense urban and low-income areas of developing countries, are characterised by the following features (Orsini et al., 2014):

Figure 1. Rooftop gardens in Dakar, Senegal (top left, Photo: M. Dubbeling), Cairo, Egypt (top right, Photo: Neveen Metwally), Trujillo, Peru (bottom left) and Bologna, Italy (bottom right), bottom two photos: F. Orsini.

- Growing containers are made from recycled materials (e.g. plastic bags or boxes, wooden containers, PVC pipes, bricks) (Figure 2).
- Growing media is either made out of compost (no fertilisation supplied) or by easily available and cheap materials (e.g. rice hulls, coir, sawdust, peat). Water cultures may be also used (in the form of simplified Nutrient Film Technique or floating system), although generally with reduced automation (e.g. manual water circulation and oxygenation control).
- Production is highly diversified (monoculture is rare), and mainly occurs under open air (although shade nets are used in hotter climates).
- Growers are living nearby (often in the same building), and generally cultivate as a family or a community (e.g. neighbourhood, women's groups) (Figure 3).
- Rooftop horticulture is promoted not only as a response to lack of alternative space on the ground, but also for safety issues (e.g. against theft) or social purposes (improvement of the environment, community management of joint resources, creation of a multi-purpose family space).

Alternatively, more sophisticated and technological systems present the following characterising features:

- Production mainly occurs in hydroponic systems, with the root system constantly or periodically wetted by a nutrient solution composed of water and dissolved mineral nutrients.
- Greenhouses are used in order to guarantee year-round harvests or to intensify production (Figure 4).
- Production is mainly sold through defined marketing channels, trade promotion strategies (social/eco labels) and a relevant rate of income is associated to non-horticultural services (events, courses, catering, etc.).
- Professional skills are involved in agronomic and financial management and in promotion/dissemination activities. Voluntary workers are often present.
- Particular care is given to the use of alternative/renewable energy sources (e.g. solar, wind) and energy/resource use efficiency (e.g. composting, rainwater collection from greenhouse or waste water re-use, LED lighting, residual heat recovery).

Rooftop greenhouse and high-tech cultivation systems share many features with conventional greenhouses. Nevertheless, most of the available technology (greenhouse structure and covering materials, heating and cooling systems, soilless cultivation systems), must be adapted to urban and rooftop environments. In this specific context, the main challenges include optimising the use of available resources (residual heat use, rainwater or grey water use for irrigation, CO_2 exchange, etc.), as well as conflicts between building and greenhouse requirements (e.g. weight and wind load, compatibility with a building's equipment and compliance with architectural codes, fire resistance and safety/access requirements).

Managing plant cultivation on rooftops

As plant cultivation enters the city and is conducted on top of buildings, a number of agronomical, ecological and environmental issues arise. Specific challenges are associated with nutrient and water management, environmental conditions shaped by the urban environment (e.g. exposure to wind, sunlight, rain), the relationship with beneficial fauna and pests, and safety measures required to obtain high quality products.

When container cultivation is adopted, the integration of compost (either prepared individually by the garden user or obtained from community composting) is advisable, since it also reduces the urban ecological footprint (Grard et al., 2015). Alternatively, when

Figure 2. Simplified soilless systems for rooftop farming. Simplified Nutrient Film Technique on PVC pipes (top), container cultivation in pallets (center), and simplified floating system (bottom). Photos: F. Orsini.

plants are grown in hydroponics (e.g. nutrient film technique or deep water culture), mineral fertilisers need to be dissolved directly into the water. As compared to traditional commercial cultivation, problems may arise in finding adequate fertilisers (not commonly distributed within cities) and in overall meeting of plant nutritional needs whilst avoiding salinity. This may be exacerbated by the fact that water used is generally obtained from municipal distribution systems, and, although drinkable, may not be optimal for irrigating plants (mainly due to high chlorine concentration). Other drawbacks of tap water usage are its high cost, that may represent up to 80% of the total cultivation costs, excluding labour (Sanyé-Mengual et al., 2015) and competition with the use of water for drinking, especially in water-scarce areas. Possible alternatives are provided by either rainwater harvesting or greywater treatment. Rainwater is often used because of its optimal microbiological and biochemical features (care should be taken when acid rain is common) and the absence of legal limitations on its use. It is often easy to collect rain on rooftops. Retaining rainwater on rooftops has additional benefits in terms of storm water management, related reduction of flood risks and a decrease in water volume going to waste-water treatment facilities and their associated energy and environmental costs (Cohen and Wijsman, 2014). However, constraints in relying on rainwater may include the uncertainty of replenishment of the reservoirs (and therefore the need for possible alternative water sources), and the additional weight load on the building if the water is stored on the rooftop. Greywater treatment is another option that can involve the re-use of the building water. When greywater is used for irrigation of edible crops, however, care needs to be taken in order to respect regulations and standards for both chemical and microbiological quality (by including and properly maintaining filtration devices). Furthermore, greywater may have unwanted concentrations of sodium, chloride and carbonates, which may result in lower crop yields. Periodic water analyses and mixing with alternative water sources prior to distribution are recommended.

Controlling pests in rooftop horticulture also demands specific management techniques different to those commonly practiced in rural horticulture. Urban environments lack the biodiversity commonly found in the surrounding countryside. On the one hand, pest pressure is generally reduced because of the low presence of alternative host crops/plants throughout the year. On the other hand, use of closed production systems (greenhouses), may result in combinations of high moisture and temperature levels that increase pest and disease incidence. In addition, the low horticultural skills of urban farmers, together with the application of wide-spectra pesticides may not only be harmful for human health, but also seriously threaten the beneficial fauna that otherwise would find a suitable environment in rooftop green infrastructures. In order to promote biodiversity, the use of perennial plants and flowering at different times of the year will be important to offer a permanent source of food and shelter for beneficial insects. The inclusion of small ponds may enable the creation of aquatic habitats that attract water-loving insects, although care would need to be taken to avoid the creation of mosquito breeding grounds.

Sustainable cultivation management in cities should also consider how air pollution may affect produce safety. Air pollutants (including heavy metals and particulate matter) may pose a risk to the edibility of the products. Recent reports have addressed the problem of how heavy metals may accumulate in soils, in plant tissue and on plant surfaces, drawing attention to the potential risks associated with urban agriculture and horticulture (Säumel et al., 2012; Jean-Soro et al., 2015). However, when urban products were compared to those obtained in concurrent experiments in horticultural production zones (where pollution from industrial use or intensive fertilisation existed), differences in accumulation were negligible (Vittori Antisari et al., 2015). Furthermore, by using soilless systems rather than soil and moving the cultivation from the ground to a building rooftop, heavy metal risk was dramatically reduced, for example, in both rosemary and eggplant (Vittori Antisari et al., 2015).

Multi-functional rooftop horticulture

The most immediate function associated with rooftop cultivation is obviously the production of food. A study comparing different urban cultivation systems in Cleveland (Ohio, USA) showed that hydroponic systems produced an average of 19.5 kg m^{-2} $year^{-1}$ versus 1.3 kg m^{-2} $year^{-1}$ obtained in conventional on-ground urban gardens (Grewal and Grew-

Figure 3. Community rooftop garden and bee keeping at Dakakker project, Rotterdam, The Netherlands. Photos: G. Silvestri.

al, 2012). Other studies report yields ranging from 18 (Altieri et al., 1999) to 50 (Drescher, 2004) kg m^{-2} $year^{-1}$. At city level in Toronto (Canada), Peck (2003) estimated that from 65 ha of "greened" rooftops growing vegetable crops, a yield of 4,700 t $year^{-1}$ could be generated, based on a mean yield of 7 kg m^{-2} $year^{-1}$. Kaethler (2006) stated that in Vancouver (Canada), it was easy to find rooftop gardens producing food above supermarkets, restaurants and social housing. Likewise, in Bologna (Italy), it was estimated that if the 82 ha of available rooftops hosted simplified soilless gardens, a potential yield of 12,500 t $year^{-1}$ could be obtained, covering more than three quarters of the city's vegetable requirements (Orsini et al., 2014). In the same case study, other potential benefits were estimated, including the creation of green corridors for biodiversity (up to 94 km of green corridors and a density of 0.67 km km^{-2}). Additional studies on the same pilot garden enabled identification of the overall environmental and financial sustainability of the proposed growing systems (Sanyé-Mengual et al., 2015). According to the survey, cultivation technique, crop yield and crop period strongly affected the environmental and economic outputs. For all types of production, irrigation was the element that had the greatest impact on the environment, thus supporting the recommendation to implement rainwater harvesting systems or to integrate greywater regenerating units. In addition, the utilisation of re-usable elements (like building or waste materials) and the intensity of garden use improved the sustainability performance. The financial viability of the production of vegetables was maximised for eggplant (0.13 € kg^{-1}) and tomato (0.16 € kg^{-1}) grown on substrate. Consistently, rooftop farming production proved to be an environmentally-friendly option to further develop urban local food security.

Beyond food production, the presence of greened infrastructures in urban environments may contribute not only to the mitigation of the urban heat island (Rosenzweig et al., 2006) but also to a wide range of ecosystem services, such as improving air quality (Speak et al., 2012), providing resilience to exceptional meteorological events (Gregoire and Clausen, 2011), improving storm water management (Cohen and Wijsman, 2014) and improving urban biodiversity and urban greening (Madre et al., 2014).

Micro-climate/temperature effects of rooftop farms can be high, as they:

- Protect the roof from direct solar radiation and thus reduce transfer of heat into the building mass below the green surface. This reduces both temperatures on rooftops themselves (comparing a green with a dark roof) and helps improve thermal comfort in apartments just below the roof;
- By evaporation, green roofs contribute to "cooling-off" ambient temperatures;
- Absorb pollution/dust particles.

By covering and protecting the roof from direct solar radiation (directly shading the building surface, which would otherwise absorb heat), rooftop gardens can reduce heat flux into the building, thus increasing – in periods of high temperature – thermal comfort for rooms located directly under the rooftop. Green and horticultural roofs thus reduce heat transfer through the roof and also reduce ambient temperatures on the roof surface, because a concrete building mass also radiates the stored heat again to the environment. Earlier research done in Durban (South Africa) showed that the air temperature above a bare roof was indeed higher than above a green roof. The average ambient air temperature above the green roof and bare roof from 24 March 2009 to 24 November 2009 was 22 and 41°C, respectively, thus showing an 18°C temperature difference. On average, there was a 2.7°C fluctuation in ambient temperatures above the green roof habitat with a maximum difference in temperature between the lowest and highest reading of 17.6°C. In contrast, the average fluctuation in ambient temperatures above the blank roof was 9.8°C, with a maximum difference in temperature between the lowest and highest reading of 45.6°C (Van Niekerk et al., 2011).

Apart from having a direct impact on building temperature comfort and on ambient temperatures above the rooftop, rooftop gardens may also contribute to cooling the city. Hard surfaces in urban environments, such as concrete, brick, asphalt and roofing, have a high thermal mass, collecting the sun's heat during the day and re-radiating it slowly back into the atmosphere. This contributes to a rise in the ambient temperature in cities. The degree to which temperature can be affected depends on the growing medium used (degree of evapotranspiration), soil depth, proportion of rooftop coverage, and the use of vertical space (e.g. also use of rooftop building facades, use of multi-layered tables). For rooftop horticulture involving greenhouses, the overall impact on climate change adaptation and temperature effects is hard to estimate. Greenhouses will reduce direct solar radiation on rooftop surfaces and thus help reduce rooftop and building temperatures. However, compared to open rooftop farms there will be no open air evaporation and cooling, so impacts on overall ambient air temperature is estimated to be lower. There has been promotion of greenhouse rooftop gardens in temperate climates for reduction of cold temperatures (and thus heating requirements), rather than for use in more tropical climates to help lower summer temperatures (and thus cooling requirements).

■ Figure 4. Gotham Greens rooftop greenhouse on the Whole Foods Market in Gowanus, New York City. Photos: K. Specht.

Greenhouses will not directly contribute to public greening (instead roofs will be covered with glass) and high investment costs may limit the potential for larger application.

Ambient cooling effects on a city (or neighbourhood) level can be expected only if larger areas of (preferably geographically-concentrated) rooftops – and other open spaces – are covered with vegetation. A scenario study implemented in 2009 in Melbourne (Australia), indicated that Average Summer Daily Maximum (ASDM) temperatures would be reduced by 0.3°C by doubling the density of vegetation in the central business district, or by 0.4°C with green roofs (green roof vegetation was 0.5 m high and covered 50% of building rooftops completely). Increasing vegetation density both at ground level and with green roofs reduced ASDM temperatures by 0.7°C. The same relative effect of vegetation on ASDM temperatures was predicted for 2050 and 2090 scenarios following expected climate change trends (Khare and Beckman, 2013). A 2005 study in Toronto, Canada, modelled the effect of implementing green roofs on low-rise buildings with low slope and flat roofs of areas greater than 350 m², and concluded that green roofs, implemented as a city-wide strategy, could mitigate the heat island effect by reducing local ambient temperatures by 0.5 to 2°C (Banting et al., 2005).

Green and horticultural roofs can improve the living environment in cities, by bringing nature back to often densely build-up spaces. Horticultural green roofs offer opportunities for relaxation and physical exercise close to people's homes. Rooftops can also contribute to the creation of a network of green spaces (green mosaic), connecting to other green open areas in the city (e.g. gardens, parks, public green spaces, water bodies). Plants can also act as noise buffers, reflecting and absorbing some sound. For example, dense vegetation can reduce noise levels by up to 5 dB for every 30 m of vegetation, up to a maximum reduction of 10 dB. Green roof habitats could therefore play an important role in absorbing and dampening the ambient noise levels in the city centre, as well as in office complexes, dense housing developments, and industrial zones (van Niekerk et al., 2011). Noise reduction is dependent on the thickness of the roof and the amount of (permanent) vegetation cover.

Finally, green infrastructures may also have social (e.g. recreational, educational, etc.) and financial functions (e.g. by increasing property values) (Thomaier et al., 2015).

Concluding remarks

This article summarises the different models and various advantages associated with rooftop horticulture. Taking into account the multiple challenges cities are faced with to provide enough food, environmental surfaces, and green and liveable areas for their citizens, rooftop horticulture is one form of urban horticulture that has specific potential in dense urban neighbourhoods and in areas where land is scarce/polluted or highly priced.

Based on the many economic, social, environmental and ecological benefits, and the large amount of open rooftop space available, the conversion of paved rooftops into urban green infrastructures seems a suitable strategy for most of our cities. However, further technological and policy development is required to design efficient rooftop horticulture systems that optimise space and their different benefits.

Transforming rooftops into horticultural land may be seen, not only as a way to provide a function for these urban vacant spaces, but also as a feasible strategy to return horticulture and green areas to spaces that have been turned into grey, hot and built-up areas during rapid, and often ill-planned, urbanisation processes.

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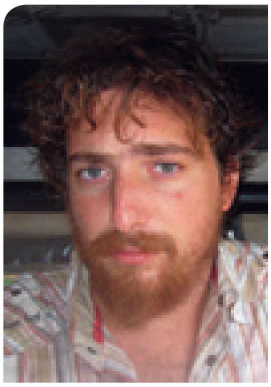

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