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Integrating agriculture into European urban landscapes matters: A systematic assessment

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ABSTRACT

Urban agriculture has emerged as a pathway to enhance food security, improve urban resilience, and reduce the environmental impact of food systems. However, its potential across cities remains underexplored. This study offers a systematic evaluation of the potential for low-tech, open-air, soil-based urban vegetable production in European cities, examining its role in meeting local food demand and contributing to sustainability goals. Leveraging geospatial, demographic, and climate data, we assess the availability of rooftop and ground-based urban spaces suitable for cultivation across 840 cities in 30 European countries for 2018 under three land-use intensity scenarios. We estimate that 4551–7586 km^2 of urban land could be allocated to vegetable cultivation, yielding 11.8–19.8 million tons annually, equivalent to roughly one-third of the reported vegetable production in the analyzed countries. Our findings reveal substantial opportunities to integrate vegetable production into urban landscapes, with pronounced spatial variation driven by differences in urban density, land availability, and climatic conditions. Our results highlight both the potential and the structural limits of urban agriculture as a complement to existing food systems and underscore the importance of spatially informed policy interventions to support sustainable urban food planning across Europe.

1. Introduction

Urban agriculture is increasingly recognized as a promising approach to addressing food insecurity and enhancing urban sustainability (Pradhan et al., 2024). It encompasses a wide range of food production practices occurring within urban and peri-urban environments. Urban agriculture can be classified based on spatial setting (e.g., rooftops, green spaces, ground-level, indoor, facades), cultivation orientation (horizontal or vertical), production environment (controlled or open-air), and growing methods (soil-based, hydroponic, aquaponic) (Payen et al., 2022). This diversity reflects the broad spectrum of technical, ecological, and social configurations through which food can be produced in cities.

As part of localized food systems, urban agriculture offers multiple benefits beyond direct food production, including social, economic, and environmental advantages (Pradhan et al., 2023). It is estimated to nourish around one billion urban dwellers—roughly 30% of the global urban population (Kriewald et al., 2019). Moreover, urban agriculture could contribute 5%–10% of global vegetable production, highlighting its relevance for food security and dietary transitions (Clinton et al., 2018). In addition, localized food production can reduce transportation-related emissions, enhance resource efficiency, and strengthen connections between producers and consumers (Kriewald et al., 2019; Pradhan et al., 2020). However, urban agriculture is not without limitations (Pradhan et al., 2024). For instance, food grown in urban settings can, in some cases, have a carbon footprint substantially higher than that of conventionally produced food, particularly when energy-intensive infrastructure and short lifespans are involved (Hawes et al., 2024). Nevertheless, many long-established urban gardens that employ circular resource flows, organic soil management, and low-input cultivation may outperform conventional systems in overall environmental sustainability (Hu et al., 2025; Payen et al., 2022).

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Many studies focus specifically on vegetable self-sufficiency, given vegetables' relatively low environmental impact and high nutritional value (Clark et al., 2022; Willett et al., 2019). Increasing vegetable consumption is central to sustainable food strategies and public health objectives, making vegetables a particularly relevant target for urban agriculture initiatives. Previous research has assessed the vegetable production potential of urban agriculture at various spatial scales and methodological resolutions. At the global scale, Martellozzo et al. (2014) estimated that cultivating one-third of urban land could theoretically meet global urban vegetable demand. At the city scale, numerous studies have examined the use of rooftops, residential gardens, green spaces, and greenhouses to estimate production potential (De Simone et al., 2023; Hu et al., 2025; Hume et al., 2021; Nadal et al., 2017; Orsini et al., 2014; Toboso-Chavero et al., 2023). These studies report widely varying outcomes, ranging from as little as 5% to over 75% of vegetable demand being met, depending on urban form, population density, climate, land availability, and methodological choices (Hume et al., 2021; Orsini et al., 2014; Toboso-Chavero et al., 2023). This wide variability highlights both the considerable potential and the structural limitations of urban agriculture, emphasizing its complementary role within broader food systems rather than its capacity to fully replace conventional agricultural production (Hu et al., 2025; Yang et al., 2024).

Despite this growing body of literature, existing assessments of urban agriculture in Europe remain uneven across regions. Most empirical and modeling studies focus on Western and Southern European cities, where data availability and long-standing planning traditions support detailed case analyses, while Northern, Eastern, and smaller urban regions remain comparatively underrepresented. As a result, it remains unclear how urban form, climate, and land-use constraints interact across Europe as a whole, thereby limiting the transferability of insights derived from individual city- or regional-level studies.

Beyond uneven spatial coverage, the dominant constraints on urban agriculture differ systematically across European regions but are rarely synthesized within a unified framework. In Southern Europe, water scarcity and high evapotranspiration constrain open-air cultivation, whereas in Northern Europe, lower temperatures, reduced solar radiation, and shorter growing seasons limit productivity. In Central and Western Europe, high population density and competing land uses dominate, whereas Eastern Europe is comparatively understudied despite distinct land availability and institutional conditions. Existing studies typically examine these constraints in isolation and at local scales, limiting cross-regional comparability.

To estimate the spatial potential for urban agriculture, researchers have used a wide range of methods. For example, Grewal and Grewal (2012) assumed that 9% of built-up residential area could support rooftop cultivation and that 7.2% of urban land could be allocated to ground-based food production. Other approaches focus on calculating the land area required to meet a city's vegetable demand under different dietary scenarios (Hume et al., 2021; Martellozzo et al., 2014). More spatially explicit methods integrate land-use maps, building footprints, and rooftop suitability models derived from photovoltaic research (De Simone et al., 2023; Hu et al., 2025), while also accounting for allotments, residential gardens, cemeteries, and parking lots. Nevertheless, many potentially cultivable spaces remain insufficiently examined, including non-built residential and industrial zones, pavements, building yards, decorative green areas, and other forms of underutilized urban land. These spaces may represent a substantial yet largely untapped resource for distributed urban food production.

The "15-Minute City" concept offers a complementary vision of sustainability. This vision proposes that essential urban services — including access to fresh food — should be reachable within a 15-minute walk or bicycle ride (Moreno et al., 2021). This concept aligns closely with the principle of short food supply chains (Jarzebowski et al., 2020), which aim to minimize transport distances, reduce emissions, and strengthen local producer–consumer relationships. Realizing such planning paradigms requires a deeper understanding of the spatial feasibility of producing food locally within dense and heterogeneous urban fabrics. Consequently, the potential of urban agriculture must be evaluated not only at the aggregated citywide scale but also at finer neighborhood and subcity scales, where accessibility, land availability, and population distribution interact most directly.

We address these research gaps by evaluating the nourishment potential of urban agriculture — specifically low-tech, open-air, and soil-based vegetable production — across 840 European cities in 2018, spanning diverse climatic zones, urban forms, and planning contexts. We deliberately focus on low-tech cultivation systems because they represent the most accessible, economically feasible, and socially inclusive form of urban agriculture, requiring minimal technological inputs, infrastructure investment, and energy demand. In contrast to high-input systems such as vertical farming, hydroponics, or controlled-environment agriculture, low-tech approaches are more easily scalable across diverse urban contexts, including small and medium-sized cities, informal gardening initiatives, and community-based food production schemes. Accordingly, our analysis deliberately excludes engineered green roof systems that rely on structural slope stabilization or specialized retention layers, focusing instead on cultivation approaches that can be implemented on existing urban surfaces with minimal technical intervention. Moreover, these systems align closely with the principles of the 15-Minute City and short food supply chains by enabling decentralized, neighborhood-scale food production and enhancing local food resilience. By establishing a conservative, widely applicable baseline, our analysis provides an estimate of urban food production potential against which more technologically intensive solutions can be evaluated in future research.

Using a GIS-based method of intermediate complexity, we integrate high-resolution land-use data, building footprints, digital surface models, population grids, crop yield data, dietary guidelines, and climate classifications. In this study, "intermediate complexity" refers to a modeling approach that balances the detailed spatial explicitness of local case studies with the scalability required for large-scale comparative assessments. This enables a consistent and systematic evaluation of urban agriculture potential across diverse city sizes, densities, and geographic settings while retaining sufficient spatial resolution to capture intra-urban heterogeneity. All analyses are conducted for a consistent baseline year of 2018, corresponding to the most recent period for which harmonized land-use, building footprint, population, and climate datasets are available across European cities. By explicitly integrating both rooftop and ground-based cultivation opportunities within a unified spatial framework, we establish a comparable pan-European baseline that provides actionable evidence to support spatial planning, urban design, and sustainable food policy.

2. Data and methods

Our study focuses on leveraging unused or underutilized urban areas, using the Urban Audit dataset (European Commission, Eurostat (ESTAT), GISCO, 2020) as the primary basis for defining city boundaries. We assess the potential for urban agriculture in European cities using a structured three-step analytical framework. Prior to analysis, all spatial datasets were harmonized by reprojecting raster and vector layers to a common coordinate reference system and aligning spatial resolutions where required. Raster-vector intersections were processed using area-weighted aggregation to ensure mass conservation when grid-irregular city boundaries intersected context data on a regular grid.

First, we identify urban rooftop and ground-based areas that are biophysically suitable for cultivation. Second, we integrate and analyze relevant spatial datasets (Table S1) to quantify these potential spaces. Third, we estimate the total urban agriculture area and associated production potential under scenario-specific constraints derived from the literature. The complete study workflow is summarized in Fig. 1A.

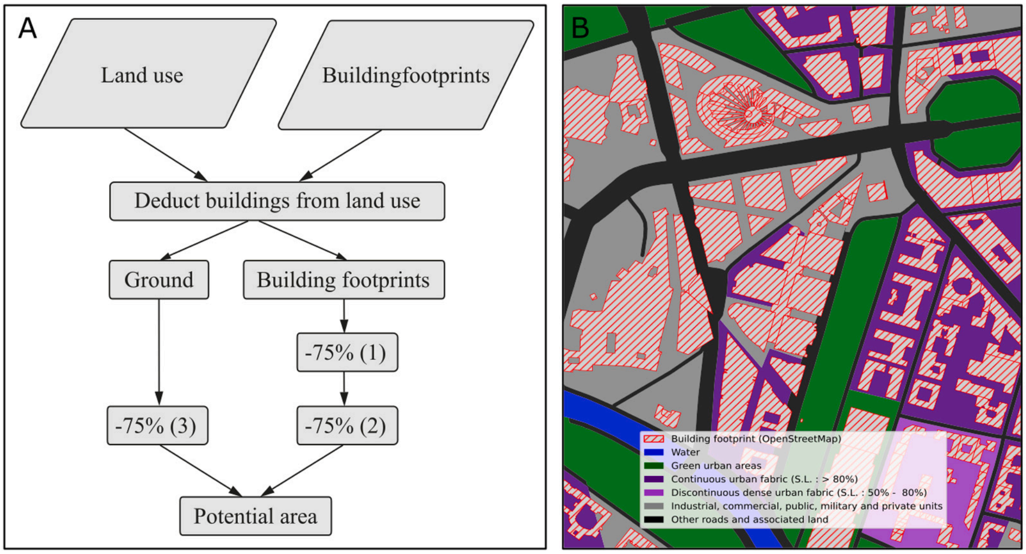

Fig. 1. (**A**) Workflow for estimating the maximum potential cultivation area. *Notes:* (1) DSM-based analysis in a subset of cities (23 cities evaluated using two independent building footprint datasets: OpenStreetMap and Microsoft) shows that 14%–36% (mean approximately 20%) of rooftops have slopes ≤2° (Table S3). This subset is not statistically representative of all European cities; rather, it is used to establish robust bounds on low-slope rooftop availability and to assess consistency across alternative building-footprint datasets. (2) A uniform 25% usability factor is applied to flat roofs to account for functional constraints (e.g., HVAC, access, shading), following Koch (2020). (3) For ground-based cultivation, up to 25% of non-built urban land is assumed available under the most ambitious scenario. (**B**) Illustration of land-use (EEA, 2018) and building footprint (OpenStreetMap contributors, 2023) data for Berlin (Potsdamer Platz). Colors denote different land-use classes, while building footprints are shown as a hashed red overlay. Building footprints are used to identify potential rooftop cultivation areas and are subtracted from selected land-use classes (“Urban fabric”, “Industrial, commercial, public, military and private units”, “Green urban areas”, and “Isolated structures and land without current use”) to delineate potential ground-based cultivation spaces.

2.1. Potential area estimation

To estimate the potential for urban agriculture, we evaluate both rooftop and ground-based spaces. Rooftop areas are identified using OpenStreetMap (OSM) and Microsoft building footprint datasets, while rooftop morphology is characterized using digital surface models (DSMs; see Table S2). We conduct a DSM-based slope analysis for a subset of European cities (23 cities using OpenStreetMap building footprints and an additional 17 using Microsoft building footprints, depending on data availability) to assess rooftop suitability for low-tech cultivation. This subset is used to establish empirical bounds for plausible shares of low-sloped rooftops rather than to infer rooftop morphology for all 840 cities. The DSM analysis is subject to several constraints, including the spatial resolution of the elevation data, potential vertical noise, and uncertainties arising from the alignment between raster DSM data and vector building footprints. These factors limit the accuracy of slope estimation at the individual roof level, particularly for small or geometrically complex structures. Accordingly, the DSM results are interpreted as aggregate indicators of rooftop slope distributions and are used to define robust bounds for scenario assumptions rather than to provide city-specific estimates. These bounds are subsequently operationalized as scenario-level shares applied uniformly across cities.

The suitability of rooftops for low-tech cultivation is influenced by roof slope. Experimental green-roof studies show that stormwater retention and drainage performance are sensitive to roof inclination even at low slopes (VanWoert et al., 2005), while technical guidance indicates increasingly stringent requirements for erosion control and substrate stabilization with higher slopes. Accordingly, rooftops with slopes ≤2° are conservatively classified as suitable in our analysis. This threshold intentionally restricts the analysis to near-flat roofs, provides a definition of suitability that is independent of building typology, and ensures that cultivation can be implemented without requiring slope-adapted engineering solutions such as erosion control, terracing, or structural stabilization, thereby enabling consistent application across diverse urban forms and climatic conditions.

Previous studies commonly adopt less restrictive thresholds, often considering rooftops with slopes well above 2° as potentially cultivable (Slootweg et al., 2023; Xie et al., 2024). While cultivation at such slopes is technically feasible, it generally requires slope-adapted management practices, including substrate stabilization, erosion control, or engineered growing systems. These requirements introduce additional technical complexity, higher costs, and context-specific design considerations that fall outside the scope of the low-tech systems considered here. The 2° threshold is therefore not intended to represent all potentially cultivable rooftops, but to define a conservative and methodologically consistent lower bound that can be applied across diverse European building typologies and climatic conditions without introducing region-specific assumptions.

Across the cities included in the DSM-based slope analysis, the share of rooftops meeting the ≤2° criterion varies substantially, ranging from approximately 14% to 36% (Table S3). At the same time, the rooftop area is strongly concentrated at very low slope values, followed by a gradual transition toward steeper roofs, with relatively limited area in intermediate slope ranges. This distribution implies that extending the threshold to higher values (e.g., 10°) would increase estimated cultivation potential, but not proportionally to the increase in slope range. Rather than extrapolating city-specific values from our limited DSM sample, which is constrained by data availability and computational feasibility, we use the observed range (14% to 36%) to define scenario assumptions (15%, 20%, and 25%) that represent plausible bounds for low-slope rooftop availability. These values are not intended as statistically representative estimates for all European cities, but rather as conservative scenario parameters applicable across diverse building typologies and climatic conditions.

While roof slope determines geometric suitability for low-tech cultivation, not all geometrically suitable flat rooftops are practically usable for agriculture. To account for functional constraints, we apply an additional usability factor only to the estimated flat-roof area. This factor reflects competing rooftop uses, including HVAC (heating, ventilation, and air conditioning) installations, access paths, safety zones, shading, and maintenance requirements, as assessed empirically for rooftop usability (Koch, 2020). It is therefore implemented as a post-processing constraint on flat-roof area, rather than as an additional geometric suitability filter. A detailed justification of this usability factor, including its empirical basis and implications for uncertainty, is provided in the Supplementary Information (Text S1). All rooftop suitability and usability assumptions are applied to the city-level aggregated rooftop area, rather than evaluated on a roof-by-roof basis.

Ground areas suitable for agriculture are identified by combining land-use maps and building footprints. Fig. 1B illustrates the land-use and building footprint analysis for Berlin (Potsdamer Platz). We define three scenarios in which 15%, 20%, or 25% of non-built-up urban land is assumed to be available for cultivation. Refer to the Supplement (Text S1) for complete details.

We do not impose minimum patch size or contiguity thresholds when identifying rooftop or ground-based areas suitable for urban agriculture. Empirical evidence shows that low-tech urban cultivation commonly occurs on small and spatially fragmented surfaces, including private gardens, community plots, vacant land, and rooftops of varying size, many of which are productive despite limited spatial extent (Appolloni et al., 2021; Orsini et al., 2013; Payen et al., 2022). Imposing minimum area or contiguity constraints would therefore systematically exclude widespread household- and community-scale practices and bias estimates toward large, centralized installations. At the city scale, spatial fragmentation primarily affects management and labor requirements rather than per-unit-area biophysical production potential. Accordingly, as in previous city-scale assessments, we operate on aggregated rooftop and ground-based areas without patch-size filtering to estimate biophysical upper bounds (De Simone et al., 2023; Grewal & Grewal, 2012; Martellozzo et al., 2014). While this assumption may lead to optimistic absolute production estimates, it does not materially affect relative city-level comparisons, which are robust to land-availability assumptions as confirmed by sensitivity analysis (Text S1).

2.2. *Production estimation*

Vegetable production is estimated by combining the potential cultivation area with spatially explicit crop-yield data. Baseline vegetable yields are derived from the global gridded conventional agriculture dataset developed by Grogan et al. (2022), which provides yield estimates at 5-arcminute spatial resolution, averaged over 2014–2016, and captures large-scale climatic gradients across Europe. For each city, baseline yields are calculated by spatially intersecting the gridded yield dataset with the city boundary and computing the area-weighted mean yield of all grid cells overlapping the city geometry. Refer to the Supplement (Text S2) for complete details.

We deliberately adopt conventional agriculture yields as a conservative baseline for urban vegetable production. Empirical evidence indicates that yields in urban agriculture systems can be comparable to conventional yields (Payen et al., 2022). Uncertainty arising from climatic variability, crop composition, management intensity, and spatial aggregation in gridded yield datasets is explicitly addressed through a dedicated sensitivity analysis (Section 2.5).

2.3. *Assessment of nourishment potential*

Vegetable self-sufficiency is evaluated at both the city level and within a finer 1 km^2 grid resolution. Self-sufficiency measures the proportion of vegetable demand met through urban agriculture, calculated using Eq. (1).

$$\textit{self-sufficiency} = \frac{\textit{production}}{\textit{demand}}, \tag{1}$$

in which

$$\textit{production} = \textit{area} \times \textit{yield}, \quad \textit{demand} = \textit{population} \times \textit{requirement}$$

Inputs to our modeling include potential areas, yield data, and population statistics. Further methodological specifics are available in the Supplement (Text S3).

2.4. *Model scenarios*

We define three model scenarios (A–C) to explore the range of possible outcomes for urban agriculture potential across European cities. Table 1 summarizes the main assumptions. These scenarios differ in the assumed availability of suitable rooftops and ground-based areas, representing conservative, moderate, and ambitious levels of land-use intensity. The 15%, 20%, and 25% share values for both flat rooftops and ground-based areas are derived from empirical analysis of rooftop morphology. Estimates of available ground-based areas follow the ranges adopted in previous urban agriculture studies (De Simone et al., 2023; Grewal & Grewal, 2012). For further methodological details, refer to Supplementary (Text S1).

2.5. *Sensitivity analysis*

To evaluate the robustness of model outcomes to uncertainty in key assumptions, we conduct a systematic sensitivity analysis focusing on the most influential parameters: vegetable yields, rooftop availability, and ground-based land availability. Each parameter is perturbed within plausible ranges reported in the literature, and the resulting impacts on city-level vegetable production and self-sufficiency are quantified. Model robustness is assessed using Spearman's rank correlation coefficient between baseline and perturbed scenarios.

Yield uncertainty: Baseline vegetable yields derived from Grogan et al. (2022) are uniformly perturbed to represent uncertainty arising from climatic variability, heterogeneous crop composition within aggregated vegetable categories, management intensity, and spatial aggregation in gridded yield datasets. A symmetric perturbation is applied to avoid imposing directional assumptions on urban vegetable productivity while capturing the magnitudes of uncertainty commonly reported in crop model intercomparisons and yield gap analyses. Inter-model and structural uncertainties in simulated crop yields frequently fall within the 20%–30% range (Asseng et al., 2013; Folberth et al., 2016). In contrast, experimental benchmarks typically quantify yield variability among plots or seasons within individual experimental fields and therefore underestimate uncertainty associated with spatial aggregation and the transfer of city-mean gridded yields to heterogeneous urban environments (Payen et al., 2022; Van Ittersum et al., 2013).

Land availability uncertainty: The share of flat rooftops and non-built urban land available for cultivation is varied between 15%–25% to reflect uncertainty in accessibility, building typology, competing land uses, and socio-institutional constraints. Relative city-level rankings remain stable across this range (Spearman $\rho > 0.99$), while absolute production scales proportionally.

3 Results

Our investigation has revealed that, across the 840 European cities, the total potential cultivation area ranges from approximately 4551 km^2 under Scenario A to 7586 km^2 under Scenario C (Table S5), corresponding to 2.9–4.9% of the analyzed urban area. At the city level, available cultivation space ranges over more than two orders of magnitude, from less than 0.2 km^2 in compact cities such as Mislata (Spain) to over 100 km^2 in large metropolitan areas such as Paris (France), reflecting differences in city size, density, and land-use structure.

3.1 *Rooftop areas*

The potential rooftop areas available for cultivation across the 840 European cities examined vary widely, reflecting differences in urban structure and population density. Depending on the intensity of land-use, the total rooftop cultivation area ranges from approximately 274 km^2 under Scenario A to 456 km^2 under Scenario C (Table S5), equivalent to about 0.2 – 0.3% of cities' total area.

Table 1
Summary of model scenario assumptions for rooftop and ground-based urban agriculture potential.

Parameter	Scenario A	Scenario B	Scenario C
Share of flat roofs suitable for cultivation	15%	20%	25%
Share of ground-based urban area suitable for cultivation	15%	20%	25%

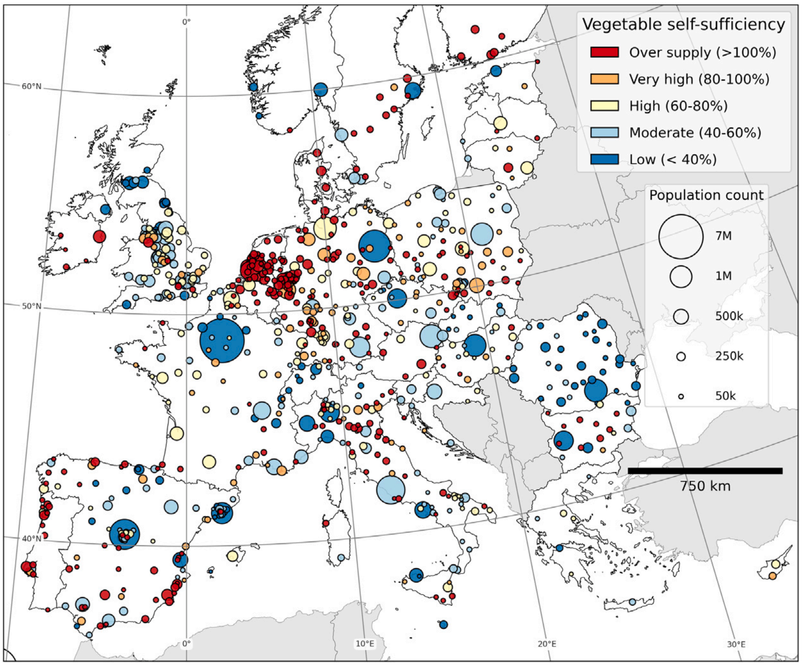

Fig. 2. Vegetable self-sufficiency levels in 840 European cities under Scenario A. Cities are categorized into five self-sufficiency levels: Low (< 40%), Moderate (40%–60%), High (60%–80%), Very High (80%–100%), and Oversupply (> 100%). The bubble size is proportional to the city's population. Larger bubbles represent more populous cities. Countries shown in gray are excluded from the analysis.

The spatial distribution of available rooftop areas under Scenario A, as shown in Figure S3A, highlights how population density and urban design influence cultivation potential. Cities with larger populations generally have larger rooftop areas. For example, Paris and Berlin exhibit some of the highest potential for rooftop cultivation, whereas smaller cities, such as Mislata and Igualada, have far less available space.

At the city level, the range of available rooftop areas varies significantly from just 0.01 km^2 in Mislata, Spain, under Scenario A, to up to 11 km^2 in Paris, France, under Scenario C. This wide range underscores the diverse opportunities for rooftop cultivation across different urban centers. For instance, Olomouc, Czechia, and Leuven, Belgium, each with a population of approximately 0.1 million, offer 0.08 km^2 and 0.2 km^2 of potential rooftop space under Scenario A, respectively, demonstrating how factors such as urban structure and population density shape rooftop cultivation opportunities.

3.2 Urban free spaces

The availability of ground-based areas for urban agriculture also varies widely, reflecting the diverse urban configurations of the analyzed cities. Across the 840 cities, these areas range from 4278 km^2 under Scenario A to 7130 km^2 under Scenario C, representing approximately 2.7–4.0% of the total urban area. At the individual city level, the availability spans from as little as 0.163 km^2 in Mislata under Scenario A to as much as 101 km^2 in Paris, France, under Scenario C, highlighting the significant impact of city-specific characteristics on the potential for urban agriculture.

Larger cities, such as Paris and Berlin, generally show substantial ground-based potential, whereas more compact cities, such as Mislata, exhibit far smaller cultivation areas (Supplemental Figures S3-S5). A closer look at cities with approximately 0.5 million residents reveals notable differences in the availability of ground-based areas. For instance, Duisburg, Germany, has 13.4 km^2 of ground-based area under Scenario A, compared to 5.6 km^2 in Lisbon, Portugal.

3.3 Production potential

Urban vegetable production varies widely across cities, depending on land availability, urban form, and climate. Under Scenario A, the analyzed cities collectively produce an estimated 11.8 million tons of vegetables annually. Under Scenario C, production increases to approximately 19.8 million tons, corresponding to roughly one third of reported vegetable production in the analyzed countries during the same period (Faostat, 2023).

Cities with similar population sizes can exhibit markedly different production potentials due to climatic and spatial factors. For example, Stockholm (cold, no dry season, warm summer climate) produces 35,197 tons annually under Scenario A. In contrast, Greater Amsterdam (temperate, dry summer, warm summer climate) produces 83,000 tons — approximately 2.4 times more — despite a smaller urban area. These contrasts highlight the role of climate and land availability in shaping urban vegetable productivity.

3.4 Vegetable self-sufficiency

We found considerable geographic variations in nourishment potential across the surveyed cities. To interpret the obtained range of self-sufficiency, we categorize it into five levels: Low (0%–40%), Moderate (40%–60%), High (60%–80%), Very high (80%–100%), Self-sufficient/Oversupply (≥100%). Fig. 2 presents a map of vegetable self-sufficiency levels of the examined cities under Scenario A. Lower

Table 2
Number of cities across self-sufficiency levels under three distinct land-use intensity scenarios (A, B, and C). The table classifies 840 European cities into five groups according to self-sufficiency levels.

	Scenario A	Scenario B	Scenario C
Low (0%–40%)	190	98	58
Moderate (40%–60%)	193	142	80
High (60%–80%)	149	143	140
Very high (80%–100%)	104	113	106
Self-sufficient (100%) + Oversupply (>100%)	204	344	456

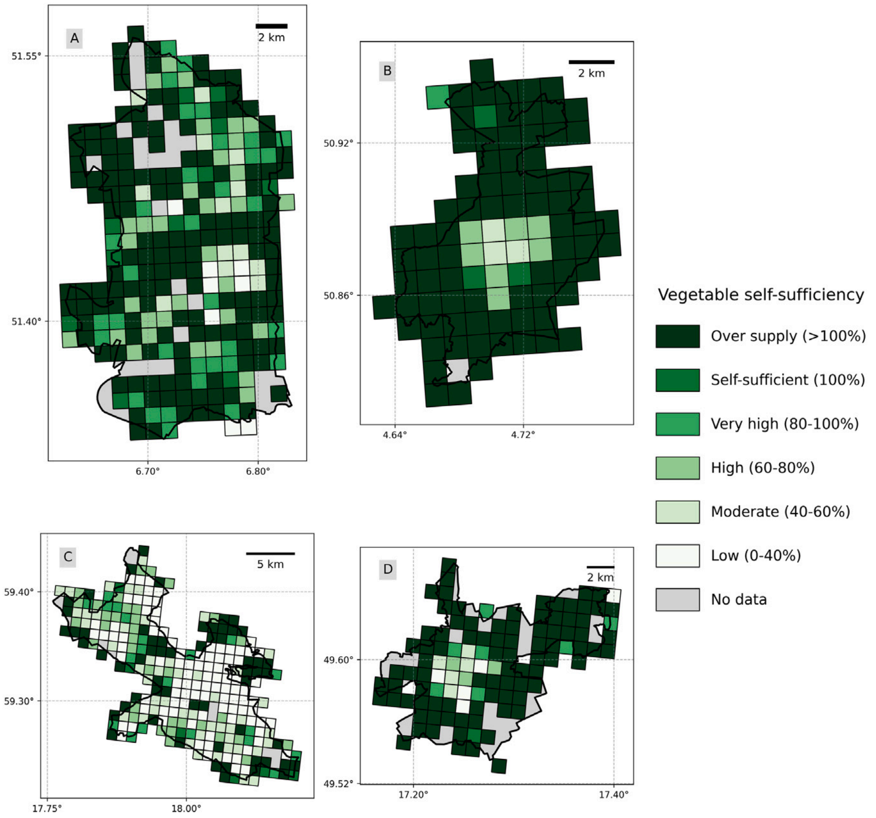

Fig. 3. (**A**) Duisburg, Germany (population ≈0.5 M), (**B**) Leuven, Belgium (population ≈0.1 M), (**C**) Stockholm, Sweden (population ≈1 M), (**D**) Olomouc, Czechia (population ≈0.1 M). Vegetable self-sufficiency levels are estimated under Scenario A, where 15% of roofs are flat and 15% of ground area is usable for food production. Each grid cell represents a 1 km^2 area. Darker shades indicate higher self-sufficiency, with oversupply (> 100%) in the darkest areas. The maps reveal spatial variations, with higher self-sufficiency typically observed on the outskirts and lower levels in densely populated city centers.

self-sufficiency levels are more common in densely populated cities, whereas higher levels are associated with less populous areas.

The nourishment potential numbers span from a minimum of 5.8% in Tower Hamlets, Great Britain (Scenario A) to a maximum of 634% in Lorca, Spain (Scenario C). The aggregated results of the vegetable self-sufficiency analysis at the city level under three distinct land-use intensity scenarios (A, B, and C) are presented in Table 2. Under Scenario A, 308 out of 840 cities achieve a potential self-sufficiency of at least 100%. In the most ambitious Scenario C, this number rises to 456 cities achieving full self-sufficiency or oversupply.

In terms of nourishment potential, approximately 190.7 million people reside in these 840 cities, according to the 1 km^2 gridded population dataset by European Commission (2018), which we use for this analysis. We obtain gridded self-sufficiency maps for each of 840 cities as shown in Fig. 3. The maps reveal distinctive spatial patterns of self-sufficiency levels within each city.

Generally, self-sufficiency tends to be higher in the outskirts and lower in the densely populated city center. This discrepancy is primarily due to limited cultivation space in city centers, which coincide with high population density. Conversely, the outskirts offer greater potential for cultivation. However, it is worth noting that there are some cells near the city center where self-sufficiency exceeds 100%. This phenomenon is attributed to the presence of parks or open spaces with very low population values assigned to them. For instance, a heritage site with very few residents may be situated in a cell where a park occupies most of the area.

The nourishment potentials across three scenarios are classified into five categories, as shown in Table 3. Under the most ambitious scenario (Scenario C), approximately 27.7% of the analyzed urban population could be supplied by local vegetable production. However, even under this scenario, 31.5% of the population resides in grid cells with low self-sufficiency (< 40%), highlighting persistent spatial mismatches between population density and cultivation potential.

3.5 Interplay between urban areas, population, and self-sufficiency

To aid interpretation, four illustrative cities (Duisburg, Leuven, Stockholm, and Olomouc) are explicitly highlighted in Fig. 4, representing contrasting urban forms, population densities, and self-sufficiency outcomes across the broader city distribution under Scenario A.

The roof-to-city area ratio ranges from 0.00005 to approximately 0.02 in highly compact administrative units, while the ground-to-city

Table 3

Nourishment potential across 840 examined cities is categorized into five self-sufficiency levels under three distinct land-use intensity scenarios (A, B, and C). The table presents the number of people (in millions) and the percentage of the total population that can be nourished in each self-sufficiency category. Percentages, given in parentheses, represent the proportion of the total population (190,672,200 people) residing within 1 km^2 grid cells, based on data from European Commission (2018).

	Scenario A	Scenario B	Scenario C
Low (0%–40%)	100.1 (52.5%)	76.3 (40.0%)	60.0 (31.5%)
Moderate (40%–60%)	35.2 (18.5%)	37.3 (19.6%)	35.6 (18.7%)
High 60%–80%	19.3 (10.1%)	23.1 (12.1%)	25.1 (13.2%)
Very high (80%–100%)	11.3 (5.9%)	15.1 (7.9%)	17.1 (9.0%)
Self-sufficient/Oversupply (≥100%)	24.7 (13.0%)	38.8 (20.4%)	52.9 (27.7%)

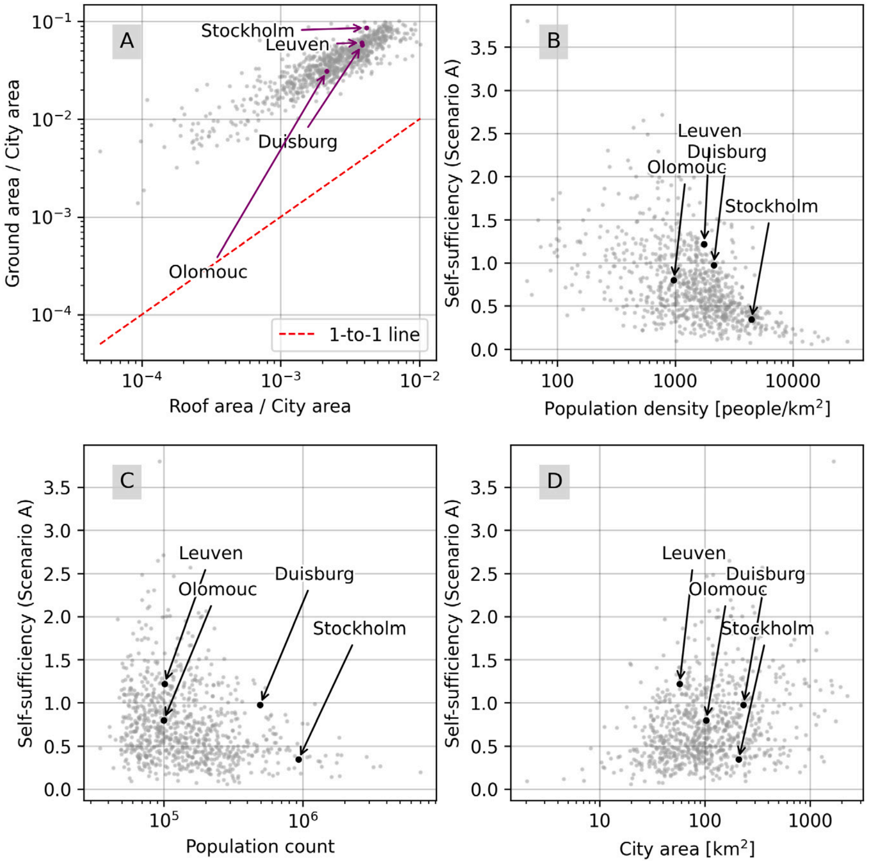

Fig. 4. Interplay among urban areas, population, and self-sufficiency under scenario A. (**A**) Ratio of roof area to total city area in relation to the ratio of ground area to total city area. The red dashed line represents the 1:1 line. (**B**) Population density in relation to self-sufficiency. (**C**) Population in relation to self-sufficiency. (**D**) City area in relation to self-sufficiency. Selected cities (Duisburg, Leuven, Stockholm, and Olomouc) are highlighted as illustrative examples representing contrasting combinations of city size, population density, urban morphology, and self-sufficiency outcomes, rather than as extreme or outlier cases.

area ratio spans from 0.001 to 0.1 in cities with extensive peri-urban land within their boundaries, as shown in Fig. 4A. The data show that ground area consistently exceeds roof area. Additionally, our findings indicate that both roof and ground areas tend to increase in proportion to city size. The same four highlighted cities are shown across Panels B–D to provide a visual reference for how contrasting urban forms and population characteristics translate into differences in vegetable self-sufficiency.

Notable outliers in Fig. 4 reflect specific administrative and morphological characteristics rather than typical urban patterns. Cities with unusually high roof-to-city-area ratios tend to have compact boundaries dominated by dense commercial or industrial building stock, whereas cities with very high ground-to-roof ratios often include extensive peri-urban land within their administrative limits. These cases illustrate how boundary definitions and land-use composition can influence area ratios without representing generalizable pathways of urban agriculture.

The populations of the examined cities range from 9 thousand in Melun, France, to 7 million in Paris, France. Population density plays a big role for large cities as seen in Fig. 4B. This figure depicts the relationship between population density and self-sufficiency levels under Scenario C. The data reveal an inverse relationship: higher population density is generally associated with lower self-sufficiency. At lower population densities, self-sufficiency levels tend to be more dispersed and higher, with some areas reaching as high as 3.8. Conversely, urban areas with very high population densities face notable limitations in achieving high levels of self-sufficiency through urban agriculture, underscoring the challenges posed by dense urbanization.

Under Scenario A, vegetable self-sufficiency declines with increasing total population (Fig. 4C). Cities with lower population counts show more dispersed and occasionally higher levels of self-sufficiency, reaching values up to 3.8. However, as the population increases, self-sufficiency levels cluster around lower values, indicating diminishing potential in larger cities. This pattern highlights the spatial constraints associated with supplying large urban populations through local cultivation alone.

In contrast, total city area shows a weaker and less systematic relationship with self-sufficiency (Fig. 4D). Larger cities tend to exhibit moderate to low self-sufficiency levels, clustering around 1–2, although some exceed 2. Smaller cities exhibit greater variability, occasionally reaching up to 3.8. This variability suggests that city area alone is not a decisive determinant of self-sufficiency, and that factors such as land-use structure and population density play more influential roles.

The potential cultivation area, and consequently the production and self-sufficiency potential, varies widely among cities with similar population sizes. The following analysis examines these differences in greater detail, focusing on potential cultivation areas for both roof- and ground-based systems. Additionally, we examine the production and self-sufficiency potential at both the aggregate level across all 840 European cities and through detailed 1 km^2 grid analysis for cities with populations of approximately 0.1, 0.5, and 1 million inhabitants.

3.6 Sensitivity analysis

Our sensitivity analysis demonstrates the strong robustness of city-level vegetable production and self-sufficiency rankings to uncertainty in yields and land availability. Across all yield perturbations and scenario ranges for rooftop and ground-based land availability (15%–25%), Spearman rank correlations consistently exceed 0.99 (Table S4). While absolute production and self-sufficiency scale proportionally with assumed yields and available area, relative city rankings and spatial patterns remain invariant. Accordingly, the results below focus on the magnitude and spatial variability of cultivation area, production, and self-sufficiency.

4 Discussion

Our findings highlight the significant potential of urban agriculture to address key urban challenges, including enhancing food security, promoting sustainability, expanding economic opportunities, and fostering social well-being. By estimating land availability for urban agriculture, we show how cities can reduce dependence on external supply chains by using underutilized spaces such as industrial zones and green urban areas, which are often overlooked. Importantly, our analysis bridges gaps in prior research (De Simone et al., 2023; Kriewald et al., 2019; Martellozzo et al., 2014) by incorporating both rooftop and ground-based approaches, thereby strengthening the case for urban agriculture as a practical solution for food production in densely populated regions.

However, urban agriculture can have unintended negative effects that must be critically considered (Pradhan et al., 2023, 2024). Soil-based cultivation in urban environments may expose crops to heavy metals or legacy contaminants, posing food safety risks if soils are not properly assessed or remediated. The conversion of urban land to food production can create trade-offs with other functions, including recreation, biodiversity conservation, housing provision, and commercial activities. In densely built areas, rooftop cultivation may impose structural load constraints, increase maintenance requirements, or conflict with alternative uses such as photovoltaic installations. Additional irrigation demand in water-scarce regions may intensify pressure on already stressed water resources. These considerations underscore that urban agriculture is not inherently sustainable and requires careful planning, regulation, and social safeguards to avoid unintended consequences.

Importantly, the magnitude and nature of these negative effects are not uniform across Europe but vary systematically with regional environmental conditions. In Southern European cities, water scarcity amplifies the risks associated with irrigation demand, increasing pressure on already limited water resources and potentially creating conflicts with other urban water uses. In these contexts, mitigation requires strict prioritization of water-efficient practices, including rainwater harvesting, greywater reuse, deficit irrigation, and the selection of drought-tolerant crops. In contrast, in Northern and parts of Western Europe, where precipitation is more abundant, water-related constraints are less critical, while risks related to soil contamination and reduced solar radiation become more prominent. Here, mitigation strategies should focus on systematic soil testing, the use of raised beds or imported, clean substrates, and site-specific crop selection adapted to low-light conditions. In densely built Central European cities, where land competition and legacy industrial land use are common, potential contamination hotspots and conflicts with other urban functions are particularly relevant, requiring integrated planning approaches that combine soil remediation, multifunctional land use, and regulatory oversight. These regionally differentiated risk profiles highlight that the sustainability of urban agriculture depends not only on maximizing production potential but also on aligning implementation with context-specific environmental constraints and appropriate mitigation measures.

Furthermore, our study demonstrates that variations in land-use scope, rooftop suitability criteria, and cultivation assumptions substantially influence estimated production and self-sufficiency outcomes. At the pan-European scale, these methodological sensitivities interact with pronounced regional differences in climate, urban structure, and land availability.

For Berlin, Germany, our most ambitious scenario estimates 10,210 hectares of potential urban agriculture space, exceeding the estimates reported by De Simone et al. (2023). This difference is mainly driven by the inclusion of additional ground-based land-use classes, such as green urban areas and selected industrial zones, which were excluded in residential-focused assessments. At the same time, we do not consider allotment gardens because they are classified as sports and leisure areas. Rooftop estimates also differ: our estimate of 702 hectares, compared with 546 hectares reported by De Simone et al. (2023), reflects different assumptions regarding the availability of flat roofs. In Bologna, Italy, our estimated vegetable production potential is lower than values reported by Orsini et al. (2014), who focused on intensive rooftop cultivation systems. This discrepancy reflects differences in system boundaries: while previous studies include engineered green roofs, our analysis is restricted to low-tech cultivation and excludes engineered stabilization systems. In smaller cities such as Braunschweig, Germany, and Rubí, Spain, methodological choices regarding rooftop inclusion have a proportionally larger effect. For example, Rubí's rooftop potential approximately doubles under our approach compared to Nadal et al. (2017), who excluded rooftops smaller than 500 m^2. Similarly, differences observed in Braunschweig arise from varying thresholds for rooftop size and slope, underscoring the importance of small-scale, fragmented rooftop spaces. The city cases discussed above are selected because comparable estimates from prior studies are available, enabling a transparent comparison of how differences in land-use definitions, rooftop suitability criteria, and cultivation assumptions affect estimated urban agriculture potential (see Table S6).

From a spatial planning perspective, the observed patterns of cultivation potential imply differentiated policy pathways across urban contexts, primarily structured by urban form. In dense urban cores, where ground-based space is structurally limited, urban vegetable production is most realistically supported by small-scale rooftop cultivation, integration with green infrastructure strategies, and neighborhood-scale food access initiatives, rather than by volumetric self-sufficiency targets. Medium-sized and lower-density cities exhibit greater flexibility to combine rooftop and ground-based cultivation, for example, through zoning regulations that permit food production in underutilized residential, industrial, and mixed-use areas, and through the designation of urban green spaces that explicitly incorporate productive functions. Across all urban contexts, such forms of vegetable production should be framed within European urban food strategies as a complementary measure that enhances resilience and spatial equity, rather than as a substitute for conventional agricultural systems.

These planning pathways operate along two complementary dimensions: urban form and regional context, which jointly determine spatial feasibility. While urban morphology determines the spatial configuration of available cultivation areas, regional climatic conditions constrain the biophysical feasibility and resource requirements of these systems.

At the same time, the spatial patterns identified in this study imply region-specific implementation constraints that require differentiated policy responses. In Southern European cities, where water scarcity and high evapotranspiration rates are dominant limiting factors, urban agriculture strategies require implementing water-efficient practices, including rainwater harvesting, greywater reuse, drought-tolerant crop selection, and seasonal production adjustments. In contrast, Northern European cities are primarily constrained by shorter growing seasons, lower temperatures, and reduced solar radiation; here, policy should focus on climate-adaptive measures such as crop selection, soil management to retain heat, and low-tech season-extension approaches (e.g., mulching, cold frames). In Central and Western Europe, where land competition is a dominant limitation, planning instruments such as multifunctional land use, zoning incentives, and integration with green infrastructure are likely to be more effective. These regionally differentiated pathways highlight that the feasibility of urban agriculture is not only a function of spatial availability but also of climate-specific resource constraints that must be explicitly addressed in implementation strategies. These region-specific strategies translate biophysical constraints into actionable planning interventions, thereby strengthening the policy relevance of urban agriculture across diverse European contexts.

Our self-sufficiency analysis also demonstrates the transformative potential of urban agriculture. For example, Berlin could achieve 45% self-sufficiency and Cerdanyola del Vallès (Spain) up to 140% under ambitious scenarios—differences that arise not only from land-use categorization but also from demand assumptions, such as vegetable consumption rates. Urban agriculture has the potential to help close nutritional gaps across a range of climates, populations, and urban settings.

Taken together, these considerations indicate that the findings are best understood as a strategic spatial framework that provides a strong foundation for informed planning and future implementation decisions. They highlight where urban agriculture could contribute meaningfully under favorable conditions and where structural constraints dominate. From a policy perspective, this framing supports using the results for exploratory planning, scenario analysis, and the identification of priority areas for further local assessment, rather than as prescriptive land-allocation targets.

Importantly, our approach emphasizes low-tech cultivation methods, which make urban agriculture highly accessible and cost-effective. This strategy can be implemented with comparatively low capital requirements by leveraging existing green spaces and natural rainfall, thereby lowering barriers to entry for community- and city-level food production initiatives.

Our study assesses biophysical potential but does not explicitly account for several key constraints affecting real-world implementation. All production and self-sufficiency estimates represent upper bounds on spatial potential rather than immediately deployable production. While the analysis evaluates the *potential* suitability of rooftop and ground-based areas with respect to agronomic and spatial criteria, it does not model institutional, economic, governance, or water constraints. Crucially, the identification of suitable land does not imply legal, social, or political availability for food production. Except for barren land, urban surfaces are typically already allocated to specific uses, and even apparently vacant spaces (e.g., sidewalks, courtyards, open areas) generally require formal approval for alternative functions. Accordingly, the assumed land-use shares of 15%–25% should be interpreted as hypothetical allocation envelopes rather than realistic short-term implementation levels.

Relaxing the slope threshold beyond 2° (e.g., to 10° as in previous studies (Slootweg et al., 2023; Xie et al., 2024)) would increase estimated cultivation area. However, this would primarily include rooftops that require more technically demanding cultivation approaches and would not materially affect the relative spatial patterns among European cities discussed here or the overall interpretation of our results.

Further limitations arise from assumptions regarding land usability and spatial configuration. All identified rooftop and ground-based areas are treated as potentially utilizable regardless of size, fragmentation, contiguity, or shading conditions. No minimum patch-size thresholds are imposed, and solar radiation is not explicitly modeled, although shading in dense urban environments may reduce effective productivity. While small and fragmented plots can support cultivation, fragmentation and microclimatic variability increase management complexity and may limit scalability.

Yield estimates introduce additional sources of uncertainty. They are derived from spatially explicit conventional agriculture datasets and aggregated at the city level to provide a consistent baseline. These estimates may overestimate productivity in climatically marginal regions or underestimate yields in intensively managed urban systems. Furthermore, input data limitations and aggregation to a 1 km^2 grid introduce smoothing effects that reduce fine-scale heterogeneity. These factors primarily affect absolute production levels, whereas relative city-level comparisons and large-scale spatial patterns remain robust, as confirmed by sensitivity analysis (Table S4).

Future research should integrate water availability, irrigation demand, solar radiation, soil quality, and microclimatic conditions to refine productivity estimates. Coupling spatial potential with socio-economic and governance data – for example, national or local land-use ordinances – would enable assessment of deployable potential. Finally, incorporating climate change projections would allow evaluation of how evolving temperature and precipitation regimes may alter the feasibility of urban agriculture across Europe.

5 Conclusion

Our study provides a pan-European, spatially explicit assessment of the potential of low-tech urban vegetable production across 840 cities. By integrating rooftop and ground-based cultivation opportunities within a unified GIS framework, we establish a comparable baseline for evaluating where urban agriculture can meaningfully complement existing food systems. Our results show substantial spatial variability in cultivation potential, production, and self-sufficiency, driven primarily by differences in urban density, land availability, and climate. Under the most ambitious land-use scenario, local vegetable production could supply approximately 27.7% of the analyzed urban population, while a majority of residents in dense city cores remain constrained by limited space. These findings underscore that urban vegetable production is not a substitute for conventional agriculture, but a complementary strategy that can enhance resilience, shorten supply chains, and support neighborhood-scale food access.

The framework developed here enables the translation of spatial potential into concrete urban planning and food system interventions. From a planning perspective, the results can inform the targeted reservation and designation of urban land for food production within municipal land-use plans, particularly by identifying underutilized green spaces, industrial areas, and suitable rooftop zones. In dense urban cores, where spatial constraints are most pronounced, the findings support prioritizing rooftop cultivation and integrating food production into green infrastructure strategies. In less-dense urban areas, the results highlight opportunities to allocate multifunctional ground-based spaces that combine food production with recreational and ecological functions.

Beyond spatial planning, the identified patterns of production potential provide a foundation for strengthening short food supply chains by aligning local production capacities with urban demand at the neighborhood scale. This enables cities to operationalize concepts such as the 15-Minute City by embedding decentralized food production within accessible urban areas, thereby reducing transport distances and enhancing food system resilience.

At the policy level, the results support the development of differentiated strategies for municipal and regional authorities that combine zoning instruments, incentive structures, and regulatory frameworks to facilitate urban agriculture while addressing context-specific constraints. Instead of prescribing uniform land-use targets, the findings enable cities to identify priority areas for implementation, design locally adapted interventions, and integrate urban agriculture into broader sustainability and food system transformation agendas.

Future research should integrate water availability, solar irradiance, soil quality, governance constraints, and socioeconomic factors to refine estimates of deployable production. Nevertheless, by focusing on widely accessible, low-tech cultivation systems, this study provides a spatially explicit and policy-relevant foundation for advancing sustainable urban food planning and resilient local food systems across Europe.

CRediT authorship contribution statement

Stepan Svintsov: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Prajal Pradhan:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Taylor Smith:** Writing – review & editing, Supervision, Methodology. **Diego Rybski:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

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.

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Appendix A. Supplementary texts, tables, and figures

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.scs.2026.107422.

Data availability

Data will be made available on request.

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