

## Urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future

S. L. G. Skar<sup>a,\*</sup>, R. Pineda-Martos<sup>b</sup>, A. Timpe<sup>c</sup>, B. Pölling<sup>d</sup>, K. Bohn<sup>e</sup>, M. Külvik<sup>f</sup>, C. Delgado<sup>g</sup>, C. M.G. Pedras<sup>h</sup>, T. A. Paço<sup>i</sup>, M. Čujić<sup>j</sup>, N. Tzortzakis<sup>k</sup>, A. Chrysargyris<sup>k</sup>, A. Peticila<sup>l</sup>, G. Alencikiene<sup>m</sup>, H. Monsees<sup>n</sup> and R. Junge<sup>o</sup>

<sup>a</sup> Division of Food Production and Society, Dept. of Horticulture, Norwegian Institute of Bioeconomic Research (NIBIO), P.O. BOX 115, 1431 Aas/Reddalsveien 215, 4886 Grimstad, Norway

<sup>b</sup> School of Agricultural Engineering, University of Sevilla, Sevilla, Spain

<sup>c</sup> RWTH Aachen University (Rheinisch-Westfälische Technische Hochschule Aachen), Germany

<sup>d</sup> South-Westphalia University of Applied Sciences, Soest, Germany

<sup>e</sup> School of Architecture and Design, University of Brighton, UK

<sup>f</sup> Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Friedrich Reinhold Kreutzwaldi 1, Tartu 51006, Estonia

<sup>g</sup> Faculdade de Ciências Sociais e Humanas – Interdisciplinary Center of Social Sciences – CICS.NOVA, Universidade Nova de Lisboa, Av. de Berna, 26-C, 1069-061 Lisboa, Portugal

<sup>h</sup> Faculdade de Ciências e Tecnologia, University of Algarve, Faro, Portugal

<sup>i</sup> LEAF, Linking Landscape, Environment, Agriculture and Food, Instituto Superior de Agronomia, Universidade de Lisboa, Lisboa, Portugal

<sup>j</sup> Vinca Institute of Nuclear Sciences, University of Belgrade, Mice Petrovica Alasa, Belgrade, Serbia

<sup>k</sup> Department of Agricultural Sciences, Biotechnology and Food Science, Cyprus University of Technology, Anexartisias 33, P.O. BOX 50329, 3603, Limassol, Cyprus

<sup>l</sup> USAMV Bucharest, Marasti Blv 59, Bucharest, Romania

<sup>m</sup> Kaunas University of Technology, Food Institute, K. Donelaičio St. 73, 44249 Kaunas, Lithuania

<sup>n</sup> Dpt. Ecophysiology and Aquaculture, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587 Berlin, Germany

<sup>o</sup> IUNR Institute of Natural Resource Sciences, ZHAW Zurich University of Applied Sciences, P.O. Box, CH-8820 Wädenswil, Switzerland

\*Corresponding author. E-mail: siv.skar@nibio.no

### Abstract

Research and practice during the last 20 years has shown that urban agriculture can contribute to minimising the effects of climate change by, at the same time, improving quality of life in urban areas. In order to do so most effectively, land use and spatial planning are crucial so as to obtain and maintain a supportive green infrastructure and to secure citizens' healthy living conditions. As people today trend more towards living in green and

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sustainable city centres that can offer fresh and locally produced food, cities become again places for growing food. The scope of urban agriculture thereby is to establish food production sites within the city's sphere; for example, through building-integrated agriculture including concepts such as aquaponics, indoor agriculture, vertical farming, rooftop production, edible walls, as well as through urban farms, edible landscapes, school gardens and community gardens. Embedded in changing urban food systems, the contribution of urban agriculture to creating sustainable and climate-friendly cities is pivotal as it has the capacity to integrate other resource streams such as water, waste and energy. This article describes some of the current aspects of the circular city debate where urban agriculture is pushing forward the development of material and resource cycling in cities.

**Key words:** agriculture, circular city, ecosystem services, infrastructure, recirculation, urban farming

## INTRODUCTION

Humans today face a plethora of environmental challenges. Some of them are aggravated by concentration of the populations in the cities, all of which constitute a complex set of future challenges; transport of people and goods (i.e. excessive carbon emissions), need for substantial rainfall absorption, high levels of air pollution, urban heat island effect, drinking water supply, waste management, lack of biodiversity. All these challenges result in illness and stress syndromes in the population. Urban agriculture has the potential to contribute towards minimising several of these adverse effects and thus improve the liveability of cities. This review aims to address and clarify some of these aspects, in order to facilitate the implementation of urban agriculture within the context of nature-based solutions (NBS) in circular cities of the future.

Currently, the majority of the world population growth is in the cities, especially in developing countries. Urban areas worldwide are expected to absorb all the population growth expected over the next four decades and continue to draw in the rural population (United Nations 2018). While cities today cover about 2–3% of all land area, they consume approximately 75% of the world's energy and generate 80% of the CO<sub>2</sub> emissions (UN 2018). The cities also utilise large quantities of water, create an enormous quantity of waste and pollute the air. Climate changes are predicted to cause more environmental stressors in the future, while we need to intensify food production (Junge & Graber 2014). The required transition will need increased flexibility of the urban environment, more sustainable use and re-use of natural resources as well as the adaptation of infrastructure systems (Herrera-Gomez *et al.* 2017). All this requires future city development to be smart and to integrate innovative solutions. One key to a more sustainable and healthy city development in the future might be in a relocation of the food system and a narrowing of the cities' foodsheds. This idea perfectly coincides with the idea of a circular city, where organic disposals are reused as resources to produce new agricultural products. The contemporary linear understanding of a city, where most independent entities consume, metabolise and dispose of resources, urgently needs – not only but especially in the field of food – a more systematic perspective to solve existing challenges.

In contrast to other infrastructures like water and electricity, the food production, and provisioning system did not get much attention in city planning and are still a neglected field (Pothukuchi & Kaufman 1999). It needs to be considered that in the process of building the modern city historical ties and links to the localised food system have been disrupted. During expansion, cities lost large areas of their surrounding fertile farmland and have mostly benefited from access to a globalised food system. The consequences of the globalisation of the food system can be seen in an abundance of food but also in the creation of a not sustainable industrialised system that overproduces, pollutes natural resources, declines biodiversity and stimulate obesity and malnourishment (Kennedy *et al.* 2004; IPBES 2019). It has also favoured massive path dependencies (Moragues-Faus *et al.* 2017) that can have a significant impact on food security and that needs to be identified and overcome to shape localised, circular economy-based food systems for the circular city.

Urban environment conditions, such as air quality, solar radiation and climate are inherently different from rural environments, and these differences may have an impact on crop growth (Eriksen-Hamel & Danso 2010). One of the risks for urban farming that stems from air pollution is decreased irradiance, caused by solar dimming, which is caused by increased reflectance of radiation away from the ground, due to air pollutants and aerosols over urban areas. Polluted urban areas can receive 8% less solar radiation than rural areas (Eriksen-Hamel & Danso 2010).

This article summarises major aspects related to urban agriculture in order to implement circular agriculture-based schemes in urban settings. What resources exist in an urban biosphere to bring into the context of urban agriculture? The main purpose of urban farming is to produce food within a city, but we also want to pay closer attention to other resources available from urban farming systems, which are usually considered to be waste.

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## URBAN AGRICULTURE AND CIRCULAR CITIES

### Urban food systems: urban agriculture and urban farming

As an increasingly popular phenomenon in different domains during the last twenty years, Urban Agriculture (Table 1) is discussed in science, policy-making, media and society and its definition is context-dependent (Delgado 2018). Because of the rapid development of the field, several interpretations of the term ‘urban agriculture’ exist, capturing nuances within different contexts. Amongst those, two definitions stand out: one from the seminal publication of the United Nations Development Program (UNDP) (Smit 1996); and the other from Mougeot (2001) which provides an extension of the former stressing that it is ‘its integration into the urban economic and ecological system’ that distinguishes urban from rural agriculture rather than its urban location only.

Smit’s and Mougeot’s definitions are nowadays the most commonly used ones and are valued for their simplicity, openness and implicit inclusion of a circular-city approach.

Urban agriculture spans all actors, communities, activities, places, and economies which focus on primary production in a spatial context categorised as ‘urban’ (Vejre *et al.* 2015), it can be structured into two sub-groups; urban food gardening and urban farming (Table 1). The common denominator of both is the bio-based output of products, which are harvested and consumed while other effects of urban agriculture on environment and society can be classified as by-products, externalities or co-benefits. These benefits can be classified into four dimensions: food security, economic, social and environmental (McEldowney 2017), and include contributing to employment, improved education and health, to social inclusion through integrating those at risk of social exclusion. *The business-as-usual farming* operation, as well as non-urban adapted farming, also exist in urban areas (Deelstra & Girardet 2000; Simon-Rojo *et al.* 2015). The key benefits include contributing to employment and the development of small-scale rural entrepreneurs; improved education and health; and to social inclusion, through integrating those at risk of social exclusion, such as migrants.

A food system encompasses the full value chain of producing food for human consumption, from agricultural activities and other means, through transportation, handling, processing, storage, distribution and consumption, to organic – including human – waste management and disposal/reintroduction into productive use (Eriksen 2008). A food system gathers all the elements: people, environment, infrastructures, inputs, processes, institutions and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes (Figure 1).

**Table 1** | Definitions of urban agriculture, urban farming and urban gardening

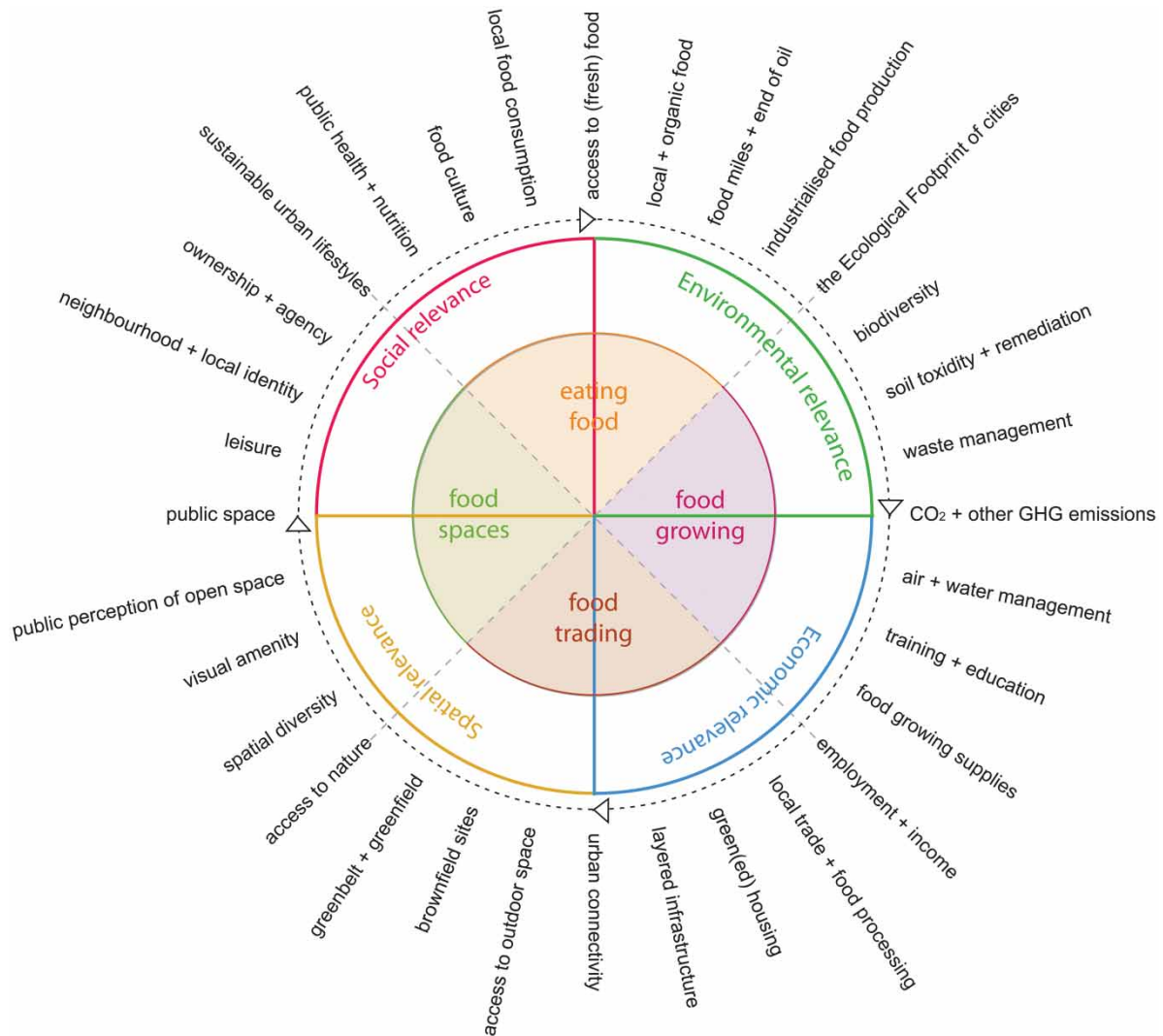
| Definition  | Source                               |
|---|--------------------------------------|
| Urban and peri-urban agriculture (UPA) can be defined as the growing of plants and the raising of animals within and around cities.<br>Urban and peri-urban agriculture provides food products from different types of crops (grains, root crops, vegetables, mushrooms, fruits), animals (poultry, rabbits, goats, sheep, cattle, pigs, guinea pigs, fish, etc.) as well as non-food products (e.g. aromatic and medicinal herbs, ornamental plants, tree products).<br>UPA includes trees managed for producing fruit and fuelwood, as well as tree systems integrated and managed with crops (agroforestry) and small-scale aquaculture. | FAO (2019)                           |
| Urban and peri-urban agriculture can be defined as the growing, processing and distribution of food and other products through plant cultivation and (seldom) raising livestock in and around cities for feeding local populations  | Game & Primus (2015)                 |
| Urban agriculture spans all actors, communities, activities, places and economies that focus on biological production in a spatial context which – according to local standards – is categorised as ‘urban’. Urban agriculture takes place in intra- and peri-urban areas and one of its key characteristics is that it is more deeply integrated into the urban system compared to other agriculture. Urban agriculture is structurally embedded in the urban fabric; it is integrated into the social and cultural life, economics and the metabolism of the city.  | Vejre <i>et al.</i> (2015)           |
| Urban agriculture is growing, processing and distribution of food or livestock within and around urban centres with the goal of generating income.  | McEldowney (2017);<br>Roggema (2016) |
| Urban agriculture is an industry that produces, processes and markets food and fuel, largely in response to the daily demand of consumers within a town, city or metropolis, on land and water dispersed throughout the urban and peri-urban area, applying intensive production methods, using and reusing natural resources and urban wastes, to yield a diversity of crops and livestock.  | Smit (1996)                          |
| Urban agriculture is an industry located within (intra-urban) or on the fringe (peri-urban) of a town, a city or a metropolis, which grows and 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.   | Mougeot (2001)                       |
| Urban food gardening encompasses agricultural activities with generally low economic dependence on the material outputs while using food production for achieving other, mostly social, goals.  | Simon-Rojo <i>et al.</i> (2015)      |
| Urban farming refers to intentional business models taking advantage of proximity to the city by offering local or regional agricultural products or services. The importance of the production in proportion to the other societal benefits can vary strongly (...), both, the production-oriented side or the co-benefit-oriented side may prevail depending on the individual practices of an urban farming operation.   | Pölling <i>et al.</i> (2015)         |

### Continuous productive urban landscapes (CPUL) and growing space typologies

Agriculture is space and time-bound: plants and animals grow in a certain place and at a certain pace. Thus finding space in cities and city-regions is a prerequisite for urban farming. While some of these spaces are well known, such as traditional farming land, allotment gardens or family gardens, other spaces might offer the potential for urban farming in a permanent or a temporary way (Table 2).

The *Continuous Productive Urban Landscapes (CPUL City)* concept (Viljoen *et al.* 2005) describes an urban future based on the planned and designed introduction interconnected urban landscapes defined by urban agriculture into existing and emerging cities. It follows a systemic approach using quantifiable and qualitative arguments to propose that urban agriculture contributes to more sustainable and resilient food systems while also adding beneficially to the spatial and social quality of the urban realm (Bohn 2016). A CPUL aims to interconnect urban food-producing landscapes within a city and to the citizens on the one hand and to connect these landscapes to the rural hinterland on the other and thereby facilitates activities across all parts of the urban food system.

This was illustrated also by the outcomes of the studies that evaluated the stakeholder perceptions of rooftop agriculture in Berlin and Barcelona (Sanyé-Mengual *et al.* 2015a; Specht *et al.* 2015a, 2015b) and concluded that even if there are a number of potential risks associated with the urban



**Figure 1** | This diagram shows the many links food, and the food system has with most aspects of urban life. It gives weight to spatial aspects related to urban food, including those related to urban agriculture.

farming system, stakeholders establish new market structures (e.g., short supply-chains) to overcome barriers and to ensure a socially accepted development of this new form of urban agriculture.

### Relationship between urban agriculture and green infrastructure

The significance of urban agriculture has been highlighted by a set of UN-Habitat reports on how cities can work with nature. In these reports, it is argued that to achieve environmental and economic resilience; biodiversity needs to be reinstated in urbanised areas (UN Habitat 2012). One of the major co-benefits of urban agriculture lies in its contribution to the urban environment, green infrastructure and the related ecosystem services (Viljoen *et al.* 2005; Santo *et al.* 2016; McEldowney 2017; Samson *et al.* 2017; Golden & Hoghooghi 2018; Piorr *et al.* 2018).

Green infrastructure is a significant element in European planning policies on all scale levels. It is one of the primary tools for achieving the EU Biodiversity Strategy 2020 (European Commission 2011) as well as smart, sustainable and inclusive growth defined by the Europe 2020 Strategy (European Commission 2010). Urban agriculture contributes to the ecosystem services of green infrastructure as a provisioning service for food, energy and raw materials, as well as through a range of other ecosystem services (Table 3).



**Table 2** | A typology of growing spaces for urban farming (adapted after *Santo et al. 2016*; *Simon-Rojo et al. 2015*)

| Typology of the city area           | Urban farming spaces in cities                 | Examples and references                      |
|-------------------------------------|--|--|
| Soil-bound spaces                   | Arable land                                    |  |
|                                     | Allotment gardens                              | Individual gardening (commune patch)         |
|                                     | Family gardens                                 | Individual gardening (private patch)         |
|                                     | Squatter gardens                               |  |
|                                     | Community gardens                              |  |
|                                     | Parks and other public green spaces            | <i>Van Leeuwen et al. (2010)</i>             |
|                                     | Urban derelict land                            | <i>Brown et al. (2016)</i>                   |
|                                     | Guerrilla gardening                            | Manchester, UK*                              |
| Mobile and soil-independent systems | Growing boxes and bags                         |  |
|                                     | Mobile containers                              | e.g. PAFF Box ( <i>Delaide et al. 2017</i> ) |
| Building bound spaces               | Rooftops:                                      | <i>Buehler &amp; Junge (2016)</i>            |
|                                     |  | Glasshouses                                  |
|                                     | – Open rooftops                                |  |
|                                     | – Covered rooftops                             |  |
|                                     | – Flat roof                                    |  |
|                                     | – Roof with inclination                        |  |
|                                     | Facades:                                       | Glasshouse                                   |
|                                     | – Open facades                                 |  |
|                                     | – Covered facades                              |  |
|                                     | Building extensions:                           |  |
| – Balconies                         |  |  |
| – Window sills                      |  |  |
|                                     | Indoor spaces with/without artificial lighting |  |
| Water bound spaces                  | Urban streams                                  |  |
|                                     | Urban stagnant waters                          | e.g. ponds, lakes                            |
|                                     | Amphibia systems                               | e.g. floating islands                        |

\*[http://www.urbanallotments.eu/fileadmin/uag/media/STSM/Binder\\_shortreportSTSM\\_final.pdf](http://www.urbanallotments.eu/fileadmin/uag/media/STSM/Binder_shortreportSTSM_final.pdf).

*Tóth & Timpe (2017)* have shown the quantitative importance of urban agriculture in the green infrastructure networks of four differently structured European urban regions (Dublin/Ireland, Sofia/Bulgaria, Ruhr Metropolis/Germany and Geneva/Switzerland). The regional green infrastructure systems of urban regions, which form a continuous system of open spaces often described as spatially coherent figures (green corridors, green wedges or green belts), can, in most cases, only achieve this claim of continuity if they include the semi-natural areas used for urban agriculture. Urban agriculture is an indispensable component of green urban systems.

### Biodiversity and ecosystem services

Due to their population density, urban areas have a very high demand for multiple ecosystem services. Moreover, cities play an essential role in climate change mitigation and is increasingly vulnerable to climate change impacts (*Rosenzweig et al. 2010*). To achieve well-functioning circular cities that ensure good quality of life for their residents, it is urgent to safeguard biodiversity and improve the supply of regulating, cultural and supporting ecosystem services (*McPhearson et al. 2015*). Environmental benefits associated with urban agriculture include increased biodiversity, mitigation of the ‘urban heat-island effect’ and a reduced risk of flooding (*McEldowney 2017*). Urban agriculture has enormous potential to provide multiple ecosystem services in addition to food production, significantly contribute to the functioning of green/blue infrastructure and mitigate climate change (*Lwasa et al. 2014*). However, to maximise multiple benefits that can arise from urban food production, urban agriculture has to adopt sustainable farming practices (for instance organic farming, use of agroecological approaches), ensure functional integration to the urban fabric, and

**Table 3** | Contributions of urban agriculture as green infrastructure (GI) based on [Timpe et al. \(2015\)](#)

| <b>Ecosystem Services TEEB (2015)<sup>a</sup>: ES Benefits Group</b> | <b>European Commission (2013a, 2013b): GI Benefits</b> | <b>Possible contribution of urban agriculture</b>  |
|--|--|--|
| Provisioning services  | Multifunctional resilient agriculture and forestry     | Providing food, fibre and biomass and enhancing pollination.   |
|  | Investment and employment                              | Employment in agriculture, investment in agricultural enterprises and buildings, productive and maintained land as contributions to a better local image.                        |
| Cultural services  | Tourism and recreation                                 | A broad range of recreational activities proposed on farms and in gardening associations, farms and gardens as a destination.  |
|  | Education  | Agriculture as a teaching resource and 'natural laboratory'.   |
|  | Health and wellbeing                                   | Farm work and gardening as activities for physical and mental health, access to healthy local food.  |
| Regulation services  | Enhanced efficiency of natural resources               | Maintenance of agricultural soil fertility, pollination through urban beekeeping.  |
|  | Climate change mitigation and adaptation               | The cooling effect of agricultural areas, carbon storage in soils.   |
|  | Water management                                       | Groundwater recharge and purification under agricultural soils, stormwater retention.  |
|  | Land and soil management                               | Reduction of soil erosion, maintaining/enhancing soil's organic matter, increasing soil fertility and productivity, mitigating land consumption, fragmentation and soil sealing. |
|  | Disaster prevention                                    | Flood hazard reduction through stormwater retention and agricultural polders, erosion control.   |
| Habitat  | Conservation benefits                                  | Maintenance of agrobiodiversity, maintenance of agricultural habitats.   |
|  | Low-carbon   | Short-chain food provision, local bioenergy from agriculture.  |

<sup>a</sup>The Economics of Ecosystems and Biodiversity – TEEB.

safeguard biodiversity key areas ([IPBES 2019](#)). This applies to both small-scale food production for personal or community use (urban food gardening) as well as commercial farming in urban areas (urban farming). [Table 3](#) shows the contributions of urban agriculture as this is what the green infrastructure is based on.

### Air pollution risk and agronomic considerations on urban farming

Pollution risks of urban food farming, understanding food production outdoors in open city spaces, can be combined with risk for food safety and content of pollutants in the food products. There are a few articles on this topic but more research is needed to fully understand the risks. There are three primary risks of gardening in cities and urban environment: soil, water and air pollution. For air pollution, there are three categories: (1) not accumulated in plants, (2) transport-vectors of pollutants and (3) pollutants that are taken up in plants. Within a city, many sources of pollution are present: e.g. traffic, industries, heating ([Ortolo 2017](#)).

Fruit trees are most affected by air pollution. The air pollution in China has caused damage to fruit trees by delaying sprouting, shortening the flowering period, accelerating senescence and reducing CO<sub>2</sub> assimilation. This resulted in a reduction of fruit numbers and premature dropping of fruit ([Zheng & Chen 1991](#)). High ozone concentrations cause chlorotic spotting, necrotic lesions and premature senescence in trees, vegetable crops and cereals ([Rich 1964](#); [Krupa et al. 2001](#)). The ambient air pollutants (SO<sub>2</sub>, NO<sub>x</sub>, SPM and RSPM) caused a significant reduction in total chlorophyll, carotenoid, ascorbic acid, plant height, shoot fresh weight, root fresh weight and yield of wheat and mustard crops grown at polluted sites ([Chauhan & Joshi 2010](#)). The elevation of CO<sub>2</sub> concentration has been shown to increase the yield of crops under laboratory conditions, but in reality the degree of growth stimulation is dampened in the environment due to high temperatures and increasing

tropospheric O<sub>3</sub> (Ainsworth 2008). A case study in Varanasi, India concluded that gaseous pollutants such as SO<sub>2</sub>, NO<sub>2</sub> and O<sub>3</sub> have damaging effects on the yield of wheat, mustard, mung and palak plants (Agrawal *et al.* 2003).

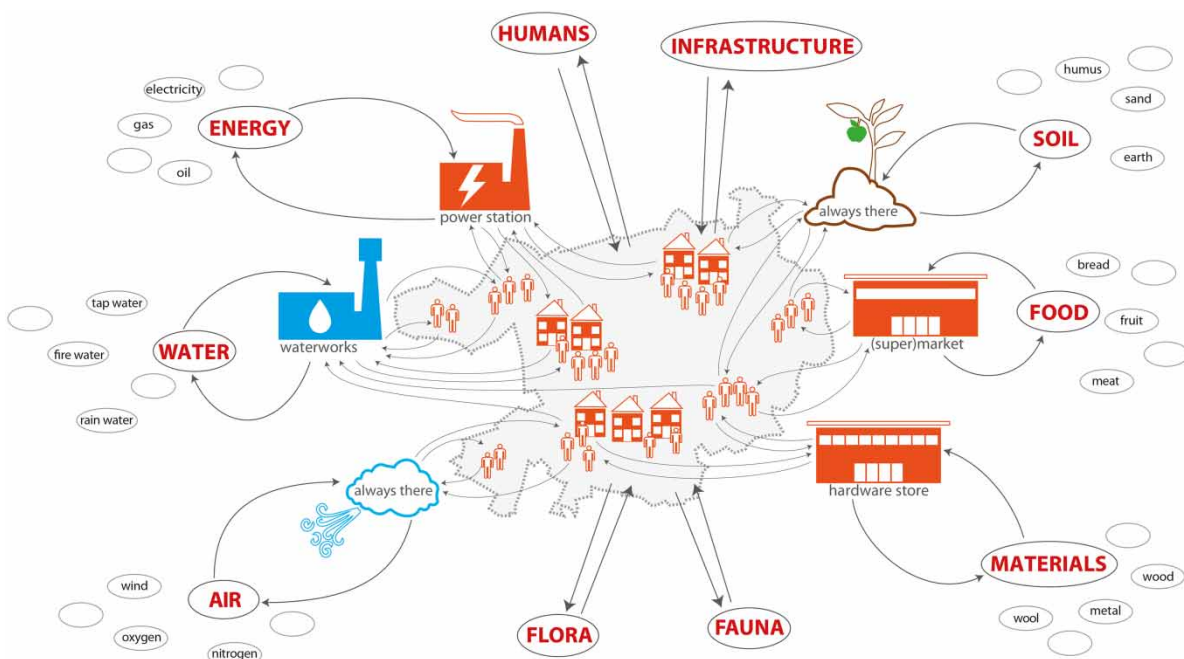
Apart from ozone, it can be difficult to identify the causal link between a specific gas and damage to crops, which is why there are few studies made on this topic (Hamel & Danso 2011). A study in Greece used a combined air quality and GIS modelling approach to estimate crop damages from photochemical air pollution (O<sub>3</sub>) and depict the corresponding economic damages. Total economic damage to crops turned out to be significant and estimated to be approximately 43 M€ for the reference year (Vlachokostas *et al.* 2010).

Suspended particulate matter has the most significant effect on crop yields and the quality of the crops. Atmospheric pollutant deposition has been noted as the most common pathway for lead contamination of leafy greens in Uganda (Nabulo *et al.* 2006). A study in Nigeria of the correlation between traffic emissions of Cd, Cu, Cr, Ni, Pb and Zn near a highway and the concentration of heavy metals in the vegetation and soil samples near the highway has been conducted. The study showed that roads have a significant effect on heavy metal accumulation in vegetation (Ndiokwere 1984).

## MATERIAL AND RESOURCE MANAGEMENT

### Resource management

Resources such as water, food and energy are what cities need to function (Figure 2). The entirety of resource streams and their interactions with each other, citizens and urban space are incredibly complex. Despite some of these resources being nature-based, most resources flows are linear: they are used and then disposed of. This linear urban metabolism (Rogers 1997; Daigger 2009) dominates in contemporary towns and cities all over the world, and it is causing a plethora of problems. The



**Figure 2** | Resource streams in urban metabolism. This diagram shows how food and the food system are located as part of other resource streams into and out of the city (Source: Bohn 2016).



circular approach explores how to manage resources by reducing, reusing and recycling. As a consequence, this leads to redesign of the urban, peri-urban and rural space, and to a new conceptualisation of their interlinkages. One of the critical elements in the development of closed-loop designs is a localised food systems approach, which also links to a broader understanding of a (peri-)urban water–energy–food nexus (Figure 2).

### Growing media

Soil is the ‘default’ growing substrate for plants, however urban soils are often degraded (De Kimpe & Morel 2000) and do not enable healthy plant growth. Therefore, replacing the soil with other substrates in urban environments, can contribute towards healthy produce. Based on chemical properties, growing media can be split into organic and inorganic (Table 4). The most important physical property is particle size, which affects the physical characteristics (e.g. porosity, water holding capacity, air space). Well-balanced physical and chemical properties of the growing media induce the plant growth and also promote biological activity (Maucieri *et al.* 2019). Also, it should be free of weeds, pathogens and toxins.

In circular cities of the future, it is important to focus on renewable materials from agricultural, industrial and municipal waste streams to identify beneficial and environmentally sustainable materials as growing media (European Commission 2019). It is environmentally beneficial to reuse and recycle renewable materials, and contributing to the circular economy (CE) which is, together with bioeconomy, supporting concepts in order to facilitate the transition to a sustainable society.

### Deposition of pollutants in soil

Particulate air pollutants are usually settleable by gravity and are deposited on the ground through wet and dry deposition. They cause acidification, salinisation and high heavy metals concentrations. To assess the influence of air pollution on soil composition, a study of heavy metals concentrations (Cd, Pb, Ni, Sb and Bi) in the settleable particulate matter in two locations in Spain has been performed. The study showed significant seasonal variability for heavy metal content and a strong dependence on rainfall in the area. The maximum values of heavy metals were measured in spring or autumn when there was the highest rainfall (Soriano *et al.* 2012).

Werkenthin *et al.* (2014) reviewed studies of metals in European roadside soils and concluded that the highest levels of Cr, Cu, Ni, Pb and Zn, were determined in the topsoil layer, and located in the first 5 m beside the road. Generally, the influence of traffic on soil contamination decreased with increasing soil depth and distance to the road.

Based on these findings, there are some concerns about the quality of food produced in the urban environment. The suitability of food produced in close proximity of urban traffic or other sources of pollution, should be closely examined.

### Available water resources

Treated domestic or municipal wastewater, also designated as reclaimed water, is used worldwide as an alternative water source. In some countries is even used as a water source for drinking water, such as in Singapore and Texas-USA (Yi *et al.* 2011). In California-USA, in full-scale large dimension projects, reclaimed water is being used for irrigation. In the near future, when the health and social objections existing presently in Europe, are overcome by the overwhelming current efficiency of advanced wastewater and water treatment technology, reclaimed water will become one of the most important sources of urban water (Norton-Brandão *et al.* 2013).

**Table 4** | Overview of substrates used in urban agriculture

| Substrate                                | Description  | References   |
|--|--|--|
| Soil                                     |  |  |
| Urban soil                               | Urban soil is often exposed to many strong influences which result in contamination and structural deterioration. Among others, urban soils can be contaminated with hydrocarbons and/or heavy metals, which can accumulate in produce and compromise human health. Before growing food in urban soils, soils have to be tested for exceeding the contaminant limits. Contaminated soil can be remediated with physical (soil excavation, washing and vapour) and biological (microbial, fungal remediation, phytoremediation) techniques. | Clarke <i>et al.</i> (2015); Jean-Soro <i>et al.</i> (2015); Schwarz <i>et al.</i> (2012)  |
| Substrates of organic origin             |  |  |
| Peats                                    | Result from anaerobic decomposition of peat mosses under waterlogged conditions. Depending on conditions under which they were generated, peats possess superb physical, chemical and biological properties suitable for plant growth. However, peat bogs are an endangered ecosystem and are mostly under protection. Therefore, peat substitutes should be used preferentially.  | Krucker <i>et al.</i> (2010); Michel (2010); Maucieri <i>et al.</i> (2019)   |
| Peat alternatives                        | Motivated by environmental, but also technical issues, many peat alternatives have been investigated, for example, ground fresh rice hulls (GRH), anaerobic digestion residues (ADR), coir dust or cocopeat, wood fibre substrates. Some have excellent properties to be used in soilless culture for the production of seedlings and transplants.   | Schmilewski (2008); Zanin <i>et al.</i> (2012); Gruda & Schnitzler (2006)  |
| Compost                                  | The result from the aerobic decomposition of plant material. When mature, composts ensure minimal medium shrinkage, oxygen consumption, nitrogen immobilisation and phytotoxicity. A wide array of organic waste can provide feedstocks for composting, this being the reason why it can be widely implemented also on a household level and in the cities.  | Maher <i>et al.</i> (2008); NiChualain <i>et al.</i> (2011); Raviv (2013); Barrett <i>et al.</i> (2016); Perez-Murcia <i>et al.</i> (2006) |
| Vermicompost                             | Results from the composting process using various species of earthworms and organic materials, such as plant and food waste.   | Bachman & Metzger (2008)   |
| Pyrolysis biochar                        | Biochar resulting from the pyrolysis of organic matter. It can be used as a soil amendment or as a part of substrate mixture. Pyrolysis process requires predominantly dry substrates (e.g. straw, faeces, wood chips).  | Bruun <i>et al.</i> (2012); Gold <i>et al.</i> (2018)  |
| HTC (hydrothermal carbonisation) biochar | Biochar resulting from hydrothermal carbonisation of organic matter. HTC also functions with predominantly wet substrates like sewage sludge or whey. It can be used as a soil amendment.  | Escala <i>et al.</i> (2012)  |
| Inorganic media                          |  |  |
| Sand and gravel                          | The coarse fractions of the soil minerals have particle size 0.02–2.0 mm (sand), and 5–20 mm (gravel). Coarse sand is preferred as a substrate for plant growth and rooting cuttings while fine sand is preferred for seedling production. Quartz (SiO <sub>2</sub> ) is the most common component of the sand fractions. Due to environmental constraints, natural sand dune extractions limit the use of sand as a growing media. Gravel is less used due to the low water holding capacity and heavyweight.                             | Lennard & Leonard (2006)   |

(continued)

**Table 4** | continued

| Substrate                            | Description  | References   |
|--------------------------------------|--|--|
| Perlite                              | A volcanic based inert, lightweight mineral with high porosity. It is produced at temperatures above 1,000 °C. It has a pH of 7.0–7.5 and contains no minerals available for plant needs. It is produced in various particle sizes. It is used in mixtures with other media. Similar to perlite, pumice is another volcanic based material.  | Verdonck <i>et al.</i> (1981); Maucieri <i>et al.</i> (2019) |
| Zeolites                             | Are usually formed by the metamorphosis of volcanic rocks but also from non-volcanic materials in marine deposits or aqueous environments. They have high ion exchange, adsorption, hydration-dehydration and catalysis properties, therefore also high pollutant removal capacity. Zeolite is used as a growing media component.  | Ming & Mumpton (1989); Harland <i>et al.</i> (1999)          |
| Vermiculite                          | A natural clay mineral with water molecules within its structure layers. It is produced similarly to and has similar physicochemical properties as perlite. It is produced in several particle sizes, which affects the physical characteristic of the material (e.g. porosity, water holding capacity, air space). Vermiculite has a pH of 7.0–7.5, low electrical conductivity (EC), and contains potassium (K) and magnesium (Mg).        | Verdonck <i>et al.</i> (1981); Maucieri <i>et al.</i> (2019) |
| Mineral wool/<br>Rockwool            | It is industrially produced by melting minerals at up to 1,600 °C and spinning the molten mixture at high speed into thin fibres (~5 µm diameter). Rockwool is often used in soilless cultures, providing advantages (sterile, inert and consistent in performance) but also limitations (lacks nutrient buffering capacity) in its use. However, it is a non-renewable resource, and the possibilities for recycling are currently limited. | Verdonck <i>et al.</i> (1981); Maucieri <i>et al.</i> (2019) |
| Nano-fertilisers                     | Nanotechnology can be used in the production of fertilisers due to the high efficiency and the homogenous distribution of nano-form of the nutrients. Nanoparticles (1–100 nm) confer improved efficacy in their physicochemical properties. However, the plants response to the nano-fertilisers is significantly different and dependent on plant type.  | Torabian <i>et al.</i> (2017); Nair <i>et al.</i> (2010)     |
| Light expanded clay aggregate (LECA) | LECA (ISO 10–20) is a building material made of clay, burnt and converted into small, porous, hard-surface spheres. The balls are used in growing beds for plants, as insulation, and as raw materials for blocks, pipes and other elements.   | Maucieri <i>et al.</i> (2019)                                |

Linking urban water usage to urban agriculture has the potential to be mutually beneficial. Availability of safe alternative water sources may: (i) facilitate higher uptake of urban agriculture, (ii) proper use or reuse of municipal water which may improve stormwater and wastewater management, reduce sewer overload and nutrient loads to urban rivers and allow sewer mining for resource recovery (e.g. nutrients) (Tahir *et al.* 2018; Voulvoulis 2018). However, any long-term studies on the combined benefits, health risks and robustness of reuse systems in farming projects appear to be missing and are the research focus of only very few current projects, such as the case of Roof Water Gardens project (Million *et al.* 2016) and the HOUSEFUL project on innovative circular solutions and services for the housing sector ([www.houseful.eu](http://www.houseful.eu)).

Urban agriculture in a circular city should meet its water requirements by water resources which originate from within the urban watershed (Fletcher *et al.* 2013; Tahir *et al.* 2018; Voulvoulis 2018; Pratt *et al.* 2019); and, in this framework, tap water should not be the first choice. More appropriate

resources may comprise natural rainfall for rainfed farming, the usage of rainwater temporarily stored in cisterns – also called rainwater harvesting – or the usage of urban wastewater. Untreated urban wastewater is usually not considered in farming projects in developed countries due to significant public health concerns for farmers and consumers (Khalil & Kakar 2011; Drechsel *et al.* 2015; Khan *et al.* 2015; Okorogbona *et al.* 2018). However, the usage of treated or untreated greywater – wastewater generated in households or office buildings from streams without fecal contamination – (i.e. all streams except for the wastewater from toilets) recently received more attention as it also reclaims fertiliser resources such as nitrogen, potassium, calcium, magnesium, sodium and phosphorus (non-renewable resource) (Qadir *et al.* 2007; Chen *et al.* 2013; Oteng-Peprah *et al.* 2018). Some studies have shown that nutrient-rich wastewater can be productively reused in urban and peri-urban agricultural systems, contributing to crop yield and improving soil fertility, thus enhancing the resilience of urban areas (Murray & Buckley 2010; Drechsel *et al.* 2015).

### Irrigation water requirements

Some projects – including Urban GreenUP ([www.urbangreeup.eu](http://www.urbangreeup.eu)), CITYFOOD ([www.cityfood.igb-berlin.de](http://www.cityfood.igb-berlin.de)) and TUNESinURB ([www.tunsinurb.org](http://www.tunsinurb.org)) – have studied the sustainability of gardens, edible gardens and urban farming (Paço *et al.* 2019). The knowledge on irrigation water requirements considers a scenario where rainwater is harvested and stored for the irrigation season as a possible alternative or supplement to the current irrigation sources in Mediterranean cities, mainly where rainfall is less than 500 mm/year, concentrated in some months in wintertime, and the current water source is tap water. However, technical solutions to accommodate the water volumes involved, in what regards building structure and architecture, are needed as well as water pumping and irrigation systems costs analysis. Urban landscapes for environments with hot/dry summers can benefit from the use of low water requirements plants, namely native species (Paço *et al.* 2019). It is essential to quantify the water requirements of such species as little information exists.

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## CULTIVATION TECHNIQUES AND PRODUCTION SYSTEMS

The lack of soil fertility, available rural and urban land space, agricultural sectors' long distances from the urban centres provide the challenges and opportunities to develop urban agriculture. Therefore, in addition to conventional growing techniques in soil, different soilless techniques are implemented.

### Soilless cultures and hydroponics

Soilless culture is a technique to grow plants without soil, using inert media (e.g. rockwool, clay pebbles, coconut fibres) or no media, and supplied with a nutrient solution (i.e. water and soluble nutrients). Currently, the terms soilless culture and hydroponics are used as synonyms; however, hydroponics originally meant cultivation in a nutrient solution without supporting growing substrate as soil (Zanin *et al.* 2009).

In the horticulture, soilless cultures are the most important cultivation methods for effective production in greenhouses (Jensen 2010). The criteria for classification of soilless cultures are: presence and properties of substrates and containers, vertical or horizontal system, location (greenhouse, garden, integrated into the building), how the nutrient solution is administered to the plant (dripping watering, immersing in stagnant solution or through mist spray), and type of water circulation (open or closed systems) (see also Maucieri *et al.* 2018a, 2018b; Maucieri *et al.* 2019). Among the newest hydroponic technologies are 'aeroponic systems', drip irrigation and nutrient film technique (NFT). The most frequently cultivated species in this type of culture are vegetables, herbs and

medicinal plants. Under suitable conditions, decorative plants (e.g. roses, gerberas, carnations) can be grown as well (Savvas & Passam 2002).

### Aquaponics

To succeed with integrated production units, producing more than one type of product for sale, are highly sought. Aquaponics is a production technology which combines aquaculture production in recirculating aquaculture systems (RAS), with the soilless cultivation of plants (Graber & Junge 2009; Rakocy 2012; Monsees *et al.* 2017). The effluent from the fish (or other aquatic organisms) production unit supplies the horticultural unit with water and nutrients for plant growth. Since the nutrient profile can be individually adjusted by measuring the nutrient profile and adding missing nutrients, multiple plant species can be grown as monocultures or in polycultures (e.g. intercropping, companion planting (Maucieri *et al.* 2017)). A wide array of vegetables (Graber & Junge 2009; Monsees *et al.* 2019), flowers (Agha Rokh 2008), fruits (Schmautz *et al.* 2016), herbs (Nozzi *et al.* 2018) and berries (Villarroel *et al.* 2011) can be produced and serve the local market. Pest and disease management focuses on prevention and is based on principles of integrated pest management and organic agriculture (Némethy *et al.* 2016). Very different system set-ups can be customised to diverse requirements; high-/low-technological, commercial sizes, backyards systems, education and hobbies set-ups (Maucieri *et al.* 2018a, 2018b). Most common are freshwater systems on-land (Skar *et al.* 2015).

### Vertical farming

Vertical farming is a system of farming whereby living organisms (animals, plants, fungi and other forms of life) that are cultivated for food, fuel, fibre and other products or services are artificially stacked above each other, vertically. The concept of vertical farming is integrated into the urban production of fresh produce. These systems are very efficient in terms of land use due to reduced dependency on land resources (Pérez-Urrestarazu *et al.* 2015). Moreover, vertical farming can contribute to the effectiveness of the arable area for crops by constructing a high-rise building with many levels on the same footprint of land (Despommier 2010). Soilless culture and hydroponics can add inputs to that direction, with considerable savings on water, minerals and phytochemicals through the sustainable cultivation cropping systems.

## POLICIES AND REGULATIONS

### Governance

The governance of UA may primarily include such issues as land, land use, access, food and ecosystem health, education and the environment as well as heritage and cultural practices (Corcoran & Calvin 2015). Prové *et al.* (2015) established a conceptual framework for urban agriculture governance processes and identified characteristics which influence the processes of management of urban agriculture initiatives. The three levels of this framework, which include the main features of the governance of urban agriculture are: (i) **Urban context** (including the local geographic situation, economic and political situation, the agricultural context and the status of urban-rural relations); (ii) **External governance characteristics** (including public policies, partnerships, legitimisation processes); and (iii) **Internal governance characteristics**, which include the project objectives, spatial scale, temporality, actors and resources (land, finance and knowledge mobilised in the project). All these are embedded into the local situation, characterised by geography, climate, economic and political situation, cultural values and urban-rural relationships.



Of course, public policies that influence these three categories are very different (Figure 3). For example, urban gardening is not affected by agricultural policy. Thus, the analysis of governance will focus on urban agriculture initiatives with the active involvement of professional farmers and public policies that influence these initiatives, mainly agricultural policy and planning. The focus will be on the integration of agriculture and agrarian actors in the development of cities and especially in regional planning (UNUIAS 2010).

There are huge variety of UA activities and interventions, which can involve domestic, public and commercial projects, involving actors of different resources, skills, orientations and motivations. In general, because of intrinsic hybridity of UA governance, the policy linkages are often unexplicit and not considered strategical either by national governments or municipalities (Corcoran & Calvin 2015).

## BUSINESS MODELS IN URBAN AGRICULTURE

### Economically viable urban food production

City environments influence agriculture (Heimlich & Barnard 1992). Farmers located in such areas will have to adjust their farming to exploit all opportunities and to counter most of the restraints (van Huylenbroeck *et al.* 2005). The main hurdles for urban agriculture can be summarised into land-related constraints, conflicts caused by improper behaviours of urban dwellers, and economic incentives within cities outside farming. However, urban areas hold chances for economically viable food production strategies. Little attention was given to these positive effects of cities and agglomerations on farming in the past (Beauchesne & Bryant 1999). Cultivation, processing and marketing of urban farming’s food and non-food products take place in an environment of the highest demands (McClintock 2010). The potential of nearby and easily accessible large consumer groups, the concentration of particular societal demands and trends, and the innovative milieu in cities offer favourable framework conditions for local and short marketing channels both for agricultural products and for the provision of services associated with farming.

### Urban influence on business performance and success

Cities and agglomerations increasingly incentivise farms to adjust to the urban conditions aiming to achieve profitability and business success. By doing so, farms increase chances to maintain economically viable or enhance their business performance (van Veenhuizen & Danso 2007). When farms do not adjust adequately to the multifaceted and dynamic urban influences, they increasingly tend to give up

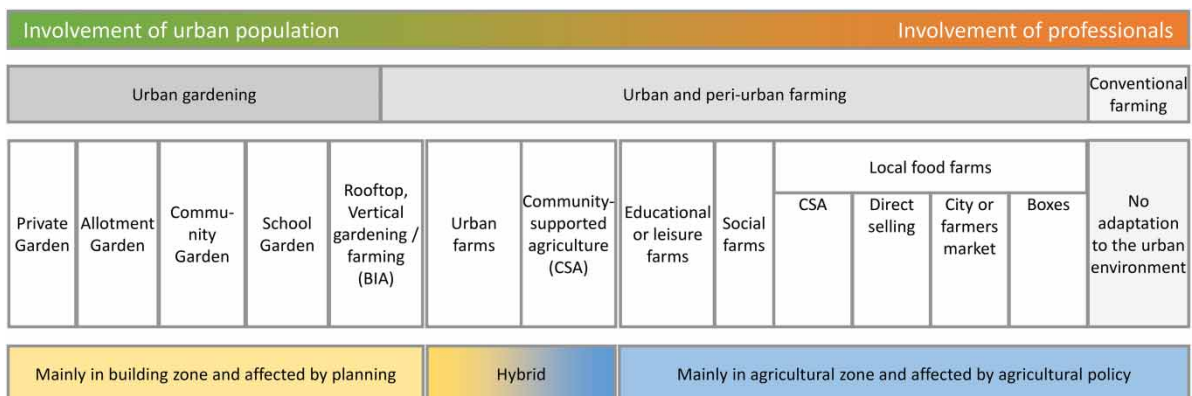


Figure 3 | Typologies and social aspects of urban agriculture initiatives (adapted after Mumenthaler 2015).

or turn into part-time or hobby farming with main revenues originating outside of agriculture (Zasada 2011). Gardner (1994) says that commercial farming in urban areas is surviving and even prospering when adjusting adequately to the cities. Thus, the diversity and complexity of urban influences result in a variety of city-adjusted farm strategies. Urban agriculture has been identified as being more diversified, polarised and multifaceted than elsewhere (Zasada 2011). Common strategies of urban agriculture focus on high-value production, product niches, short supply chains, Alternative Food Networks (AFNs) and the provision of services connected with agriculture (e.g. Heimlich & Barnard 1992; Gardner 1994; Bailey *et al.* 2000; Mougeot 2000; Houston 2005; Zasada 2011; Aubry *et al.* 2012; Aubry & Kebir 2013). Specialisation, niche production, multifunctionality, food chain management, quality of food, and embeddedness of food are listed by Wästfelt & Zhang (2016) as appropriate for urban agriculture activities. By focusing on the consumer side, Barbieri & Mahoney (2009) and Inwood & Sharp (2012) highlight that better chances of farm business survival and development exist for those city-adjustments which apply immediate consumer orientations and relationships. Agricultural innovations often take place on farms within metropolitan areas and subsequently diffuse into rural areas (Prain & de Zeeuw 2007; Elgåker & Wilton 2008; Zasada 2011).

### Business model classifications

The heterogeneity of urban farming's city adjustment strategies, as well as the lack of business model approaches are highlighted by Boons & Lüdeke-Freund (2013). Both have been providing the basis for the recent emergence of business model classifications in urban agriculture since a few years. While economies of scale is still an essential rural farming business model to stay competitive under intense cost pressures in the food sector, urban agriculture business models have to distinguish by adjusting to cities and move away from mainstream commodity market and global prices mechanisms. New business concepts have emerged on established (peri-)urban farms and also by newcomers and start-ups in urban agriculture. The specifically challenging, but also enabling urban conditions encourage innovations in farming, and result in the appearance of business models, which in many respects are different from rural farms. Product differentiation and enterprise diversification are the prevailing business models, but new forms of and new actors in urban agriculture raise experimental, shared economy and experience to emerging business models (Pölling *et al.* 2015; van der Schans *et al.* 2015).

The business model differentiation is frequently applied in urban areas to create distinctions in production, processing and marketing from the bulk market. Short food chains, especially direct sale, along with premium prices for specific product features (for instance super-fresh, ethnic, tasteful) are based on personal, transparent and honest producer/consumer relationships. Cost reduction represents the business model closest to rural farming. However, also farms located in agglomerations' peri-urban fringes use this low-cost approach for profitability, and in the urban context, specific expressions have emerged. Commons are specialisation in high-value crops (horticulture) and methods to reduce costs, like using available and cheap urban surplus resources (heat, sewage water, biomass) (Pölling *et al.* 2015).

### The business model: sharing economy model

Lately initiatives based on 'sharing economy' (or 'the commons') increasingly gain importance as an expression of the new economy. Resources required to run urban agriculture in the form of a shared economy model, e.g. Community Supported Agriculture, are jointly mobilised and managed: land, labour, credit, tools, machinery, network contacts and knowledge. The experience focuses on providing authentic and catchy memories by selling a story (experience) in addition to a product. Place-making and training or leisure activities are essential elements that in this model are combined with food production.

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## ANALYSIS OF CURRENT EUROPEAN PROJECTS

### Methods

The publications and projects were analysed regarding the potential contribution of the elements of urban farming systems to circular economy approach for a resourceful, resilient and sustainable city.

This study was based on the literature available from various bibliographic reference databases (namely Google Scholar, Research Gate, Web of Science, Scopus) and the work of CA17133 members. The systematic literature review process was applied to select the latest and the most relevant studies on this particular topic. Specific terms were used, like ‘nature-based solutions in cities and vegetable production’ and synonyms for ‘urban agriculture’, ‘urban farming’, ‘closed circular systems’, ‘business models’. The article’s relevance was discussed and grouped into three to six persons (authors) per groups, dealing with each topic related to urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future.

Defining all the terms, from urban agriculture to the contribution of elements of urban farming systems – specially developed for dense urban areas (e.g. underground, vertical and rooftop farming) – in a circular economy approach, helping to understand the status of a circular city based on project-database of COST Action CA17133. Two surveys were developed to the COST members concerning the: (1) projects participating in the COST Action; and (2) water sources, treatment, storage and irrigation systems. In the first survey, we combined expertise in food systems governance (Moragues-Faus *et al.* 2017), innovative production systems and business models, food safety, food waste, water consumption, irrigation systems, knowledge transfer, education, participation, alternative protein sources for feed and urban–rural nexus analysis. It was screened through the project-database and added peer-reviewed publications which we identified as key-articles for our field of research. It was also identified research gaps and extracted research questions which need to be answered to proceed into the design of a circular city. No quantitative information on current water sources, treatment, storage and operating irrigation system are available for current urban farming projects. To fill up this gap, the second survey was carried out within the 250 participants of the COST Action CA17133 Circular City, in February 2019 on water resources of urban farming research projects. (To find the nine questions, the list of surveyed research projects and their geographical distribution, please see the supplemental material.) The case of *green roofs in Lisbon* with native species study of urban landscape area, allows enhancing water use and sustainability in Mediterranean conditions.

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## CIRCULAR CITIES: A SURVEY OF PROJECTS PARTICIPATING IN THE COST ACTION CA17133

The relevant projects based on a keyword search through the COST Project collection are shown in Table 5. Fourteen keywords were selected based on the definitions of Food Systems (Table 1) definition and are listed on the table (see columns D to R). About our 14 words searched, several gaps were identified with significant absence: Food transportation and distribution, Food processing and transformation, Food storage, Consumption and Compost. Few references were found related to governance, consumers, citizens, and authorities. We analysed 13 projects (Table 5). However, some of them need to be seen as extremes. Project 9 (Pyrolysis of faecal wastes) is listed due to its potential to close the loop of the system.

The research areas addressed were: food policies, food systems, stakeholders engagement and awareness, urban and peri-urban agriculture for sustainable local development.

The survey includes also answers from COST members on the following questions:

1. What are the critical questions from a members point of view?
2. Critical points (gaps) enabling the contribution of urban farming to circular cities?

**Table 5** | Relevant projects identified by searching project-database of the COST Action on Circular Cities and publications

| No. | A<br>Project  | B<br>Website if applicable  | C<br>Location  |
|-----|---|---|--|
| 1   | Integrating Edible City Solutions for social resilient and sustainably productive cities – EdiCitNet  | <a href="https://cordis.europa.eu/project/rcn/216082/factsheet/en">https://cordis.europa.eu/project/rcn/216082/factsheet/en</a>   | Tygron and other world cities                                |
| 2   | Urban and Peri-Urban Agriculture for sustainable local development: The Multi-stakeholder Policy Action Planning as a tool for reconciling sectorial policies   | <a href="http://bit.ly/UPAforSustainableDevelopmentMulti-StakeholderPolicyAction">http://bit.ly/UPAforSustainableDevelopmentMulti-StakeholderPolicyAction</a>   | Portugal   |
| 3   | CITYFOOD – Smart integrated multi-trophic city food production systems – water and energy-saving approach for global urbanisation (2018–2021)   | <a href="https://www.igb-berlin.de/en/project/cityfood">https://www.igb-berlin.de/en/project/cityfood</a>   | Norway, Sweden, Germany, the Netherlands, Brazil and the USA |
| 4   | Continuous Productive Urban Landscape: Designing urban agriculture for sustainable cities   | <a href="http://www.foodurbanism.org/cpuls-continuous-productive-urban-landscapes/">http://www.foodurbanism.org/cpuls-continuous-productive-urban-landscapes/</a>   | Worldwide (sustainable urban design concept)                 |
| 5   | GEOFOOD (2018–2021)   | <a href="https://geofoodproject.eu/">https://geofoodproject.eu/</a>   | Iceland, Slovenia and the Netherlands                        |
| 6   | Living from the Earth – OTKA 116219 and OTKA 100682 (2016–2019) dealing with rural-urban divide and to make rural life attractive in Hungary, the changing role of the local small-scale agri-food production | <a href="https://www.aur.edu">https://www.aur.edu</a>   | Hungary  |
| 7   | NACHWUCHS – Nachhaltiges Agri-Urbanes zusammenWachsen (Sustainable AgriUrban Growth)  | <a href="https://urbact.eu/agri-urban">https://urbact.eu/agri-urban</a>   | Germany  |
| 8   | Plattform ‘Produktive Stadt’ [Platform ‘Productive City’]   | <a href="http://blogs.brighton.ac.uk/pulr/2019/06/10/platform-productive-city-holds-its-2nd-participatory-workshop-germany/">http://blogs.brighton.ac.uk/pulr/2019/06/10/platform-productive-city-holds-its-2nd-participatory-workshop-germany/</a> | Berlin (Germany)   |
| 9   | Pyrolysis of faecal wastes  | <a href="https://www.zhaw.ch/de/lsm/institute-zentren/iunr/ecological-engineering/oekotechnologie/biochar-sanitation/">https://www.zhaw.ch/de/lsm/institute-zentren/iunr/ecological-engineering/oekotechnologie/biochar-sanitation/</a>             | Waedenswil (Switzerland)                                     |
| 10  | Productive Green Infrastructure for post-industrial urban regeneration (proGIreg)   | <a href="http://www.progireg.eu/">http://www.progireg.eu/</a>   | Aachen (Germany)   |
| 11  | Urban Allotment Gardens in European Cities: Future, Challenges and Lessons Learned  | <a href="https://www.cost.eu/actions/TU1201">https://www.cost.eu/actions/TU1201</a>   | Riga (Latvia)  |
| 12  | Characterisation of nutrient recycling processes of a model aquaponic system  | <a href="https://www.zhaw.ch/de/lsm/institute-zentren/iunr/ecological-engineering/oekotechnologie/aquaponic/">https://www.zhaw.ch/de/lsm/institute-zentren/iunr/ecological-engineering/oekotechnologie/aquaponic/</a>                               | Waedenswil (Switzerland)                                     |
| 13  | The smart and sustainable city district of the future   | <a href="https://www.balticurbanlab.eu/goodpractices/hiedanranta-smart-and-sustainable-city-district-future-tampere">https://www.balticurbanlab.eu/goodpractices/hiedanranta-smart-and-sustainable-city-district-future-tampere</a>                 | Häme (Finland)   |

The search keywords were: circular cities.

- Why is the understanding of urban farming within the food system critical to circular cities?
- Why the understanding of urban farming within the food system is a critical shift from linear cities to circular cities?

The topics presented in the thirteen projects were (Table 6): stakeholders, food, production, transportation and distribution, storage, processing and transformation, food policy(-ies), food system, governance and authorities, consumers and citizens, farmers, urban farming, compost and the

**Table 6** | The goals of relevant projects identified by searching project-database of the COST action on circular cities and publications

| Topic                       | Project number |   |   |   |   |   |   |   |   |    |    |    |    |
|-----------------------------|----------------|---|---|---|---|---|---|---|---|----|----|----|----|
|                             | 1              | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| Stakeholders                | x              | x | x | x |   |   |   | x |   |    | x  |    |    |
| Food                        | x              | x | x | x | x | x | x | x | x |    | x  | x  | no |
| Production                  | x              |   | x | x |   | x | x | x | x | x  |    |    |    |
| Transportation/Distribution |                |   |   | x |   |   |   |   |   |    |    |    |    |
| Storage                     |                |   |   | x |   |   |   |   |   |    |    |    |    |
| Processing/Transformation   |                |   |   | x |   |   |   |   |   |    |    |    |    |
| Food Policy(-ies)           |                | x | x | x |   | x |   |   |   |    |    |    |    |
| Food System                 | x              | x | x | x | x |   |   |   |   |    |    |    |    |
| Governance/Authorities      |                |   |   | x |   |   |   | x |   |    | x  |    |    |
| Consumers/Citizens          | x              | x |   | x |   |   |   | x |   |    |    |    |    |
| Farmers                     |                |   | x | x |   |   |   |   |   |    |    |    |    |
| Urban Farming               |                |   |   |   |   | x | x |   |   |    |    | x  |    |
| Compost                     |                |   |   | x |   |   |   |   |   |    |    |    |    |
| Circular city               |                |   |   | x |   |   |   |   |   |    |    |    | x  |

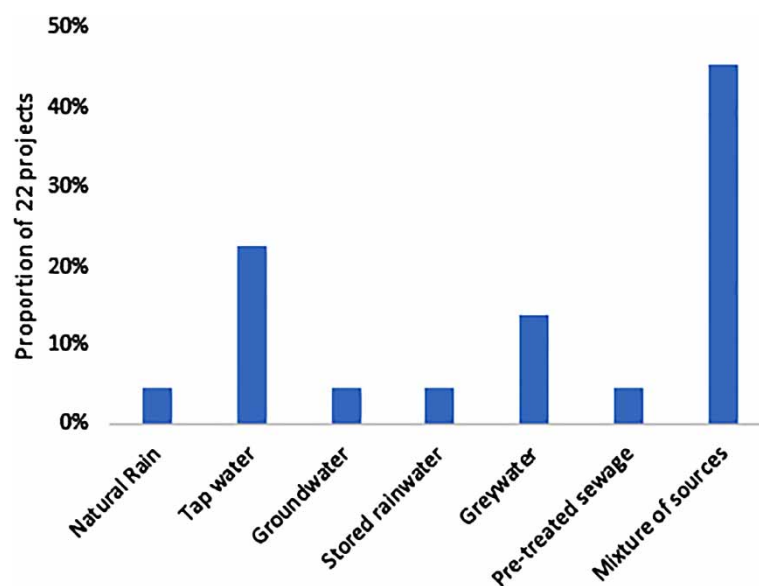
The numbers 1–13 denote the projects listed in Table 5.

circular city. Most projects covered topics related to food (11 out of 13), production (8 out of 13) and stakeholders (6 out of 13).

### Water sources, treatment, storage and irrigation systems

The survey yielded 22 research projects, which geographically covered most of Europe. Water sources used by the projects were very diverse (Figure 4).

Interestingly tap water, as the only water source was used by only 23% of the projects, while most projects (45%) used a mixture of sources. The use of wastewater, greywater or stored rainwater was rare – one project relied to 100% on natural rain.

**Figure 4** | Sources of water supply for 22 recent urban agriculture research projects participating in the COST Action CA17133, February 2019.



Regarding prior water treatment, 59% of the projects did not use any treatment of their water. The remaining used a variety of treatments including mechanical filters, plant-based, bio-reactor, sedimentation or disinfection systems. Only two of the ten hydroponic systems used greywater as a source.

The survey showed that (i) rainwater management or reuse infrastructures are often not readily in place to be used for urban agriculture projects, (ii) farming projects rely heavily on tap water and (iii) circular usage of water is not yet common except in the hydroponic projects.

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## CONCLUSIONS

The development of future cities is now advancing into smart and sustainable cities with a global understanding of how vital food production, supporting the circular economy, is. In 2050 about 50% of all people on earth are living in cities and will need clean water, food, energy, social space, meeting points, relax areas and knowledge pools.

### Land use and planning

It is visible that municipalities around the world are beginning to consider food issues in their city planning proactively, most evident perhaps in the Food Policy Pact signed by more than 180 cities since its foundation in 2015 during the Milan World Expo. This rapid development has followed the mainly practice-based, citizen-led experiences with urban agriculture that emerged, as a conscious movement, in cities and at their edges for nearly 20 years. It is now of great importance to integrate urban food production and other food system activities into urban planning, thereby linking sustainable food provision and circular resource processes to infrastructural productive urban landscape development.

### Water systems

Assessment of underlying spatial and temporal variability in water use decisions at a landscape scale regarding the water demand and irrigation water requirements in response to climate change and different urban farming location. Some projects (e.g. URBAN GreenUP; NativeScapeGR, Nature4-Cities, CITYFOOD) focus on mitigation the effects and risks of climate change and improving the water management cities. Other projects contribute to a better understanding of ecosystem services through evaluation and mapping the urban environments (TUNESinURB, Nedkov *et al.* 2017).

A better understanding how irrigation is used in the urban farming is needed to reduce pressures on limited freshwater resources, based on the knowledge how to use it efficiently based on economics, yield, environmental and social issues, aesthetics and safety for human health criteria. Assessment of underlying spatial and temporal variability in water use decisions at a landscape scale regarding the water demand and irrigation water requirements in response to climate change and different urban farming location.

What appears to be missing in most projects are concepts and experiences of water storage, rainwater harvesting and optimised usage of water with state-of-the-art irrigation systems. Very few long-term experiences exist at the moment for combining urban agriculture and any wastewater usage – as would fit within the concept of the circular city. As many current projects are using hydroponic systems, more research into a combination of hydroponic systems and wastewater reuse could be beneficial.

### Air pollution

The economic growth, industrialisation and urbanisation has caused increased concentrations of pollutants such as ozone (O<sub>3</sub>), nitrous oxides (NO<sub>x</sub>), sulphur dioxide (SO<sub>2</sub>) and suspended particulate matter (SPM) in urban areas. These gases can cause significant damage to crops.

Suspended particulate matter has the most significant effect on crop yields and the quality of the crops. Several studies ascertained the correlation between the atmospheric pollutant deposition originating from traffic emissions (e.g. Cd, Cu, Cr, Ni, Pb and Zn) and the concentration of heavy metals in the vegetation and soil samples. Therefore it is necessary to assess the suitability of produce grown near pollution sources for human consumption and also identify causal links between a specific pollutant and damage to crops.

### Education and knowledge transfer

Combined circular food systems – aquaculture and plant production together in the same system – are entirely new in the perspective of food production techniques and can also be implemented widely in education and knowledge transfer (Junge *et al.* 2019). In Norway, researchers have focused on the development of recirculating aquaculture systems (RAS) during the past 30 years, and the production of the most salmonids fingerlings grow in land-based RAS. In NIBIO Landvik, an aquaponics facility is operated with salmonids (brown *Salmo trutta*, rainbow trout *Oncorhynchus mykiss* and a relict salmon species called ‘bleke’ *Salmo salar* (Barlaup 2011), together with a wide range of plant species, such as wild herbs, Asian greens, edible flowers, leafy plants and several lettuce varieties (Skar *et al.* 2015). The system is used for research and education, and works as a showcase for an innovative approach to a more sustainable food production. The latest development is to apply the system to prisons, to create jobs, build skills and build prisoners’ social acceptance in city communities by producing local and healthy food for the surrounding community (Skar 2018). Together with the system in Norway, further aquaponic systems were constructed for educational and knowledge transfer purposes, e.g. within the CITYFOOD project in Brazil and Germany and within the AQU@TEACH project in the United Kingdom, Slovenia, Spain and Switzerland. These so-called ‘living labs’ are serving as perceptible demonstration sites and are a central part of a diverse communication and dissemination agenda.

### Knowledge gaps and further research question in urban agriculture

Consolidating the current knowledge on urban agriculture in green urban systems is needed. More knowledge is needed on multifunctionality and the relation to green infrastructure and food-productive urban landscapes, circular city debates and discussions of the possible adverse effect of air pollution on urban agriculture products’ quality. Improved sustainability in the cities by integrating with buildings and waste conversion sites.

To encourage more holistic solutions to the problem, we present a comprehensive overview of European projects and examples which consider circular city approaches on urban farming. Examples of solutions from our expertise and database COST Action is found here: [http://www.circular-city.eu/images/pdf\\_download/Proceedings\\_COST\\_WS\\_13-15Feb.pdf](http://www.circular-city.eu/images/pdf_download/Proceedings_COST_WS_13-15Feb.pdf).

Due to the mainstreamed globalisation of urban food systems, the entire production and marketing schemes have shifted to comfort the needs of globalised value chains. Changes like these in the built environment and the socio-cultural practice create path dependencies. A significant gap of research on what a change in food production, processing, distribution and consumption can and will do to the cities, especially in the area of transportation/logistics, green infrastructure, resource streams and all the physical requirements on which they are based (streets, shops, pipes, wires, channels and more). We also identified a gap in food governance research and realised an almost complete absence of the social dimension meaning the analysis of socio-cultural patterns and practices in the food preparation and consumption.

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## SUPPLEMENTARY MATERIAL

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