Landscape and Urban Planning 241 (2024) 104930

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

# Beyond food: A stochastic model to estimate the contributions of urban agriculture to sustainability

Josep Pueyo-Ros [a,b,*], Mateja Škerjanec [c], Joana A.C. Castellar [a,b], Nataša Atanasova [c], Joaquim Comas [a,d], Lluís Corominas [a,b]

[a] ICRA-CERCA. Catalan Institute for Water Research, Emili Grahit 101, 17003, Girona, Spain
[b] University of Girona, 17003, Girona, Spain
[c] University of Ljubljana, Faculty of Civil and Geodetic Engineering, Jamova 2, 1000, Ljubljana, Slovenia
[d] LEQUIA, Institute of the Environment, University of Girona, E-17071, Girona, Spain

## HIGHLIGHTS

- We estimate 8 indicators indicating the impacts of urban agriculture at a city scale.
- Urban agriculture impacts are sensitive to the type of urban garden.
- There are trade-offs among social and environmental benefits of urban agriculture.
- The model we introduce provides quantifiable evidence to reduce those trade-offs.

## ARTICLE INFO

*Keywords:*
Sustainability
Edible city solutions
Urban challenges
Nature-based solutions
Urban gardening

## ABSTRACT

In the first decades of the 21st century, urban agriculture has gained attention for its role in enhancing food security, particularly in developing nations. Additionally, it is commonly assumed that urban agriculture also has positive implications for other aspects of urban sustainability, such as mitigating runoff and creating job opportunities. However, the extent of these contributions has not been extensively quantified. This study aims to address this gap by presenting a stochastic model that quantifies the contributions of urban agriculture to urban sustainability, using Sant Feliu de Llobregat, a Mediterranean city, as a case study. We assessed eight indicators, including accessibility to green areas, food self-reliance, green surface area per capita, job creation, $NO_2$ sequestration, runoff mitigation, urban heat island effect, and volunteer participation. These indicators were estimated across twelve different simulated scenarios using 1000 Monte Carlo simulations for each scenario, to account for uncertainties. The findings revealed that the contributions of urban agriculture are not straightforward, as they are influenced by factors such as garden typology and location. Although urban agriculture typically originates as a grassroots movement, it often receives administrative support. Therefore, strategic planning can be employed to maximize the contributions of urban agriculture to urban sustainability and minimize trade-offs between social and environmental benefits.

## 1. Introduction

Urban agriculture can be defined as the practice of agricultural activities in urban areas (Tornaghi, 2014). However, it encompasses a wide range of typologies, including community gardens, backyards, school gardens, rooftop gardens, and animal-related activities such as beehives or chicken farms (Camps-Calvet et al., 2016). In recent decades, urban agriculture has garnered attention in academic and urban planning spheres for various reasons (Yan et al., 2022). Many of these reasons highlight the significance of urban agriculture in the context of a growing urban population (Ackerman et al., 2014). Consequently, urban agriculture is believed to play a critical role in ensuring food security in future cities, just as it has done during times of crisis or conflict (Barthel et al., 2015).

Urban agriculture has gained attention beyond academic circles. It is estimated that approximately 15–20 % of the world's food is produced

* Corresponding author at: ICRA-CERCA. Catalan Institute for Water Research, Emili Grahit 101, 17003, Girona, Spain.
*E-mail address:* jpueyo@icra.cat (J. Pueyo-Ros).

https://doi.org/10.1016/j.landurbplan.2023.104930
Received 23 August 2022; Received in revised form 11 October 2023; Accepted 17 October 2023
Available online 21 October 2023
0169-2046/

in cities worldwide (Artmann & Sartison, 2018). While cities in the Global South, such as La Havana, have been prominent in this phenomenon (Säumel et al., 2019), there are also noteworthy examples in the Global North, like Berlin, which boasts over 80,000 community gardens (Ghosh et al., 2008). Another illustration is the United Kingdom, where in 2010, the government announced the allocation of "underused and uncared-for land" to local communities to meet the demand of 100,000 people on allotment waiting lists and enable them to cultivate their own food (Tornaghi, 2014).

Within this context, several studies have focused on the actual or potential food production of urban agriculture (Grafius et al., 2020; McClintock et al., 2013; Richardson & Moskal, 2016). Meanwhile, others have examined social issues related to urban agriculture, such as the concept of commons or the social mechanisms involved, often with a critical perspective (Ambrose et al., 2020; Barthel et al., 2015; Tornaghi, 2014). However, other studies have embraced a broader understanding of urban agriculture, aligning it with the concept of Nature-Based Solutions (NBS) and recognizing its potential to address various urban challenges beyond food security (Artmann & Sartison, 2018), including its role in post-growth climate scenarios (Hickel et al., 2021). For instance, urban agriculture has been shown to contribute to public health by enhancing psychological and physical well-being (Soga, Gaston, et al., 2017). Moreover, in terms of economic well-being (Ackerman et al., 2014), urban agriculture can foster social cohesion and public engagement (Säumel et al., 2019). Furthermore, urban agriculture can play a part in climate mitigation and adaptation by reducing the urban heat island effect (Clinton et al., 2018), mitigating runoff during extreme rain events (Gittleman et al., 2017), and promoting circularity in cities (Ackerman et al., 2014). Lastly, urban agriculture can also support urban biodiversity (Lin et al., 2015).

Although previous studies have highlighted the various benefits provided by urban agriculture, the quantification of these benefits remains limited and lacks systematic approaches (Langemeyer et al., 2021). In many cases, the evidence presented is qualitative and difficult to replicate or generalize (Tong et al., 2020). Moreover, it often relies on stakeholders' perceptions and beliefs (Camps-Calvet et al., 2016). Nevertheless, certain studies have made efforts to quantify the benefits of urban agriculture beyond food production (Artmann & Sartison, 2018). However, most of these studies focus on single case studies, examining one initiative and one specific benefit. This lack of quantification is a common issue across various urban challenges addressed by urban agriculture. For example, there is limited understanding of the role of urban agriculture in reducing the urban heat island effect (Lin et al., 2015), contributing to a greener economy (Säumel et al., 2019), or promoting urban biodiversity through rooftop gardens (Artmann & Sartison, 2018). Furthermore, previous research has emphasized the need to assess these benefits at the city scale rather than through individual initiatives.

Therefore, our objective was to develop a model that estimates the potential of urban agriculture to contribute to multiple urban challenges at a city scale, serving as a proxy for urban sustainability. In pursuit of this objective, we adopted the urban challenges defined by the Eklipse project (Raymond et al., 2017), which include climate resilience, water management, green space management, air quality, urban regeneration, public participation, social justice, public health, green economy, and coastal resilience. This approach is consistent with most European projects focused on Nature-Based Solutions (NBS) (Castellar et al., 2021). We selected eight indicators directly linked to one or more urban challenges and estimated them within a specific city, considering twelve different scenarios, including a Business-as-Usual (BAU) scenario. The scenarios encompassed two attributes: the location of gardens (private gardens, vacant plots, and rooftops) and the level of commercialization (percentage of commercial gardens versus community gardens). The eight selected indicators were: urban heat island, runoff mitigation, accessibility to green areas, NO2 sequestration, job creation, volunteer involvement, green space per capita, and food self-reliance.

We selected Sant Feliu de Llobregat as our case study, a medium-sized city with approximately 44,000 inhabitants, located in the Metropolitan Area of Barcelona, Spain. This city presented itself as an appropriate case study due to its high population density (3853 inh $km^{-2}$) and its active involvement in various urban agriculture networks and projects, such as the EdiCitNet project (www.edicitnet.com). Furthermore, Sant Feliu de Llobregat features an agrarian-protected park on the outskirts of the city. Nonetheless, our model can be applied to nearly any city, provided that the necessary data is available.

To the best of our knowledge, this study is the first to introduce a model that simulates urban agriculture scenarios and quantitatively estimates their benefits using a holistic and generalizable approach that considers all three dimensions of sustainability—environmental, social, and economic.

## 2. Methods

### 2.1. Urban representation

#### 2.1.1. Data acquisition

The urban representation of Sant Feliu de Llobregat (SFL) was constructed by merging information from three public databases. The primary source of data was the Spanish National Cadastre (www.sedecatastro.gob.es), which provided details on private buildings and their main uses (residential, industrial, commercial, etc.), as well as gardens, vacant plots, and trees. Additional information was obtained from the municipality's open data portal (https://opendata.santfeliu.cat), specifically regarding public green areas. This allowed us to identify areas with lawn, mulcher, raised beds, and vegetated pergolas. To fill any remaining data gaps, we utilized information from the Urban Atlas 2018 (European Environment Agency, 2020), particularly pertaining to roads, railways, and other grey public areas.

Furthermore, the height and slope data of buildings and other elements in the city were obtained from LIDARCAT v.2, which is a LIDAR dataset developed by the Catalan Institute of Cartography and Geology (ICGC, 2017). We processed this dataset to generate a digital surface model with a resolution of 1 m, utilizing the las2dem algorithm from LAStools (LAStools, 2021).

#### 2.1.2. Building the urban representation

The initial step involved preparing the tree layer. The cadastre provided a point layer indicating the location of each tree in the city. To estimate the tree canopy diameter, we randomly selected 200 trees and measured their diameters using aerial photography with a resolution of 0.5 m. The average diameter was found to be 4.56 m, the median diameter was 4.4 m, and the standard deviation was 1.80 m. The 95 % confidence interval for the diameter ranged from 2.2 to 7.95 m. After analysing the relationship between tree diameter and factors such as distance between trees and land cover, we determined that the median diameter would be the appropriate measure to use. Thus, we applied a buffer of 4.4 m to each tree point to represent the tree canopy. To ensure accuracy, we removed trees that overlapped with buildings using a difference algorithm.

Regarding vacant plots, the Spanish cadastre includes a specific category to identify these parcels, simplifying the extraction process along with private buildings and gardens.

All the prepared layers were merged using a sequential difference algorithm to prevent overlapping areas, following this prioritization order: trees > vacant plots > public green areas > urban atlas.

Furthermore, considering the slope of the terrain is crucial in determining suitable areas for urban gardening. In our study, we adopted a similar approach to a previous research conducted in Boston (Saha & Eckelman, 2017). However, instead of assigning a generalized slope value to each building based on the average slope, we quantified the effective flat surface by calculating the number of pixels with a slope of less than 5 degrees for each roof, garden, and vacant plot.

The resulting urban representation is a spatial dataset presented as a GIS vector layer, containing information about the land use categories (e.g., grass, paved area, tree, street, rooftop, etc.) and the corresponding flat area (area with a slope of less than 5 degrees) for each polygon within the city (Fig. 1).

### 2.2. Definition of scenarios

The urban representation served as the base scenario, and from there, additional scenarios were constructed by modifying two key aspects: the elements transformed into urban agriculture and the ratio between community and commercial gardens.

We identified three types of elements with potential for conversion into urban gardens: private gardens, vacant plots, and rooftops. These elements have been widely utilized in previous urban agriculture models (Grafius et al., 2020; Grewal & Grewal, 2012; Haberman et al., 2014; Hsieh et al., 2017; Saha & Eckelman, 2017; Tong et al., 2020). Consistent with these studies, our scenarios involved transforming private gardens into private edible gardens, vacant plots into soil-based community or commercial gardens, and rooftops into raised bed (community) or hydroponic (commercial) gardens. However, we only considered elements with a flat area larger than 100 $m^2$ for community and commercial gardens, and 10 $m^2$ for private gardens, following the approach of Saha & Eckelman (2017). Additionally, we assumed that community gardens would not utilize hydroponic technologies, as soilless methods are generally less prevalent in community initiatives (Caputo et al., 2020).

Similarly, we considered the feasibility of different types of urban gardens, with private gardens being the most feasible, followed by community and commercial gardens in vacant plots, and gardens on rooftops being the least feasible. Therefore, apart from the BAU scenario, we defined 11 additional scenarios (S1 to S3) with varying degrees of feasibility and proportions between community and commercial gardens (Fig. 2).

In terms of determining the area dedicated to growing vegetables within each parcel, it is important to note that previous studies have reported significant variations in the percentage values (Grafius et al., 2020; Grewal & Grewal, 2012; Hsieh et al., 2017). To address this variability, we established ranges for the percentage of the parcel area considered for urban agriculture: 2 %–30 % for private gardens, 52 %–75 % for vacant plots, and 60 %–62 % for rooftops. Within each scenario, the percentage of the edible area was randomly assigned within the corresponding range for each element converted to urban agriculture.

To account for the uncertainties in both the parameters and the indicators, we conducted a stochastic Monte Carlo simulation with 1,000 iterations for each scenario. The parameters were randomized using random uniform distributions based on the range found in the literature. Subsequently, the 5 % and 95 % confidence intervals, along with the median, were calculated for each indicator to provide a comprehensive understanding of the results.

### 2.3. Selection of indicators

The Urban Challenges, primarily defined by the Eklipse project (Raymond et al., 2017), can be assessed using a wide range of indicators. To guide our selection process, we referred to the handbook of indicators published by the NetworkNature of the European Commission (Dumitru & Wendling, 2021). The handbook provides a comprehensive list of 73 recommended indicators, along with an additional 373 indicators, organized into 12 urban challenges categories. From this extensive list, we carefully chose indicators that met the following criteria: (1) Measurability: The indicators can be quantitatively measured based on the area or location. (2) Direct Influence: Urban agriculture has a direct impact on the indicators, meaning that changes in urban agriculture will affect the indicator's values. (3) Relevance to urban challenges: The indicators are directly linked to a specific urban challenge, and at least

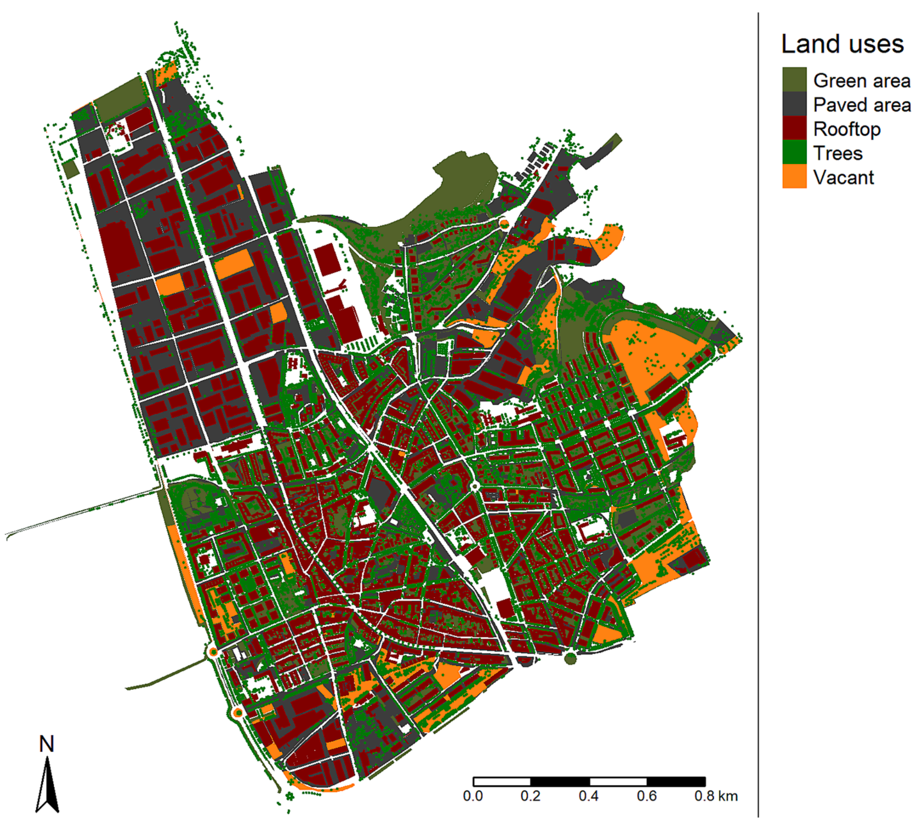


**Fig. 1.** The urban representation of Sant Feliu de Llobregat, showcasing the land uses employed by the model for the chosen case study. It is important to note that the model can accommodate alternative land covers, provided that the required parameters are specified.

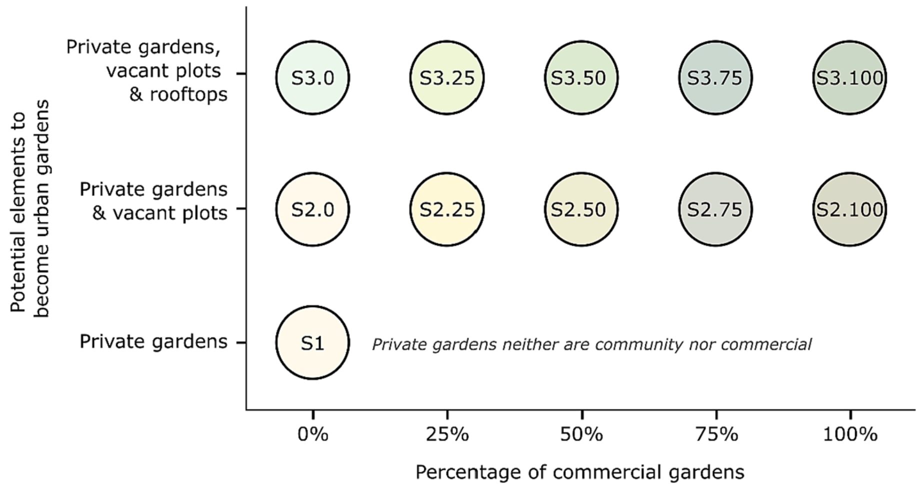


**Fig. 2.** Scenarios defined considering the potential of elements to become urban gardens and the percentage of commercial ones that is inverse to the proportion of community gardens (% of community + % of commercials = 100 %). Please note that, for private gardens, the percentage of commercial ones is not applicable. The BAU scenario is not included in the figure.

indirectly connected to another urban challenge, allowing us to capture multiple dimensions of urban sustainability.

By considering these criteria, we ensured that the selected indicators align closely with the objectives of our study and provide a holistic understanding of the impact of urban agriculture on urban challenges.

### 2.4. Description of indicators

All indicators were modeled using R software version 4.1 (R Core Team, 2022) and packaged into an R package accessible at https://github.com/icra/ediblecity. To facilitate the analysis, we utilized several R packages, including tidyverse version 1.3.1 (Wickham et al., 2019) for data manipulation and visualization, sf version 0.9 (Pebesma, 2018) for spatial operations, and stars version 0.5 (Pebesma, 2021) for handling raster data.

#### 2.4.1. Urban heat island

The urban heat island was selected as an indicator to measure the contributions of urban agriculture to climate change adaptation. However, it has also been proven to be closely related to public health and well-being, with heatwaves being one of the lethal consequences of climate change (Langemeyer et al., 2021; Panno et al., 2017).

This indicator calculates the temperature difference (in °C) between the urban street canyon and the rural environment. The urban heat island is most pronounced during the evening and night-time. The urban heat island equation was calculated at the cell level in a 5-meter resolution grid, following a model based on routine meteorological observations and urban morphological properties. This model has been tested in 14 different cities (Theeuwes et al., 2017), as follows:

$$UHI = \frac{1}{N}\sum_{i=1}^{N}(2 - SVF_i - Fveg_i)\cdot\sqrt[4]{\frac{\frac{Q_{ql}}{C_{air}\cdot P_{air}}\cdot\Delta T^3}{U}} \quad (1)$$

where $N$ is the number of cells in the raster, $SVF$ is the sky view factor in cell $i$, calculated using the *sky view factor* algorithm of SAGA tools (Conrad, 2008), based on the LIDAR dataset mentioned above. $Fveg$ is the percentage of vegetation in cell $i$, based on the attributes of the urban representation. $Q_{ql}$ is daily average global radiation (=6.11 W $m^{-2}$ $hr^{-1}$); $C_{air}$ is the air heat capacity (=1007 J); $P_{air}$ is the air density (=1.14 kg·$m^{-3}$); $\Delta T$ is the difference between the maximum and minimum daily average temperatures (=10.8 °C); and $U$ is the daily average wind speed (=2.77 m·$s^{-1}$). All meteorological variables ($Q_{ql}$, $C_{air}$, $P_{air}$, $\Delta T$ and $U$) were measured at the closest available station (~10 km) for the average August values from 2011 to 2020 and are assumed as constant in the entire study area.

#### 2.4.2. Runoff mitigation

Runoff mitigation was selected as an indicator to measure the contributions of urban agriculture to water management. Additionally, it plays a role in climate resilience as it helps mitigate the impacts of increased extreme rainfall events projected in all climate scenarios (Shukla et al., 2019).

This indicator quantifies the average height of runoff in the city following a rain event, measured in millimeters (mm). The model used to calculate this indicator is based on the widely recognized SCS (Soil Conservation Service) runoff curve number method (Cronshey et al., 1985):

$$Q = \frac{\sum_{i=1}^{N}\frac{(P_i - I_i)^2}{(P_i - I_i) + S_i}\cdot a_i}{\sum_{i=1}^{N} a_i} \quad (2)$$

where N is the number of plots in the city; $P$ is rainfall (for the study area, we considered a 15-minute rainfall event with a return period of 5 years, i.e., 85 mm/h); $I_i$ is the initial abstraction (which includes all losses before runoff begins) of plot $i$; and $S_i$ is the potential maximum soil moisture retention of plot $i$, which is a function of the curve number (1000/CN −10), multiplied by 25.4 to convert inches in millimetres. $S$ encompasses the effects of the land use and the hydrologic soil group. Furthermore, we made modifications to the model to accurately account for rainwater harvested. Therefore, we estimated $I_i$ as follows:

$$I_i = 0.2S_i + \min\{\mathrm{Rh}_i, \mathrm{Ws}_i\} \quad (2b)$$

where $Rh$ is estimated using the rain harvesting surface of the plot $i$, calculated as the amount of water felt on the surface of adjacent higher buildings that are not used for gardening (in litres); $Ws$ is the water storage capacity of the plot $i$, i.e., the volume of the tank (in litres), a random proportion of the garden surface is used between 0 (no tank) and 45 l·$m^{-2}$, based on common choices for tank size (Haque et al., 2016). The minimum value between rainwater harvested and stored is used.

The CN values used to calculate $S$ were obtained from the HEC-HMS Technical Reference Manual (USACE, 2022) considering hydrological soil group C (Ross et al., 2018). For situations where CN was dependent on soil conditions, we assigned a random value within the range between good and poor conditions, except for commercial gardens, where we assumed good soil conditions.

### 2.4.3. Green areas accessibility

This indicator measures the percentage of residences that are located more than 300 m away from any public green area larger than 0.5 ha, in accordance with the criteria set by the World Health Organization (WHO, 2017). In the context of urban agriculture, only community gardens situated in vacant plots or rooftops are considered as public green areas, in addition to parks and other conventional green spaces.

### 2.4.4. $NO_2$ sequestration

This indicator quantifies the amount of nitrogen dioxide (NO2) that is absorbed and sequestered by urban green spaces, including urban agriculture, measured in micrograms per second (μg/s). Nitrogen dioxide sequestration serves as a reliable indicator of overall air quality (Mayer, 1999), which is closely linked to public health, particularly respiratory diseases, heart diseases, and lung cancer (Kampa & Castanas, 2008).

$$NO_2seq = \sum_{i=1}^{N} a_i \cdot NO_2cap_i \tag{3}$$

where $a_i$ is the area in $m^2$ of the green area $i$; and $NO_2cap_i$ is the sequestration capacity of the green area $i$ in $\mu g \cdot m^{-2} \cdot s^{-1}$.

The sequestration capacity values differ based on the category of green area. For deciduous trees, the sequestration capacity is 0.11 $\mu g \cdot m^{-2} \cdot s^{-1}$, for tall herbaceous plants it is 0.09 $\mu g \cdot m^{-2} \cdot s^{-1}$, and for short grass it is 0.07 $\mu g \cdot m^{-2} \cdot s^{-1}$ (Yang et al., 2008). All green areas in the city are classified according to these values.

However, there are uncertainties in the classification of vacant plots and urban agriculture. Vacant plots can be populated by both grass and taller plants, and in urban agriculture, plants can have different heights (e.g., lettuce or tomatoes). To address these uncertainties, the indicator randomly assigns a value between 0.07 and 0.09 to each vacant plot and each urban garden. Additionally, in rooftop gardens, only the area dedicated to growing plants is considered for calculating the sequestration capacity.

### 2.4.5. Jobs created

This indicator estimates the number of full-time jobs created by urban agriculture in the city. Commercial urban agriculture, in particular, offers an opportunity for the creation of "Green-collar jobs" that require a wide range of skills (Falxa-Raymond et al., 2013). The establishment of new jobs in urban agriculture can have a significant impact, especially in areas with higher unemployment rates, thereby contributing to social equality among neighborhoods (Säumel et al., 2019). The indicator quantifies the total number of full-time jobs generated as a function of the surface of the plots:

$$jobs = \sum_{i=1}^{N} a_i \cdot k \in [0.000163,\ 0.022] \tag{4}$$

where $a$ is the area in $m^2$ dedicated to grow up plants in the commercial garden $i$; and $k$ is a random number between 0.000163 and 0.022. The value of $k$ represents the number of full-time jobs$\cdot m^{-2}$ needed in a commercial garden.

The range of $k$ was derived from an empirical study based on 50 urban gardens in Toronto, Canada (CoDyre et al., 2015). The study findings were consistent with data from the FoodMetres project (http://www.foodmetres-kp.eu), which estimated a constant value of 0.0077 jobs$\cdot m^{-2}$.

### 2.4.6. Volunteers involved

This indicator estimates the number of volunteers involved in community gardens. It uses the same equation as the previous indicator (equation (4) but assumes that a volunteer dedicates 10 % of the time compared to a full-time worker, which corresponds to 3.5 h per week. This assumption is based on data from previous studies that reported time engagement in community gardens, with average values ranging from 1.53 to 4.88 h (Ambrose et al., 2020; Soga, Cox, et al., 2017). Another study on the health benefits of community gardens considered a minimum dedication of 2.5 h per week to be considered an active gardener (Park et al., 2009).

Therefore, the Eq. (4) is used to estimate the number of volunteers, with a value of $k$ between 0.00163 and 0.22 volunteers per square meter.

### 2.4.7. Green per capita

This indicator focuses on environmental justice in green infrastructure planning, specifically addressing the distribution of public green spaces. Distributional justice refers to the unequal distribution of environmental qualities, such as the availability of green spaces (Kabisch & Haase, 2014; Rutt & Gulsrud, 2016). It is recognized that a fair and equitable distribution of green areas, particularly in socioeconomically disadvantaged neighbourhoods, can contribute significantly to urban regeneration and public health (de Vries et al., 2013).

The indicator measures the green space per capita at the district level and calculates the ratio between the district with the least green space and the district with the most green space. The calculation is as follows:

$$Ratio = \frac{min\{green \cdot inh^{-1}{}_i\}}{max\{green \cdot inh^{-1}{}_i\}} \in (0,1) \tag{5}$$

where *green* is the green surface in district $i$ and *inh* the number of inhabitants of district $i$.

In addition to public green areas, private gardens are also considered in the calculation of the district's green surface. This is important because wealthier areas tend to have more private gardens (Farahani et al., 2018), especially in densely populated cities like our study case. By including private gardens, the indicator aims to avoid favouring the wealthiest district by underestimating their actual green areas. This ensures that the indicator serves as a proxy for social justice.

Moreover, it should be noted that industrial and outskirts districts with fewer than 200 inhabitants were not included in the calculations. This decision was made to avoid disproportionately high numbers from these districts, which would not accurately represent the overall reality of the city.

### 2.4.8. Food self-reliance

This indicator quantifies the proportion of fresh food provided by urban agriculture, which has a direct impact on food security as well as on diet changes making people consume healthier food, thus positively affecting public health (Leake et al., 2009).

The equation for calculating food self-reliance is as follows:

$$Food\ security = \frac{\sum_{i=1}^{N} Yield(Type(area_i))}{inh \cdot consumption} \in (0,1) \tag{6}$$

where *Yield* is the production of a specific *Type* of urban garden (in kg$\cdot$year$^{-1}$), defined below; *area* is the area dedicated to growing up plants of garden $i$ (in $m^2$), which belongs to a specific *Type*; *inh* are the inhabitants in the city; and *consumption* is the amount of fresh food consumed per inhabitant (in kg$\cdot$year$^{-1}$).

Yield values for each type of urban garden were obtained from four studies that reported yields in soil-based gardens (CoDyre et al., 2015; Duchemin et al., 2009; Glavan et al., 2018; McClintock et al., 2013) and from two studies reporting yields on hydroponics (Asaduzzaman et al., 2015; Palencia et al., 2016). For soil-based gardens, minimum yields from selected studies were used to estimate a range for community gardens, while maximum yields were used to estimate a range for commercial gardens. This assumption is based on the idea that commercial gardens prioritize maximum production, while community gardens may have other priorities beyond production (Säumel et al., 2019). The yield range for private gardens was based on the understanding that it strongly depends on the motivations of the individuals or families managing them (Ghosh et al., 2008).

For hydroponic gardens, the yield estimation considered factors such as substrates, cultivars, irrigation methods, and environmental conditions. The range of yields for hydroponic rooftops was established by incorporating experimental values for the most commonly cultivated crops (tomato, lettuce, and cucumber) and the factors that can affect yields in this system.

In summary, the estimated yield ranges (in kg·m$^{-2}$·year$^{-1}$) for each type of urban garden are as follows. Private gardens: 0.2–6.6; community gardens (on ground or rooftop): 0.2-2-2; commercial gardens on ground: 4.0–6.6; hydroponic rooftops: 9–19.

The consumption of fresh food used in the calculation is based on the daily intake of fruits and vegetables recommended by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) in their joint report (FAO & WHO, 2004). The recommended daily intake is 200 g per day, which translates to 73 kg per year (Clark & Nicholas, 2013).

## 3. Results

### 3.1. Indicators to measure contributions to urban sustainability

We began with the ten urban challenges identified by the Eklipse project (Raymond et al., 2017). However, we excluded coastal resilience since it is not applicable to many cities that are not located by the sea. Additionally, we included food security as an urban challenge due to its significance in the urban agriculture literature.

Based on the criteria outlined in the methods section, we established a list of eight indicators (Fig. 3). Two urban challenges, urban regeneration and public health, lacked direct indicators that met the specified requirements. Nonetheless, several indicators indirectly addressed these challenges. This aspect is further discussed in the discussion section.

### 3.2. Potential contributions of urban agriculture in the case study

The first outcome of the scenario simulation is the conversion of private gardens, vacant plots, and rooftops into various forms of urban agriculture, such as edible private gardens, community gardens,

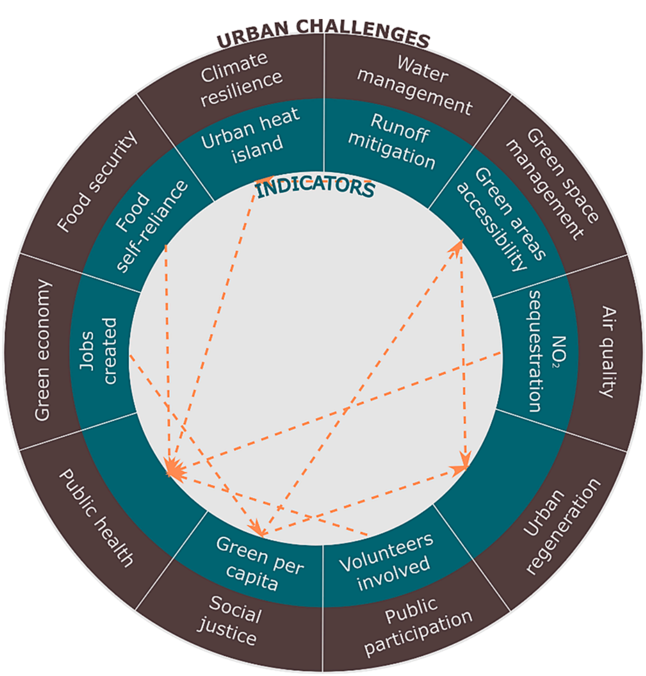


**Fig. 3.** Set of selected indicators and their relationship with urban challenges. Orange arrows indicate indirect measures of urban challenges.

commercial gardens, rooftop gardens, or hydroponic rooftops. The distribution of available spaces for urban agriculture is depicted in the maps (Fig. 4), where areas coloured in grey represent the baseline (BAU). It is observed that the majority of available spaces for urban agriculture are located in the peripheral areas of the urban zone. Due to the higher density of the downtown area, there are limited spaces large enough to accommodate urban agriculture initiatives. This is particularly evident in the case of vacant plots. Furthermore, the concentration of rooftops suitable for urban agriculture is predominantly found in the industrial northwest part of the city, as there are warehouses with flat rooftops in this area. As a result, rooftops are the most abundant spaces for urban agriculture, whereas vacant plots are the least abundant (see Table 1).

Most of the scenarios demonstrated a potential contribution to most indicators compared to the baseline (BAU) scenario. However, the magnitude of these contributions varies depending on the specific indicator. When examining the range of medians across scenarios, the indicator with the least variability was green area accessibility. The best scenario (S3.0) resulted in only a 0.1 % decrease (from 97.5 % to 87.3 %) in the proportion of houses located further than 300 m from any public green area larger than 0.5 ha. In contrast, the indicator for $NO_2$ sequestration exhibited an 18.5 % increase between the extreme values, ranging from 125 μg/s in the baseline scenario to 148 μg/s in the best scenario (S3). Considering the car emissions limitation imposed by the Euro 6 standard, this range is approximately equivalent to neutralizing emissions from 148 to 178 cars through urban green.

On the other hand, the green per capita indicator showed a 205 % improvement between the best and worst scenarios. However, the absolute values of the indicator did not change significantly between the greenest (S3.0) and greyest (BAU) scenarios, ranging from 0.0014 to 0.0043. Similarly, the urban heat island indicator also exhibited considerable variability in terms of percentual increment (25.4 %). However, the improvement in cooling between the worst and best scenarios was only 0.256 °C, ranging from a urban heat island value of 1.26 °C when rooftops were not included to a value of 1.01 °C when rooftops were considered.

Runoff mitigation presented a high percentual ratio of variability (45.5 %), and the range of absolute values was also significant, ranging from 45.76 mm in scenario S3.0 to 66.57 mm in scenario S3.100. The number of volunteers involved, jobs created, and food self-reliance were zero in the BAU scenario, making it impossible to calculate a percentual increment. However, all three indicators exhibited high variability. The highest number of volunteers involved was 34,635 (in scenario S3.0), representing 76 % of the population. The highest number of jobs created was 3,457 (in scenario S3.100), which is a significant contribution considering the city had 1,688 unemployed individuals in December 2022. The indicator for food self-reliance reached 52.67 % (also in scenario S3.100). Table 1 provides information on the number of parcels converted into specific urban agriculture elements in each scenario.

Despite the numbers provided in the previous paragraph, the indicators exhibited varying degrees of uncertainty, which were assessed through 1,000 stochastic Monte Carlo simulations for each scenario (Table 2). Some indicators showed minimal uncertainty, such as the case for urban heat island, green areas accessibility, and green per capita. Other indicators had low uncertainty, such as the most uncertain scenario for runoff mitigation, which had a range of uncertainty of 0.20 standard deviations (SD). Similarly, the uncertainty for $NO_2$ sequestration was 0.1 SD, indicating relatively low uncertainty. The food self-reliance indicator exhibited moderate uncertainty, reaching 1.32 SD. On the other hand, the number of volunteers involved and jobs created demonstrated the highest uncertainty ranges, with values of 6.14 SD and 4.54 SD, respectively.

As mentioned earlier, most scenarios contributed to the improvement of most indicators (Fig. 5). However, there was one exception. In the case of runoff mitigation, most scenarios performed worse than the BAU scenario, except for scenarios S3.0, S3.25, S3.50, and S3.75. This

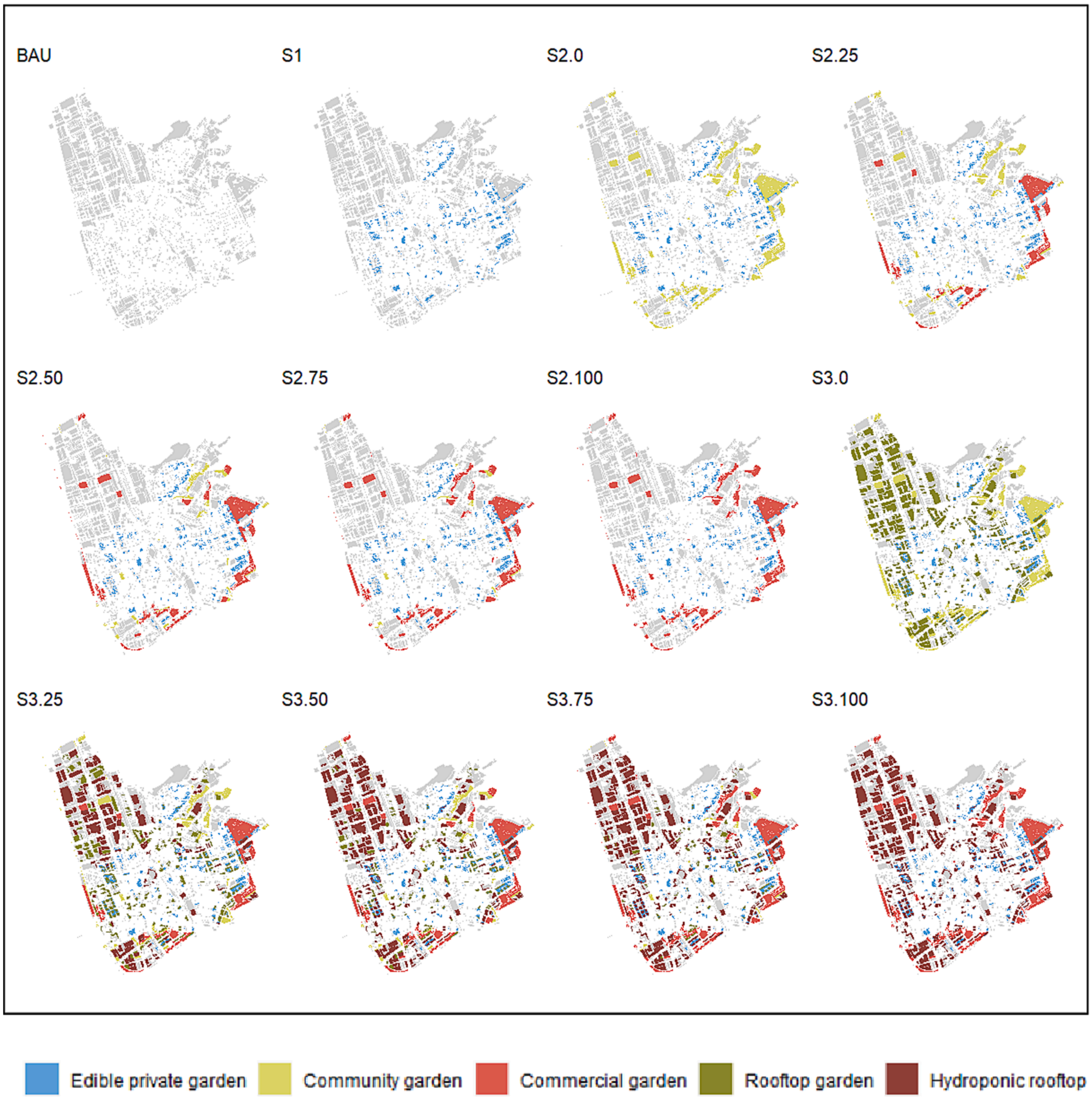


**Fig. 4.** Parcels converted to different urban agriculture elements in each scenario.

**Table 1**
Quantity and surface (in ha) of urban agriculture elements considered in each scenario.

| | BAU | S1 | S2.0 | S2.25 | S2.50 | S2.75 | S2.100 | S3.0 | S3.25 | S3.50 | S3.75 | S3.100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parcels (no.) | | | | | | | | | | | | |
| Edible private garden | 0 | 182 | 182 | 182 | 182 | 182 | 182 | 182 | 182 | 182 | 182 | 182 |
| Community garden | 0 | 0 | 57 | 42 | 28 | 14 | 0 | 57 | 42 | 28 | 14 | 0 |
| Commercial garden | 0 | 0 | 0 | 15 | 29 | 43 | 57 | 0 | 15 | 29 | 43 | 57 |
| Rooftop garden | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 339 | 254 | 169 | 84 | 0 |
| Hydroponic rooftop | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 85 | 170 | 255 | 339 |
| Surface (ha) | | | | | | | | | | | | |
| Edible private garden | 0 | 8,1 | 8,1 | 8,1 | 8,1 | 8,1 | 8,1 | 8,1 | 8,1 | 8,1 | 8,1 | 8,1 |
| Community garden | 0 | 0 | 20,1 | 7,5 | 4,1 | 1,3 | 0,00 | 20,1 | 7,5 | 4,1 | 1,3 | 0,00 |
| Commercial garden | 0 | 0 | 0 | 12,6 | 16 | 18,8 | 20,1 | 0,00 | 12,6 | 16 | 18,8 | 20,1 |
| Rooftop garden | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 52,3 | 22,1 | 10,8 | 5,2 | 0,00 |
| Hydroponic rooftop | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30,3 | 41,5 | 47,1 | 52,3 |

occurred because vacant plots and private gardens were assigned lower infiltration curve numbers compared to urban agriculture. Additionally, the presence of community rooftops designed as raised beds contributed to runoff mitigation, while commercial rooftops converted into hydroponic farming did not have the same effect.

In some scenarios, there were notable peaks observed in certain indicators. Specifically, the green areas' accessibility and green per capita indicators exhibited peaks in scenarios S2.0 and S3.0. These peaks were primarily attributed to the commercial factor, as these scenarios involved the simulation of only community gardens. Similarly, the number of volunteers involved and jobs created were influenced by the presence of community gardens and commercial gardens, respectively.

**Table 2**
Estimated median indicator values. For some, a degree of uncertainty is also presented as the 95% confidence interval (within parenthesis).

| Scenario | Green areas accessibility (%) | Food self-reliance (%) | Green per capita (ratio) | Jobs created | NO2 sequestration (μg/s) | Runoff mitigation (mm) | Urban heat island (°C) | Volunteers involved |
|---|---|---|---|---|---|---|---|---|
| BAU | 97.55 | 0 | 0.0043 | 0 | 125.39 (124.8–125.94) | 65.32 (64.53–66.22) | 1.26 | 0 |
| S1 | 97.55 | 0.27 (0.04–0.52) | 0.003 | 0 | 126.2 (125.61–126.7) | 65.67 (64.83–66.46) | 1.26 | 0 |
| S2.0 | 93.26 | 2.34 (0.78–3.93) | 0.0027 | 0 | 126.22 (125.6–126.78) | 66.31 (65.64–66.91) | 1.26 | 12,414 (1,405–23,444) |
| S2.25 | 97.55 | 7.87 (6.16–9.7) | 0.003 | 971 (110–1,840) | 126.21 (125.61–126.79) | 65.98 (65.38–66.56) | 1.26 | 2,649 (301–5,017) |
| S2.50 | 97.55 | 8.71 (6.82–10.72) | 0.003 | 1,114 (127–2,114) | 126.16 (125.55–126.81) | 65.96 (65.31–66.62) | 1.26 | 1,220 (139–2,304) |
| S2.75 | 97.55 | 9.2 (7.18–11.34) | 0.003 | 1,201 (137–2,276) | 126.18 (125.6–126.79) | 65.86 (65.31–66.52) | 1.26 | 376 (43–711) |
| S2.100 | 97.55 | 9.38 (7.31–11.57) | 0.003 | 1,236 (140–2,336) | 126.18 (125.63–126.71) | 65.86 (65.25–66.56) | 1.26 | 0 |
| S3.0 | 87.26 | 6.05 (2.69–9.42) | 0.0014 | 0 | 148.54 (147.93–149.09) | 45.76 (45.19–46.37) | 1.01 | 34,636 (3,956–65,352) |
| S3.25 | 97.55 | 39.98 (29.85–50.11) | 0.0028 | 2,564 (291–4,853) | 148.5 (147.92–149.1) | 60.14 (59.6–60.70) | 1.01 | 8,942 (1,030–16,893) |
| S3.50 | 97.55 | 46.55 (34.46–58.65) | 0.0029 | 3,034 (346–5,732) | 148.47 (147.92–149.11) | 63.47 (62.81–63.95) | 1.01 | 4,257 (483–8,041) |
| S3.75 | 97.55 | 50.19 (37.01–63.43) | 0.0029 | 3,306 (375–6,231) | 148.54 (147.98–149.14) | 65.24 (64.65–65.84) | 1.01 | 1,643 (186–3,099) |
| S3.100 | 97.55 | 52.67 (38.67–66.63) | 0.003 | 3,457 (392–6,528) | 148.47 (147.92–149.06) | 66.57 (65.99–67.18) | 1.01 | 0 |


**Fig. 5.** Comparison of indicators among scenarios. The figure demonstrates the impact of urban agriculture on sustainability, highlighting the influence of the location and level of commercialization of urban gardens. The values have been standardized for comparison purposes, with a mean of 0 and a standard deviation of 1. The orange line represents the median value of all simulations within each scenario, while the grey ribbon represents the 95% confidence interval.

Community gardens contributed to volunteering, while commercial gardens contributed to job creation.

It is important to highlight the indicators of $NO_2$ sequestration and urban heat island. Transforming vacant plots into urban gardens did not significantly impact these two indicators since vacant plots also play a crucial role in $NO_2$ sequestration and urban heat island mitigation. Notably, both indicators exhibited a significant increase only in scenarios involving the greening of rooftops (specifically, scenarios S3).

## 4. Discussion

### 4.1. The potential of urban agriculture to contribute to urban challenges

This study differs from recent analyses in the U.S. that mainly focus on political and social aspects of urban agriculture (e.g., Goldstein et al., 2017; Uludere Aragon et al., 2019; Newel et al., 2022). Instead, we concentrate on the European concept of urban challenges supported by the European Commission. Our research emphasizes modelling various quantitative indicators to address all aspects of urban challenges for sustainability.

Our case study modelling results align with previous studies, providing further support for their findings. We found that rooftops are the most abundant surface for urban agriculture, with 339 available rooftops compared to 57 empty plots and 182 private gardens. This finding is consistent with Ackerman et al. (2014), who emphasized the prevalence of rooftops as suitable spaces for scaling up urban agriculture. This observation holds particularly true in dense Mediterranean cities and similar urban typologies characterized by flat rooftops (Duarte et al., 2020).

Regarding food production, the most well-studied contribution of urban agriculture, our findings echo previous research that indicates cities in developed countries are far from achieving self-sufficiency in food production (Grafius et al., 2020). In our best scenario, we estimated food self-reliance ranging from 39 % to 68 %. Furthermore, a global assessment of urban agriculture benefits concluded that its contributions were modest in terms of $NO_2$ sequestration but substantial in terms of runoff prevention (Clinton et al., 2018). Our results align with this evidence.

However, our findings demonstrate that the contributions of urban agriculture to urban sustainability are not as straightforward as suggested by some studies (Artmann & Sartison, 2018; Säumel et al., 2019). The comparison among scenarios revealed potential trade-offs between different benefits. The most apparent trade-off was observed between creating jobs and involving volunteers. Additionally, trade-offs were identified between food production and social benefits such as green justice or green accessibility, as indicated by previous studies (Dennis & James, 2017; Taylor et al., 2017).

In summary, the contributions of urban agriculture to urban sustainability are not guaranteed (Tong et al., 2020). They are influenced by the location of parcels and the primary objectives of urban agriculture initiatives. For instance, rooftop initiatives are well-suited to provide environmental benefits such as reducing the urban heat island effect or preventing runoff because they utilize existing grey infrastructure. However, if these rooftop gardens employ hydroponic technologies, their contribution to runoff mitigation is significantly reduced. Nonetheless, hydroponic systems are ideal for optimizing production and conserving water, which can be a significant limitation for urban agriculture in Mediterranean cities in the near future (Tong et al., 2020). On the other hand, hydroponic gardens may not be suitable if the goal is to actively involve citizens in urban agriculture, as people tend to prefer soil-based cultivation methods (Caputo et al., 2020).

Therefore, an intriguing debate regarding governance has emerged in the context of urban agriculture. While urban agriculture is primarily a grassroots phenomenon (Tornaghi, 2012), maximizing its contributions to urban sustainability requires strategic planning that is closely linked to a political agenda. This strategic planning is crucial for prioritizing which benefits to emphasize and for minimizing potential trade-offs. Some authors argue that a common form of governance for urban gardens is a bottom-up approach supported by political or administrative entities (Fox-Kämper et al., 2018). Such administrative support can facilitate the development of a comprehensive perspective on urban agriculture at the city scale, providing the broader picture of the benefits and trade-offs of all urban gardens in a city, and not just at the level of an individual garden, thus enabling the necessary strategic vision. Undoubtedly, the integration of these contrasting approaches is a critical topic that needs to be addressed in the urban agendas of most cities in the Global North countries. However, exploring this topic in depth goes beyond the scope of this paper.

### 4.2. A model to estimate the contributions of urban agriculture to sustainability has the potential to enhance its effectiveness

As demonstrated in the case study, strategic planning is crucial for maximizing the benefits of urban agriculture in urban sustainability. However, decision-makers often lack the time, expertise, and information required for effective planning (Gómez-Villarino & Ruiz-Garcia, 2021). The model presented in this paper offers a solution to this challenge. The spatial data needed for the model is readily available to urban planners in municipalities, and the remaining model parameters are included by default or can be adjusted if more precise city-specific data is available, such as the number of jobs or typical size of water tanks.

Several studies have provided insights to assist decision-makers in planning urban agriculture at the city scale. For example, Gómez-Villarino and Ruiz-Garcia (2021) developed a framework to integrate urban agriculture into sustainable development based on an ecosystem service approach. Other models have focused on specific aspects such as the design of urban agriculture spaces using building integrated models (BIM) to assist architects or rainwater harvesting models (Gittleman et al., 2017; Lupia et al., 2017; Lupia & Pulighe, 2015). Additionally, numerous studies have modelled the food production potential of cities (Grafius et al., 2020; Grewal & Grewal, 2012; Hsieh et al., 2017; MacRae et al., 2010). However, none of these models aim to comprehensively maximize the contributions of urban agriculture across multiple dimensions of urban sustainability. Instead, they often focus on specific aspects such as food production or water. Therefore, our primary contribution is providing a multicriteria decision tool that urban planners can use to determine the optimal number, location, and type of urban gardens in their city to maximize urban sustainability, encompassing physical aspects like urban heat islands and social aspects like green justice. Moreover, the model can also be used to calculate individual indicators separately if decision-makers prefer to focus on specific indicators rather than the entire set.

### 4.3. Limitations of the methodology

Like any study based on scenario simulations and modelling, the proposed methodology has limitations due to the necessary simplification of reality. One limitation is that the relationships between urban challenges and the estimated indicators are not always straightforward. For example, public health cannot be directly measured with our indicators. Our indicators only capture certain factors that may influence public health in a city, but they do not directly measure it. Public health depends on various factors, including socioeconomic variables that impact people's ability to participate in urban agriculture and, consequently, who benefits from urban agriculture implementations (Ango et al., 2011). This limitation also applies to other urban challenges that are influenced by multiple factors, such as public participation or urban regeneration.

Furthermore, the study made several assumptions that may not always be accurate. For instance, we assumed that commercial rooftop gardens used hydroponic technology while community rooftop gardens used raised beds, but this may not always be the case in practice. Similarly, we made assumptions about other parameters of the models used to calculate each indicator. For example, we had to use data from generic urban green spaces such as grass, shrubs, and trees to estimate the capacity of urban gardens to remove NO2, as specific data for urban gardens was not available. We justified these assumptions in the methods section and used the best available data we could find. In some cases, the data and models were well-adjusted, while in others, the data was inconsistent, leading to high uncertainties. To address this, we ran 1,000 Monte Carlo simulations for each scenario, which required significant computational resources (12 h of computation in an Intel Core i7-8650 CPU with 16 GB RAM, using seven cores in parallel). The models developed in this study have the potential to reduce uncertainty as new data on urban agriculture is collected and published. The R package created to run the simulations was specifically designed to be easily updated with new data if needed. This flexibility allows for the incorporation of the most recent information, improving the accuracy and applicability of the model over time.

Another limitation is that the model does not incorporate constraints to ensure realistic outcomes. For example, the upper limit of volunteers in scenario S3.0 exceeds the city's population, and the median value for the number of jobs created in scenario S3.100 is higher than the number of unemployed inhabitants. We chose not to impose constraints on the results to avoid limiting the estimation of unrealistic scenarios, which may be useful for long-term policies or educational purposes.

Lastly, it is important to acknowledge that we took a simplified approach to urban agriculture by only considering its benefits and not accounting for drawbacks. However, urban gardening practices that are poorly managed can not only diminish its benefits but also generate negative impacts. Several studies have highlighted issues such as the presence of heavy metals in grown plants (Graefe et al., 2019) or the misuse of pesticides and fertilizers (Perrin et al., 2015), which pose risks to the environment and human health. Similarly, other studies have shown that while rooftop gardens effectively reduce runoff, they can also increase nutrient runoff, particularly when compared to extensive green roofs, thereby impacting the quality of runoff water (Whittinghill et al., 2016). Besides causing potential environmental and human health problems, urban agriculture can also have negative social impacts, such as green gentrification (Hawes et al., 2022; Sbicca, 2019).

## 5. Conclusions

In recent years, there were many attempts to evaluate the contributions of urban agriculture, mostly addressing food supply. On the other hand, the presented study focuses on evaluating the benefits of urban agriculture from several different perspectives, including food production, environmental impacts, and economic opportunities. To this end, a stochastic model is proposed, which is transferable to any city in the world if appropriate input data is provided, and flexible enough to accommodate other climates and other urban archetypes. The model performance was tested in the city of Sant Feliu de Llobregat (Spain).

Despite the limited availability of scientific literature on the quantification of urban agriculture's benefits, our model has demonstrated that urban agriculture does indeed make measurable contributions to urban sustainability. While there are some uncertainties in the results, the indicators clearly indicate that the type of urban garden plays a significant role in determining these contributions. Certain trade-offs, such as the balance between involving volunteers in community gardens and creating jobs in commercial gardens, are evident and should be considered. By using a model, these trade-offs can be explicitly identified and taken into account. For example, if a city aims to mitigate runoff, it should avoid hydroponic technologies, but if the goal is food self-reliance, hydroponics may be encouraged. Recognizing and understanding these differences is crucial because they give rise to trade-offs, particularly between social and environmental benefits. Therefore, a model like the one we have presented is indispensable for assisting decision-makers in maximizing the benefits of urban agriculture initiatives and minimizing trade-offs.

Further work will focus on testing the proposed model in different cities and regions across the world, and on including additional indicators or parameters, that are missing in the current version of the model (e.g., indicators for public health or parameters to account for socioeconomic diversity within a city).

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The dat are publicly avaialble as a Zenodo repository: https://zenodo.org/record/8055427

## Acknowledgements

Authors acknowledge the support from the European Union Horizon 2020 innovation & action project EdiCitNet (GA776665), the Economy and Knowledge Department of the Catalan Government through Consolidated Research Groups ICRA tech (2021-SGR-01283) and LEQUIA (2021-SGR-01352), the Slovenian Research Agency (research core funding No. P2-0180), and the CERCA program.

## References

Ackerman, K., Conard, M., Culligan, P., Plunz, R., Sutto, M. P., & Whittinghill, L. (2014). Sustainable food systems for future cities: The potential of urban agriculture. *Economic and Social Review, 45*(2), 189–206.

Ambrose, G., Das, K., Fan, Y., & Ramaswami, A. (2020). Is gardening associated with greater happiness of urban residents? A multi-activity, dynamic assessment in the Twin-Cities region, USA. *Landscape and Urban Planning, 198*, Article 103776. https://doi.org/10.1016/j.landurbplan.2020.103776

Ango, A. K., Abdullahi, A. N., & Abubakar, B. B. (2011). Role of socioeconomic parameters in determining the efficacy of urban agriculture in providing food security in Birnin Kebbi metropolitan area, Kebbi State, north western Nigeria. *International Research Journal of Agricultural Science and Soil Science, 1*(6), 185–192.

Artmann, M., & Sartison, K. (2018). The role of urban agriculture as a nature-based solution: A review for developing a systemic assessment framework. *Sustainability (Switzerland), 10*(6), 1937. https://doi.org/10.3390/su10061937

Asaduzzaman, Md., Saifullah, Md., Mollick, A. K. M. S. R., Hossain, Md. M., Halim, G. M. A., & Asao, T. (2015). Influence of Soilless Culture Substrate on Improvement of Yield and Produce Quality of Horticultural Crops. In *Soilless Culture - Use of Substrates for the Production of Quality Horticultural Crops*. IntechOpen. https://doi.org/10.5772/59708.

Barthel, S., Parker, J., & Ernstson, H. (2015). Food and green space in cities: A resilience lens on gardens and urban environmental movements. *Urban Studies, 52*(7), 1321–1338. https://doi.org/10.1177/0042098012472744

Camps-Calvet, M., Langemeyer, J., Calvet-Mir, L., & Gómez-Baggethun, E. (2016). Ecosystem services provided by urban gardens in Barcelona, Spain: Insights for policy and planning. *Environmental Science & Policy, 62*, 14–23. https://doi.org/10.1016/J.ENVSCI.2016.01.007

Caputo, S., Rumble, H., & Schaefer, M. (2020). "I like to get my hands stuck in the soil": A pilot study in the acceptance of soil-less methods of cultivation in community gardens. *Journal of Cleaner Production, 258*. https://doi.org/10.1016/j.jclepro.2020.120585

Castellar, J. A. C., Popartan, L. A. A., Pueyo-Ros, J., Atanasova, N., Langergraber, G., Sämuel, I., Corominas, L., Comas, J., Acuña, V., & Säumel, I. (2021). Nature-based solutions in the urban context: Terminology, classification and scoring for urban challenges and ecosystem services. *Science of the Total Environment, 779*, Article 146237. https://doi.org/10.1016/j.scitotenv.2021.146237

Clark, K. H., & Nicholas, K. A. (2013). Introducing urban food forestry: A multifunctional approach to increase food security and provide ecosystem services. *Landscape Ecology, 28*(9), 1649–1669. https://doi.org/10.1007/s10980-013-9903-z

Clinton, N., Stuhlmacher, M., Miles, A., Uludere Aragon, N., Wagner, M., Georgescu, M., Herwig, C., & Gong, P. (2018). A Global Geospatial Ecosystem Services Estimate of Urban Agriculture. *Earth's Future, 6*(1), 40–60. https://doi.org/10.1002/2017EF000536

CoDyre, M., Fraser, E. D. G., & Landman, K. (2015). How does your garden grow? An empirical evaluation of the costs and potential of urban gardening. *Urban Forestry & Urban Greening, 14*(1), 72–79. https://doi.org/10.1016/J.UFUG.2014.11.001

Conrad, O. (2008). *Module Sky View Factor (2.2.0)*. SAGA.

Cronshey, R. G., Roberts, R. T., & Miller, N. (1985). *Urban Hydrology for Small Watersheds (Tr-55 Rev.)*. (USDA Natural Resources Conservation Services, Ed.).

Dennis, M., & James, P. (2017). Ecosystem services of collectively managed urban gardens: Exploring factors affecting synergies and trade-offs at the site level. *Ecosystem Services, 26*, 17–26. https://doi.org/10.1016/j.ecoser.2017.05.009

Duarte, V., Martins, C., Rodrigues, J., & Pires, M. R. (2020). Improving access to greenspaces in the Mediterranean city of Faro. *AIMS Environmental Science, 7*(3), 226–246. https://doi.org/10.3934/environsci.2020014

Duchemin, E., Wegmuller, F., & Legault, A.-M. (2009). Urban agriculture: Multi-dimensional tools for social development in poor neibourghoods. *Field Actions Science Reports, 2*(1), 1–8. https://doi.org/10.5194/facts-2-1-2009

Dumitru, A., & Wendling, L. (Eds.). (2021). *Evaluating the Impact of Nature-based Solutions: A Handbook for Practitioners*. European Commission - Directorate-General for Research and Innovation. https://doi.org/10.2777/244577.

European Environment Agency. (2020). *Urban Atlas LCLU 2018*.

Falxa-Raymond, N., Svendsen, E., & Campbell, L. K. (2013). From job training to green jobs: A case study of a young adult employment program centered on environmental restoration in New York City, USA. *Urban Forestry & Urban Greening, 12*(3), 287–295. https://doi.org/10.1016/j.ufug.2013.04.003

FAO, & WHO. (2004). *Fruit and Vegetables for Health Fruit and Vegetables*.

Farahani, L. M., Maller, C., & Phelan, K. (2018). Private Gardens as Urban Greenspaces: Can they compensate for Poor Greenspace Access in lower socioeconomic neighbourhoods? *Landscape Online, 59*, 1–18. https://doi.org/10.3097/LO.201859

Fox-Kämper, R., Wesener, A., Münderlein, D., Sondermann, M., McWilliam, W., & Kirk, N. (2018). Urban community gardens: An evaluation of governance approaches and related enablers and barriers at different development stages. *Landscape and Urban Planning, 170*, 59–68. https://doi.org/10.1016/J.LANDURBPLAN.2017.06.023

Ghosh, S., Vale, R., & Vale, B. (2008). Local food production in home gardens: Measuring on-site sustainability potential of residential development. *International Journal of Environment and Sustainable Development, 7*(4). https://doi.org/10.1504/IJESD.2008.022388

Gittleman, M., Farmer, C. J. Q., Kremer, P., & McPhearson, T. (2017). Estimating stormwater runoff for community gardens in New York City. *Urban Ecosystems, 20*(1), 129–139. https://doi.org/10.1007/s11252-016-0575-8

Glavan, M., Schmutz, U., Williams, S., Corsi, S., Monaco, F., Kneafsey, M., Guzman Rodriguez, P. A., Čenič-Istenič, M., & Pintar, M. (2018). The economic performance of urban gardening in three European cities – examples from Ljubljana, Milan and London. *Urban Forestry and Urban Greening, 36*(May), 100–122. https://doi.org/10.1016/j.ufug.2018.10.009

Gómez-Villarino, M. T., & Ruiz-Garcia, L. (2021). Adaptive design model for the integration of urban agriculture in the sustainable development of cities. A case study in northern Spain. *Sustainable Cities and Society, 65*. https://doi.org/10.1016/j.scs.2020.102595

Graefe, S., Buerkert, A., & Schlecht, E. (2019). Trends and gaps in scholarly literature on urban and peri-urban agriculture. *Nutrient Cycling in Agroecosystems, 115*(2), 143–158. https://doi.org/10.1007/S10705-019-10018-Z/METRICS

Grafius, D. R., Edmondson, J. L., Norton, B. A., Clark, R., Mears, M., Leake, J. L., Corstanje, R., Harris, J. A., & Warren, P. H. (2020). Estimating food production in an urban landscape. *Scientific Reports, 10*(1), 5141. https://doi.org/10.1038/s41598-020-62126-4

Grewal, S. S., & Grewal, P. S. (2012). Can cities become self-reliant in food? *Cities, 29*(1), 1–11. https://doi.org/10.1016/J.CITIES.2011.06.003

Haberman, D., Gillies, L., Canter, A., Rinner, V., Pancrazi, L., & Martellozzo, F. (2014). The potential of urban agriculture in Montréal: A quantitative assessment. *ISPRS International Journal of Geo-Information, 3*(3), 1101–1117. https://doi.org/10.3390/ijgi3031101

Haque, M. M., Rahman, A., & Samali, B. (2016). Evaluation of climate change impacts on rainwater harvesting. *Journal of Cleaner Production, 137*, 60–69. https://doi.org/10.1016/j.jclepro.2016.07.038

Hawes, J. K., Gounaridis, D., & Newell, J. P. (2022). Does urban agriculture lead to gentrification? *Landscape and Urban Planning, 225*, Article 104447. https://doi.org/10.1016/j.landurbplan.2022.104447

Hickel, J., Brockway, P., Kallis, G., Keyßer, L., Lenzen, M., Slameršak, A., Steinberger, J., & Ürge-Vorsatz, D. (2021). Urgent need for post-growth climate mitigation scenarios. *Nature Energy, 6*(8), 766–768. https://doi.org/10.1038/s41560-021-00884-9

Hsieh, Y. H., Hsu, J. T., & Lee, T. I. (2017). Estimating the potential of achieving self-reliance by rooftop gardening in Chiayi City, Taiwan. *International Journal of Design and Nature and Ecodynamics, 12*(4), 448–457. https://doi.org/10.2495/DNE-V12-N4-448-457

ICGC. (2017). *LIDARCAT v.2*.

Kabisch, N., & Haase, D. (2014). Green justice or just green? Provision of urban green spaces in Berlin, Germany. *Landscape and Urban Planning, 122*, 129–139. https://doi.org/10.1016/j.landurbplan.2013.11.016

Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution, 151*(2), 362–367. https://doi.org/10.1016/j.envpol.2007.06.012

Langemeyer, J., Madrid-Lopez, C., Mendoza Beltran, A., & Villalba Mendez, G. (2021). Urban agriculture — A necessary pathway towards urban resilience and global sustainability?. In *Landscape and Urban Planning* (Vol. 210, p. 104055) Elsevier B.V. https://doi.org/10.1016/j.landurbplan.2021.104055.

LAStools. (2021). *LAStools - efficient LiDAR processing software* (1.4).

Leake, J. R., Adam-Bradford, A., & Rigby, J. E. (2009). Environmental Health benefits of “grow your own” food in urban areas: Implications for contaminated land risk assessment and risk management? *Environmental Health, 8*. https://doi.org/10.1186/1476-069X-8-S1-S6

Lin, B. B., Philpott, S. M., & Jha, S. (2015). The future of urban agriculture and biodiversity-ecosystem services: Challenges and next steps. *Basic and Applied Ecology, 16*(3), 189–201. https://doi.org/10.1016/j.baae.2015.01.005

Lupia, F., Baiocchi, V., Lelo, K., & Pulighe, G. (2017). Exploring rooftop rainwater harvesting potential for food production in urban areas. *Agriculture 2017, Vol. 7, Page 46, 7*(6), 46. https://doi.org/10.3390/AGRICULTURE7060046.

Lupia, F., & Pulighe, G. (2015). Water use and urban agriculture: Estimation and water saving scenarios for residential kitchen gardens. *Agriculture and Agricultural Science Procedia, 4*, 50–58. https://doi.org/10.1016/j.aaspro.2015.03.007

MacRae, R., Gallant, E., Patel, S., Michalak, M., Bunch, M., & Schaffner, S. (2010). Could Toronto provide 10% of its fresh vegetable requirements from within its own boundaries? Matching consumption requirements with growing spaces. *Journal of Agriculture, Food Systems, and Community Development, 1*(2), 105–127. https://doi.org/10.5304/jafscd.2010.012.008

Mayer, H. (1999). Air pollution in cities. *Atmospheric Environment, 33*(24–25), 4029–4037. https://doi.org/10.1016/S1352-2310(99)00144-2

McClintock, N., Cooper, J., & Khandeshi, S. (2013). Assessing the potential contribution of vacant land to urban vegetable production and consumption in Oakland, California. *Landscape and Urban Planning, 111*(1), 46–58. https://doi.org/10.1016/j.landurbplan.2012.12.009

Palencia, P., Giné Bordonaba, J., Martínez, F., & Terry, L. A. (2016). Investigating the effect of different soilless substrates on strawberry productivity and fruit composition. *Scientia Horticulturae, 203*, 12–19. https://doi.org/10.1016/j.scienta.2016.03.005

Panno, A., Carrus, G., Lafortezza, R., Mariani, L., & Sanesi, G. (2017). Nature-based solutions to promote human resilience and wellbeing in cities during increasingly hot summers. *Environmental Research, 159*(August), 249–256. https://doi.org/10.1016/j.envres.2017.08.016

Park, S. A., Shoemaker, C. A., & Haub, M. D. (2009). Physical and psychological health conditions of older adults classified as gardeners or nongardeners. *HortScience, 44*(1), 206–210. https://doi.org/10.21273/hortsci.44.1.206.

Perrin, A., Basset-Mens, C., Huat, J., & Yehouessi, W. (2015). High environmental risk and low yield of urban tomato gardens in Benin. *Agronomy for Sustainable Development, 35*(1), 305–315. https://doi.org/10.1007/S13593-014-0241-6/METRICS

Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M. R., Geneletti, D., & Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science and Policy, 77*(June), 15–24. https://doi.org/10.1016/j.envsci.2017.07.008

Richardson, J. J., & Moskal, L. M. (2016). Urban food crop production capacity and competition with the urban forest. *Urban Forestry & Urban Greening, 15*, 58–64. https://doi.org/10.1016/J.UFUG.2015.10.006

Ross, C. W., Prihodko, L., Anchang, J., Kumar, S., Ji, W., & Hanan, N. P. (2018). HYSOGs250m, global gridded hydrologic soil groups for curve-number-based runoff modeling. *Scientific Data, 5*, Article 180091. https://doi.org/10.1038/sdata.2018.91

Rutt, R. L., & Gulsrud, N. M. (2016). Green justice in the city: A new agenda for urban green space research in Europe. *Urban Forestry and Urban Greening, 19*, 123–127. https://doi.org/10.1016/j.ufug.2016.07.004

Saha, M., & Eckelman, M. J. (2017). Growing fresh fruits and vegetables in an urban landscape: A geospatial assessment of ground level and rooftop urban agriculture potential in Boston, USA. *Landscape and Urban Planning, 165*, 130–141. https://doi.org/10.1016/J.LANDURBPLAN.2017.04.015

Säumel, I., Reddy, S. E., & Wachtel, T. (2019). Edible city solutions-one step further to foster social resilience through enhanced socio-cultural ecosystem services in cities. *Sustainability (Switzerland), 11*(4). https://doi.org/10.3390/su11040972

Sbicca, J. (2019). Urban Agriculture, Revalorization, and Green Gentrification in Denver, Colorado. In *The Politics of Land* (Vol. 26, pp. 149–170). Emerald Publishing Limited. https://doi.org/10.1108/S0895-993520190000026011.

Shukla, P. R., Skea, J., Buendia, E. C., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., Diemen, R. van, Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Pereira, J. P., Vyas, P., Huntley, E., … Malley, J. (2019). *IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

Soga, M., Cox, D. T. C., Yamaura, Y., Gaston, K. J., Kurisu, K., & Hanaki, K. (2017). Health benefits of urban allotment gardening: Improved physical and psychological well-being and social integration. *International Journal of Environmental Research and Public Health, 14*(1). https://doi.org/10.3390/ijerph14010071

Soga, M., Gaston, K. J., & Yamaura, Y. (2017). Gardening is beneficial for health: A meta-analysis. *Preventive Medicine Reports, 5*, 92–99. https://doi.org/10.1016/j.pmedr.2016.11.007

Taylor, J. R., Lovell, S. T., Wortman, S. E., & Chan, M. (2017). Ecosystem services and tradeoffs in the home food gardens of African American, Chinese-origin and Mexican-origin households in Chicago, IL. *Renewable Agriculture and Food Systems, 32*(1), 69–86. https://doi.org/10.1017/S174217051600003X

Theeuwes, N. E., Steeneveld, G. J., Ronda, R. J., & Holtslag, A. A. M. (2017). A diagnostic equation for the daily maximum urban heat island effect for cities in northwestern Europe. *International Journal of Climatology, 37*(1), 443–454. https://doi.org/10.1002/joc.4717

Tong, D., Crosson, C., Zhong, Q., & Zhang, Y. (2020). Optimize urban food production to address food deserts in regions with restricted water access. *Landscape and Urban Planning, 202*, Article 103859. https://doi.org/10.1016/j.landurbplan.2020.103859

Tornaghi, C. (2012). Public space, urban agriculture and the grassroots creation of new commons: Lessons and challenges for policy makers. In A. Viljoen, & J. S. C. Wiskerke (Eds.), *Sustainable food planning: Evolving theory and practice* (pp. 349–364). Wageningen Academic Publishers. https://doi.org/10.3920/978-90-8686-187-3_29.

Tornaghi, C. (2014). Critical geography of urban agriculture. *Progress in Human Geography, 38*(4), 551–567. https://doi.org/10.1177/0309132513512542

Usace. (2022). *HEC-HMS technical reference manual*. Hydrologic Engineering Center.

Whittinghill, L. J., Hsueh, D., Culligan, P., & Plunz, R. (2016). Stormwater performance of a full scale rooftop farm: Runoff water quality. *Ecological Engineering, 91*, 195–206. https://doi.org/10.1016/J.ECOLENG.2016.01.047

WHO. (2017). Urban green spaces: A brief for action. *Regional Office For Europe*, 24. http://www.euro.who.int/_data/assets/pdf_file/0010/342289/Urban-Green-Spaces_EN_WHO_web.pdf?ua=1.

Yan, D., Liu, L., Liu, X., & Zhang, M. (2022). Global Trends in Urban Agriculture Research: A Pathway toward Urban Resilience and Sustainability. *Land 2022, Vol. 11, Page 117, 11*(1), 117. https://doi.org/10.3390/LAND11010117.

Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment, 42*(31), 7266–7273. https://doi.org/10.1016/j.atmosenv.2008.07.003