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An integrated quantitative framework for exploring sustainable scenarios in urban agriculture planning

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Abstract

Urban agriculture, encompassing ground farming, rooftop gardens, and greenhouses at building or community scales, offers solutions to various urban challenges. While existing research often focuses on resource use (food production and water and energy demands) of urban agriculture, its impact extends beyond physical resources. Additionally, the varied strategies for planning edible cities imply potential trade-offs among urban priorities. This study addresses this gap by proposing an integrated framework that incorporates land use classification, the generation of urban agricultural design scenarios, and the quantitative assessment of environmental impacts. This framework allows for a comprehensive understanding of benefits and trade-offs associated with different urban agriculture plans at the city scale. Taipei, Taiwan, serves as a case study to demonstrate the framework's feasibility. The analysis reveals that 9.4% of Taipei's area holds potential for urban agriculture, with half of this area comprised of small-scale ground plots scattered throughout existing urban green spaces. Sixteen potential urban agriculture scenarios were identified, considering factors like farming scale, farming style, cultivation method, and plant species. The quantitative assessment highlights trade-offs: planting food crops enhances food supply, while ornamental plants significantly mitigate the urban heat island effect. The proposed integrated framework can be applied to any city with adjusted factors. Through this integrated framework, alternative urban agricultural plans can be evaluated, facilitating informed decision-making towards a more sustainable urban future.

Keywords Urban agriculture, Edible landscape, Integrated framework, Spatial analysis, Life cycle assessment, Heat-island reduction

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1 Introduction

Urban agriculture, such as ground farming, rooftop gardens, and greenhouses, is gaining recognition as a potential solution to various urban climate challenges. It offers multifaceted benefits, including stabilizing food supply and enhancing food security [1], bolstering indoor thermal resistance and fostering energy conservation [2], thereby serving as an effective mitigation and adaptation strategy to reduce greenhouse gas emissions and associated climate change impacts [3, 4].

Several integrated strategies have been proposed to demonstrate the potential co-benefits of urban agriculture. For example, rooftop greenhouses integrated with buildings can concurrently reduce energy consumption, recycle water and food waste, and provide fresh food [5, 6]. Household gardens can contribute to waste management by managing wastewater and organic waste, thereby reducing environmental burdens by reducing the amount of waste exported to treatment facilities [3]. Localized food production can reduce greenhouse gas emissions owing to the shortened transport distance [5]. Additionally, plant cultivation offers ancillary benefits such as CO_2 capture [7], urban temperature regulation [8, 9], and improved air quality [10].

Quantitative investigations into urban agriculture predominantly focus on vegetation and food productivity [11]. A common approach involves spatial analysis to identify the available area for urban agriculture in a given case study region, followed by estimations of potential production and evaluations of environmental impacts [12]. Previous studies suggested that at least 15% of the total urban area in developed cities could be utilized for urban farming [12, 13], potentially leading to annual food production exceeding 50% of a city's total food consumption [13, 14].

However, McDougall et al. [15] highlighted a potential conflict between high productivity achieved through non-renewable resource use and the principles of sustainable development. Furthermore, repurposed areas such as community gardens and public parks for farming may necessitate additional resources and potentially alter their original functions, such as heat island mitigation and air quality improvement through green spaces. Moreover, existing research often focused on limited farming styles and edible plants [13, 16]. Factors such as planting methods and species selection significantly influence the direct and indirect impacts of urban agriculture [17, 18] were frequently overlooked. Therefore, a systematic approach that considers diverse scenarios in strategy planning is crucial for analyzing the impact of urban agriculture from an urban planning perspective.

This study aims to propose a systematic approach to quantify the impacts and trade-offs associated with various urban agricultural plans, with the goal of offering optimized urban design solutions. The approach adapted the sustainable design and discrete design decisions framework for the quantitative assessment of urban agriculture plans. The impacts and trade-offs for the studied plans, including heat-island reduction, were quantified using a life cycle assessment (LCA) approach. Taipei, the capital city of Taiwan, serves as a case study to demonstrate the planning procedure. The results from this study are intended to guide policy planning by addressing local urban issues to facilitate an informative decision-making process towards a more sustainable urban future.

2 Methods

This study proposes a three-step urban agriculture planning procedure to assess potential benefits and trade-offs associated with different scenarios. The framework incorporates land use classification, discrete design generation, and quantitative assessment, as illustrated in Fig. 1.

First, land use classification is conducted to identify areas with the potential for agriculture and the features of these areas. Subsequently, discrete design generation is employed to generate diverse planning scenarios. Finally, a quantitative assessment is conducted to evaluate the potential benefits and trade-offs associated with each scenario. Detailed descriptions of these steps are provided in the subsequent subsections.

To exemplify the application of urban agricultural strategies, Taipei, Taiwan was chosen as the case study area. A comprehensive overview of Taipei is presented in SM-1 for reference.

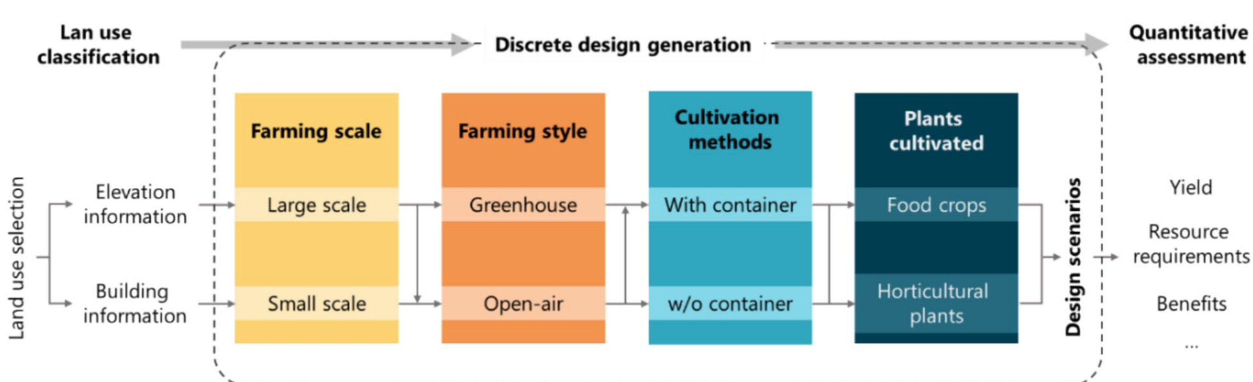

Fig. 1 Conceptual framework for the urban agriculture planning procedure, comprising land use classification, discrete design generation and quantitative assessment

2.1 Land use classification

Land use classification was performed through spatial analysis to identify areas with potential for urban agriculture. In this study, three types of urban areas—ground, rooftops, and building walls—were assessed for their suitability for plant cultivation through urban agriculture. Initially, available areas were identified utilizing a land-use investigation map [19] and a building map [20], followed by the selection of potential urban planting areas based on spatial criteria outlined in Table 1.

Ground-based agriculture areas were further categorized into large-scale and small-scale. Large-scale areas, akin to traditional agriculture but situated within urban settings, were deemed suitable for commercial farming and greenhouse cultivation. Intact green areas, such as abandoned fields and grassy patches, were earmarked for large-scale ground-based farming, with provisions for both open-air and greenhouse cultivation.

Conversely, small-scale areas, comprising fragmentations of urban green spaces, were designated for typical urban agriculture. Locations such as schools, parks, and vacant land were earmarked for small-scale ground-based farming, exclusively for open-air cultivation. Elevation information was utilized to exclude regions with steep gradients (> 15°) [12].

In the case of rooftop-based agriculture, government institutions and residential buildings were selected for assessment. Buildings with fewer than 10 stories or limited roof area were deemed unsuitable for farming and were consequently excluded [13].

For green-wall-based farming, government institutions and residential buildings with south-facing facades were considered [13]. Walls exceeding 6 m in height (equivalent to 2 stories) were omitted from analysis due to their negligible impact on the heat-island effect beyond that height [21] and the inherent maintenance challenges associated with such structures. The total green wall area was calculated by multiplying the length of each south-facing facade by a standard wall height of 6 m.

2.2 Discrete design generation

Urban agriculture planning involves multiple decisions at various scales. At the individual site level, choices include farming style (open-air or greenhouse), cultivation method (with or without containers), and plant type (edible or ornamental). These factors lead to a diverse range of potential configurations for urban agricultural spaces. When considering a city-wide scale, the combination of multiple individual sites with varying planning strategies results in numerous potential urban agriculture scenarios.

To systematically generate these scenarios, this study employed a discrete design generation approach [22] based on four key factors: farming site, farming style, cultivation method, and cultivated species (Fig. 1, middle panel). This process identified nine possible basic designs for the three types of farming sites within the case study area (Table 2). The purpose of this approach is to evaluate multiple possible configurations, rather than provide a single optimized urban agriculture design.

For example, large-scale ground spaces with farming potential could accommodate either greenhouse

Table 2 Basic designs of the urban agriculture within the case study area

Site i	Style	Methods[1]	Species
Ground	Open-air or Greenhouse[2]	w/ or w/o	Edible or Ornamental
Rooftop	Open-air	w/	Edible or Ornamental
Green wall	Open-air	w/	Ornamental

[1] with or without a container

[2] while open-air farming occurs on both large- and small-scale ground areas, greenhouse farming occurs only on the large-scale ground area and only for edible plants

Table 1 Spatial criteria for identifying potential areas for urban agriculture

Site i		Land use type	Spatial criteria
Ground	Large scale[1]	Abandoned field and grass-grown	• Slope < 15° [12] • Proportion available[2]: 1/2
	Small scale[1]	School, park, and vacant land	• Slope < 15° [12] • Proportion available[2]: 1/2
Rooftop		Government institution and residential buildings	• Building height ≦ 30 m [13] • Rooftop area: 100 m^2 [13] • Proportion available[2]: 1/2
Green wall		Buildings	• Direction: South facing facades [13] • Wall height ≦ 6 m [21] • Proportion available[2]:1/3 [13]

[1] Large-scale ground areas are suitable for both open-air and greenhouse farming, while small-scale ground areas are limited to open-air farming only

[2] Recognizing the need for other facilities in the same area, a portion of the available area suitable for agriculture was allocated for growing plants

farming, focusing on high-value food crops, or open-air farming. Considering Taipei's weather conditions, greenhouse farming was exclusively implemented in large-scale ground areas to optimize product yields and quality, with a focus on crop foods. Additionally, the decision to grow plants with or without containers influences site operation and maintenance. Moreover, the choice between edible and ornamental plants impacts the food provision service of the urban green area. Rooftop areas were designated for container-based cultivation due to their ease of maintenance; the primary design variation lies in the types of plants cultivated. Green walls were also considered, with the option of including or omitting plant coverage.

Sixteen distinct urban agricultural planning scenarios were ultimately identified, drawing upon the nine basic designs and the results of land use classification in the case study area (Table 3).

2.3 Quantitative assessment

A quantitative assessment was applied to elucidate the impacts of urban agricultural planning among studied scenarios. Rather than commercial agriculture in urban areas, urban agriculture in Taipei involves the growing of food in community gardens and the planting of edible landscapes. Furthermore, owing to the built environment and policy, urban agriculture in Taipei focuses on its influences from environmental and social perspectives. Therefore, in addition to using food production as the sole metric for performance evaluation, this study also intended to quantify its environmental performance through LCA and to assess its contributions in reducing the heat-island effect.

2.3.1 Production

Production is a direct benefit of urban agriculture. The production P_j (t) of crop j in each crop cultivation alternative is calculated using Eq. (1):

$$P_j = \sum_i A_i \times Y_j \times T_j \tag{1}$$

where, A_i (km^2) is the area of site i available for crop cultivation, Y_j (t yr^{-1} km^{-2}) is the yield of crop j per unit area, and T_j (times yr^{-1}) is the cultivation frequency of crop j during a year. Corn, tomato, and lettuce are representative edible plants and equally shared the space available for urban agriculture in the case study. A_j was derived using a spatial analysis; Y_i and T_i are derived from Ministry of Agriculture [23] and listed in Table S1 (in SM-2).

2.3.2 Environmental performance

An LCA was conducted to quantify and compare environmental impacts of studied urban agriculture scenarios. The functional unit for this assessment was defined as the operation of urban agricultural activities within available areas in Taipei over a 1-yr period. The environmental impacts of the nine basic designs identified in Table 2 were first calculated per m^2. Subsequently, these per-m^2 impacts were multiplied by the corresponding area associated with each scenario, as presented in Table 3, to quantify the total impact of each planning scenario.

The cradle-to-gate system boundary covers materials and resources used to build greenhouses, production of planting containers, manufacturing of fertilizers, and growing of plants but excludes consumption of the food products. The designing of greenhouses [24], green walls, and planting containers are shown in Fig. 2 and SM-3. Inventories of these components, as well as the maintenance and operation, such as the usage of soil media [25], fertilizers [26], and water, are listed in Table S3 and S4. Impact method of was

Table 3 Urban agricultural planning scenarios within the case study area

Sites—Types	Scenarios	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
Ground	Farming style	Open-air[2]				Greenhouse[3]				Open-air[2]				Greenhouse[3]			
	Cultivation methods[1]	w/o	w/o	w/	w/	w/o	w/o	w/	w/	w/o	w/o	w/	w/	w/o	w/o	w/	w/
	Edible plants	V	X	V	X	V	V[2]	V	V[2]	V	X	V	X	V	V[2]	V	V[2]
	Ornamental plants	X	V	X	V	X	V	X	V	X	V	X	V	X	V	X	V
Rooftop	Edible plants	V	X	V	X	V	X	V	X	V	X	V	X	V	X	V	X
	Ornamental plants	X	V	X	V	X	V	X	V	X	V	X	V	X	V	X	V
Building wall	Green wall	X	X	X	X	X	X	X	X	V	V	V	V	V	V	V	V

V: the setting is applied in the scenario; X: the setting is not applicable in the scenario

[1] with or without a container

[2] both large-scale and small-scale ground areas are for open-air farming

[3] While greenhouse farming occurs on the large-scale ground area and only for edible plants, small-scale ground areas are limited to open-air farming

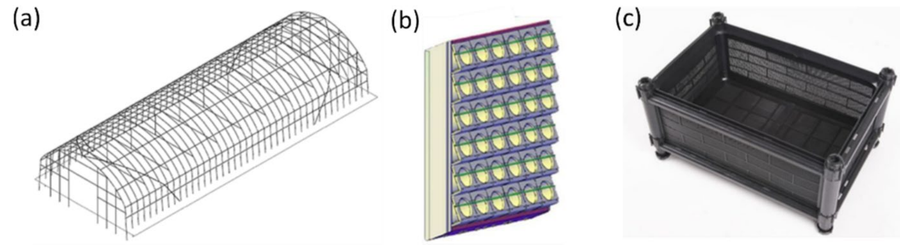

Fig. 2 The designing of (**a**) greenhouses, (**b**) green walls, and (**c**) planting containers

Table 4 Solar radiance absorption factor of surface material k [21]

k	Ornamental plants	Green walls	Greenhouses	Crops	No cultivation
β_k	0	0	0.4	0.5	0.7

applied for quantified the associated environmental impacts from urban agriculture activities.

2.3.3 Heat-island effect

Heat-island reduction is considered as another direct benefit of urban agriculture. The benefit of heat-island reduction as a result of increased green space due to landscape change is calculated using Eq. (2) adopted from [21].

$$\mathrm{H} = 1.25\left[1 - \frac{\sum_k (A_k \times \beta_k)}{\sum_k A_k}\right] \tag{2}$$

where, H (points) indicates the total reduction of heat radiation from different surfaces under each alternative, A_k (km^2) is the area available for urban agriculture covered with landscape k (surface material), and β_k (dimensionless) is the solar radiance absorption factor of surface material k.

The corresponding solar radiance absorption factors are shown in Table 4. The lower the solar radiance absorption factor (β_k), the lower the heat radiation and the higher the total reduction of heat radiation H (points). Therefore, areas with agricultural potential covered with ornamental plants (for horizontal surfaces) or green walls (for vertical surfaces) reduce the contribution of the built area to the local heat island. In the designed urban agricultural planning scenarios, areas with agricultural potential can be covered with ornamental plants, edible plants, greenhouses, or green walls (for vertical surfaces). Alternatively, they may have no cultivation.

Table 5 Areas with the potential for urban agriculture in Taipei

	Ground		Rooftop[1]	Green wall	Total
	Large scale	Small scale			
Area (km^2)	3.39	12.8	7.76	1.58	25.5
Ratio (%)[2]	1.2	4.7	2.8	0.6	9.4

[1] The rooftop areas of single- and double-story buildings available for cultivation is 1.98 km^2 and can contribute to heat-island reduction

[2] Ratios of the potential agricultural areas to the case study area

3 Results

3.1 Available area with the potential for urban agriculture

The available areas with the potential for urban agriculture were determined using spatial analysis (Table 5). The total area with the potential for urban agriculture in Taipei is approximately 25.5 km^2, accounting for approximately 9.4% of the total city area.

For the ground area, the large-scale area accounts for 13% of the area with agricultural potential and mainly occurs in northern Taipei near mountains or in western Taipei near rivers (Fig. 3d). The small-scale area, accounting for 50% of the area with agricultural potential, is the main area for urban agriculture. The small-scale area consists of fragmentations of urban green areas and mainly occurs in schools and riverside parks in the case study area (Figs. 3a and c). The rooftop area accounts for 30% of the potential area and is concentrated in southwestern Taipei, which is a densely populated region (Fig. 3b). Most of the urban rooftops are less than 500 m^2 in area. Green walls less than two stories high account for 6.2% of the potential agricultural area (Fig. 3b).

In this study, spatial analysis relied on land-use investigation maps. We overlaid the imagery map from Environmental Systems Research Institute (Esri) with the potential available space, including those on the ground and rooftop. Common and special cases used for examination are shown in Fig. 4.

The common spaces for large-scale ground-based agriculture, small-scale ground-based agriculture, and rooftop-based are areas with grass grown on hillsides, schools, and residential buildings, respectively.

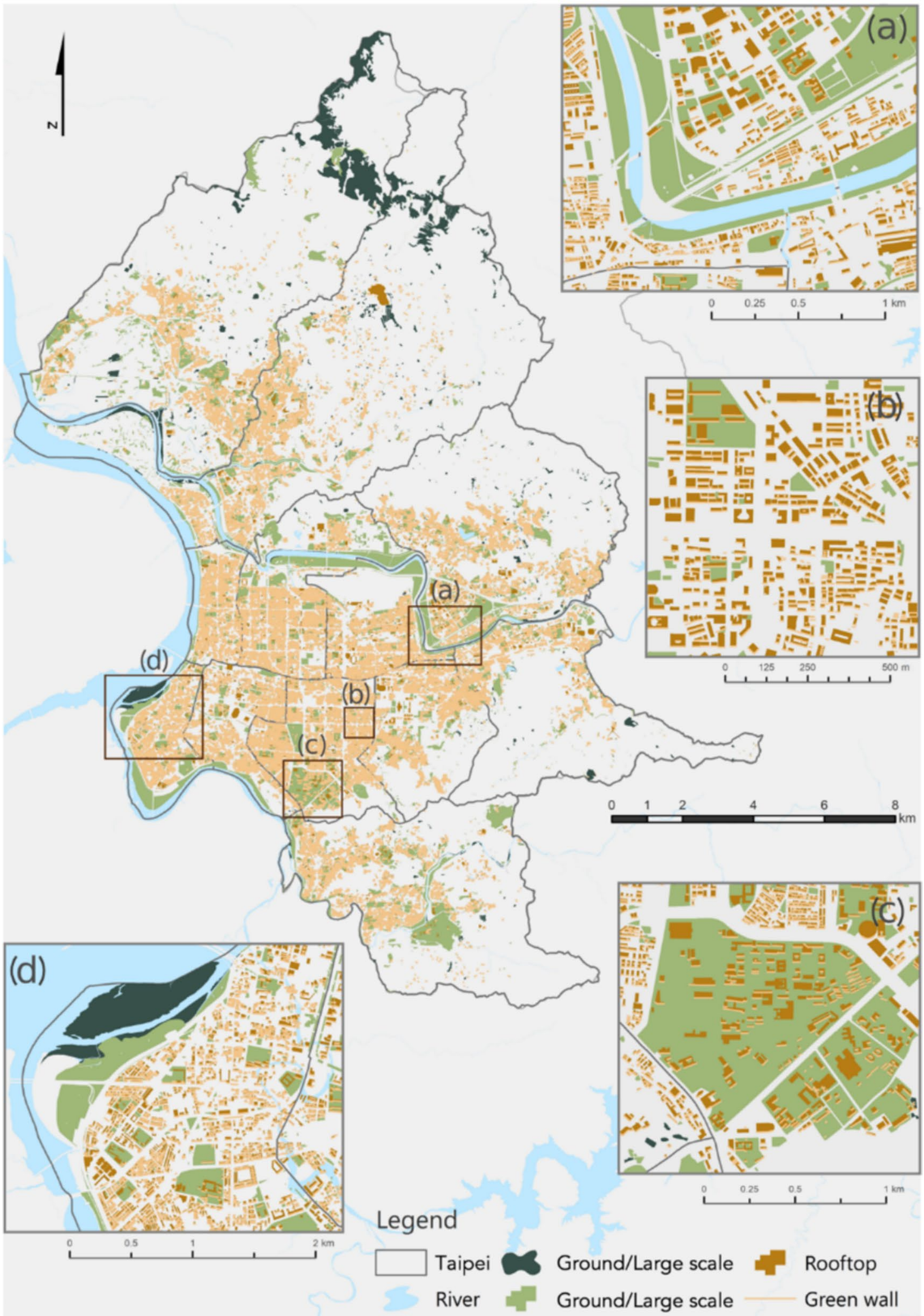

Fig. 3 Distribution of potential areas for urban agriculture in Taipei

Fig. 4 Selected parcels for examination (upper and lower panels present common and special cases, respectively)

Special cases on ground areas include abandoned fields or vacant land on riversides. When using these spaces for urban agriculture, water pollution due to fertilization should be considered in advance. In addition, a few rooftops of government institutions, such as museums, may be unsuitable for urban agriculture. This study presents the maximum potential of urban agriculture. Detailed on-site investigations are needed for special cases when implementing policies.

3.2 Quantitative assessment of urban agriculture

The urban agricultural planning scenarios presented in Table 3 are composed of nine basic discrete designs in Table 2. Quantitative results on the life-cycle end-point impacts, production, and heat-island reduction of each discrete design (per m^2 implementation for a year) are shown in Fig. 5.

The main differences in end-point impacts of human health, ecosystem and resources damages are cultivating with or without containers, mainly due to the usage of soil media. There were no significant differences in damages between planting edible plants and ornamental plants. However, the impacts of food crop cultivation primarily resulted from the utilization of inorganic nitrogen fertilizers; for planting ornamental plants, irrigation with tap water was the main impact contributor.

For ground area farming, open-air farming without containers resulted in the lowest end-point environmental impacts. Greenhouse farming provided the highest food production. Horizontal areas with ornamental plants reduced the heat-island effect to a greater degree than did the other covers. The green walls considerably reduced the heat-island effect; however, the end-point environmental impacts resulting from soil media were high.

The impacts of the urban agricultural planning scenarios are shown in Fig. 6. In general, farming directly on the ground resulted in lower environmental impacts (S1, S2, S5, S6, S9, S10, S13, and S14). Although the productions resulting from planting without a container were fewer than those resulting from planting with a container, planting without container may be preferable from an environmental perspective.

There were no significant differences in the environmental impacts and heat-island reduction benefits between the scenarios with and without green walls. However, the scenarios with green walls had potential benefits on marine eutrophication due to the supply chain of the green wall containers. The scenarios with ornamental plants consumed more water than did the crops and induced various impacts on the freshwater consumption-related impact categories (S2, S4, S10, and S12). However, the scenarios with ornamental plants considerably reduced the heat-island effect. S7 and S15 resulted in the highest food production. In these two scenarios, the available spaces with agricultural potential were used for growing food crops efficiently, including in greenhouses and using planting

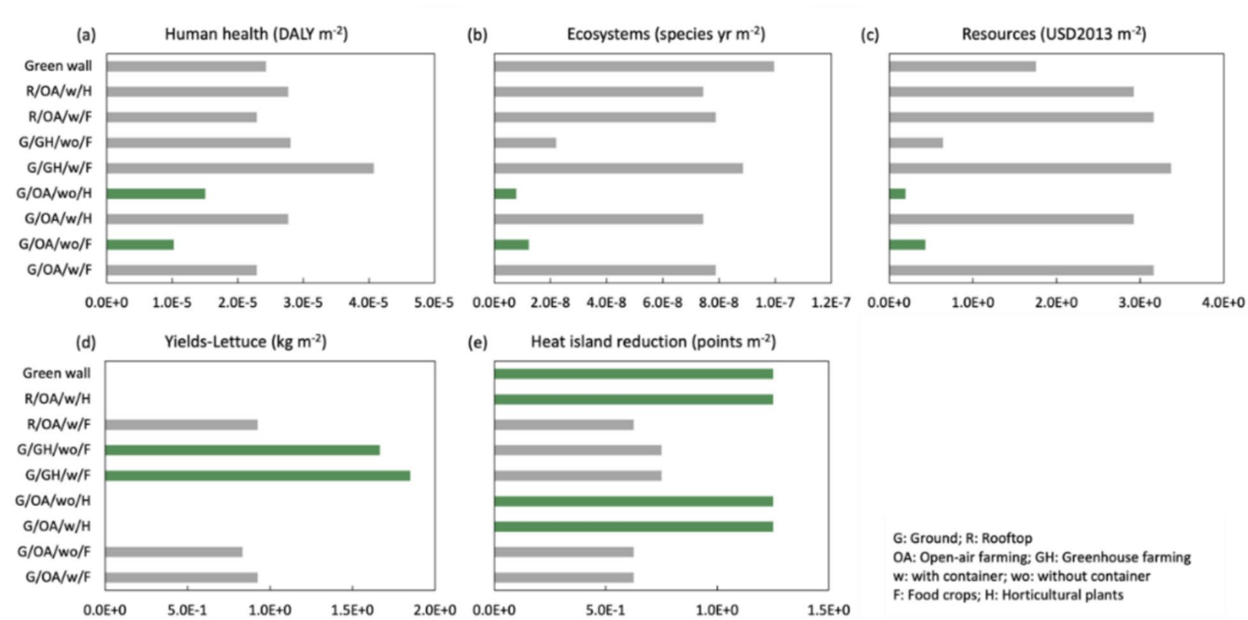

Fig. 5 Environmental impacts, (**a**) Human health, (**b**) Ecosystems and (**c**) Resources, and direct benefits, (**d**) Yields-Lettuce and (**e**) Heat island reduction, of the nine basic discrete designs (The environmental impacts were derived from ReCiPe 2016 Endpoint (I) V1.06/World (2010) I/I, normalized and weighted based on an Individualist perspective with global factors for the year 2010.)

Impact category	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
Global warming	kg CO_2 eq	4.10E+08	3.47E+08	9.63E+08	8.99E+08	4.27E+08	3.72E+08	9.79E+08	9.24E+08	5.08E+08	4.44E+08	1.06E+09	9.96E+08	5.24E+08	4.69E+08	1.08E+09	1.02E+09
Stratospheric ozone depletion	kg CFC11 eq	5.73E+02	2.26E+02	8.10E+02	4.63E+02	5.76E+02	2.79E+02	8.13E+02	5.16E+02	5.86E+02	2.39E+02	8.23E+02	4.76E+02	5.89E+02	2.92E+02	8.26E+02	5.29E+02
Ionizing radiation	kBq Co-60 eq	8.62E+06	8.77E+06	2.09E+07	2.11E+07	9.11E+06	9.23E+06	2.14E+07	2.16E+07	9.12E+06	9.26E+06	2.14E+07	2.16E+07	9.60E+06	9.73E+06	2.19E+07	2.20E+07
Ozone formation, Human health	kg NOx eq	8.12E+05	7.03E+05	1.89E+06	1.78E+06	8.46E+05	7.52E+05	1.92E+06	1.83E+06	9.62E+05	8.53E+05	2.04E+06	1.93E+06	9.95E+05	9.01E+05	2.07E+06	1.98E+06
Fine particulate matter formation	kg PM2.5 eq	1.55E+05	1.42E+05	3.82E+05	3.68E+05	1.60E+05	1.49E+05	3.87E+05	3.75E+05	1.68E+05	1.54E+05	3.94E+05	3.81E+05	1.73E+05	1.61E+05	3.99E+05	3.88E+05
Ozone formation, Terrestrial ecosystems	kg NOx eq	8.27E+05	7.16E+05	1.93E+06	1.81E+06	8.61E+05	7.66E+05	1.96E+06	1.86E+06	9.81E+05	8.70E+05	2.08E+06	1.97E+06	1.02E+06	9.20E+05	2.11E+06	2.02E+06
Terrestrial acidification	kg SO_2 eq	1.47E+06	1.26E+06	3.35E+06	3.13E+06	1.54E+06	1.35E+06	3.41E+06	3.22E+06	1.80E+06	1.58E+06	3.67E+06	3.45E+06	1.86E+06	1.67E+06	3.73E+06	3.55E+06
Freshwater eutrophication	kg P eq	1.12E+05	1.05E+05	2.51E+05	2.45E+05	1.18E+05	1.12E+05	2.57E+05	2.51E+05	1.23E+05	1.16E+05	2.62E+05	2.55E+05	1.29E+05	1.23E+05	2.68E+05	2.62E+05
Marine eutrophication	kg N eq	1.54E+04	1.30E+04	3.65E+04	3.40E+04	1.06E+04	8.52E+03	3.17E+04	2.96E+04	-5.55E+04	-5.79E+04	-3.44E+04	-3.69E+04	-6.03E+04	-6.24E+04	-3.92E+04	-4.13E+04
Terrestrial ecotoxicity	kg 1,4-DCB	2.92E+08	1.88E+08	5.14E+08	4.10E+08	3.01E+08	2.12E+08	5.22E+08	4.34E+08	3.08E+08	2.04E+08	5.30E+08	4.26E+08	3.17E+08	2.28E+08	5.39E+08	4.50E+08
Freshwater ecotoxicity	kg 1,4-DCB	6.43E+06	5.93E+06	1.13E+07	1.08E+07	6.95E+06	6.52E+06	1.18E+07	1.14E+07	6.57E+06	6.07E+06	1.15E+07	1.10E+07	7.08E+06	6.65E+06	1.20E+07	1.15E+07
Marine ecotoxicity	kg 1,4-DCB	2.20E+06	2.13E+06	3.83E+06	3.77E+06	2.39E+06	2.34E+06	4.03E+06	3.98E+06	2.24E+06	2.18E+06	3.88E+06	3.82E+06	2.44E+06	2.39E+06	4.08E+06	4.03E+06
Human carcinogenic toxicity	kg 1,4-DCB	1.37E+05	1.26E+05	3.32E+05	3.22E+05	1.43E+05	1.34E+05	3.39E+05	3.29E+05	1.60E+05	1.49E+05	3.56E+05	3.45E+05	1.66E+05	1.57E+05	3.62E+05	3.53E+05
Human non-carcinogenic toxicity	kg 1,4-DCB	7.29E+06	7.18E+06	1.49E+07	1.48E+07	7.84E+06	7.75E+06	1.54E+07	1.53E+07	7.97E+06	7.86E+06	1.56E+07	1.55E+07	8.52E+06	8.43E+06	1.61E+07	1.60E+07
Land use	m^2 crop yr^{-1} eq	9.97E+06	9.14E+06	2.63E+07	2.55E+07	1.02E+07	9.44E+06	2.65E+07	2.58E+07	1.11E+07	1.03E+07	2.74E+07	2.66E+07	1.13E+07	1.06E+07	2.76E+07	2.69E+07
Mineral resource scarcity	kg Cu eq	2.75E+06	2.28E+06	3.99E+06	3.52E+06	3.03E+06	2.62E+06	4.27E+06	3.86E+06	3.37E+06	2.89E+06	4.61E+06	4.13E+06	3.64E+06	3.24E+06	4.88E+06	4.48E+06
Fossil resource scarcity	kg oil eq	1.09E+08	9.25E+07	2.66E+08	2.49E+08	1.12E+08	9.77E+07	2.69E+08	2.54E+08	1.21E+08	1.04E+08	2.77E+08	2.60E+08	1.23E+08	1.09E+08	2.80E+08	2.65E+08
Water consumption	m^3	9.44E+07	1.54E+08	9.92E+07	1.59E+08	1.20E+08	1.71E+08	1.25E+08	1.76E+08	1.05E+08	1.64E+08	1.09E+08	1.69E+08	1.30E+08	1.81E+08	1.35E+08	1.86E+08
Yields (Lettuce)	kg	6.88E+06	0.00E+00	7.38E+06	0.00E+00	7.82E+06	1.88E+06	8.42E+06	2.09E+06	6.88E+06	0.00E+00	7.38E+06	0.00E+00	7.82E+06	1.88E+06	8.42E+06	2.09E+06
Heat island	points	4.86E-01	7.62E-01	4.86E-01	7.62E-01	5.17E-01	7.41E-01	5.17E-01	7.41E-01	5.19E-01	7.96E-01	5.19E-01	7.96E-01	5.50E-01	7.75E-01	5.50E-01	7.75E-01

Higher costs/ Fewer benefits — Lower costs/ More benefits

Fig. 6 Quantitative evaluation of each urban agricultural planning scenario (CFC11: trichlorofluoromethane; 1,4-DCB: 1,4-dichlorobenzene)

boxes. Therefore, these two scenarios also had great environmental impacts.

4 Discussion

4.1 Contribution of urban agriculture to urban food security

The possible and ongoing urban agriculture in Taipei occurs at household or community scales, rather than at the commercial scale. In addition, the gardeners are citizens who may not be professionals in growing plants. Therefore, production levels derived in this study may be the potential maximum production in Taipei.

In the case study, edible plants, including corn, tomato, and lettuce, were assumed to be equally cultivated on the ground and rooftop. Compared to the currently cultivated area in Taipei, the area with the potential for urban agriculture provided a significant amount of farming area (Table S2 in SM-2), that is, approximately 76.7 times the area currently used for corn cultivation, 61.8 times the area currently used for tomato cultivation, and 11.6 times the area currently used for lettuce cultivation.

The maximum and minimum food productions for the urban agricultural scenarios are shown in Table S2. The maximum corn, tomato, and lettuce production (S7 and S15) were approximately 9–64 times higher than current production. Even in the minimum production scenarios, food crops were only cultivated in the greenhouses covering an area of 3.39 km^2 (S6 and S14), with production approximately 2–14 times higher than current production. Growing food crops in urban green or vacant areas can considerably increase cultivation area and food production in well-developed [27, 28].

4.2 Environmental impacts of urban agriculture

From the environmental impacts results, the potential hot spot of each planting scenario was revealed, and we can take action to reduce the environmental impacts. For ornamental planting, tap water can be replaced with rainwater [13]. For food crop cultivation, compost can be used as organic-rich substrate and reduce the application of fertilizers [3, 29].

However, for planting containers with soil media, the highest impact contributor, we still recommend urban farming with containers. Soil quality can affect crops yield [12]. Furthermore, growing plants on rooftops may induce safety problems on the building structure and increase the economic cost of urban agriculture maintenance and operation [12]. These concerns can be alleviated by using planting boxes. In addition, using soil media can improve production efficiency and maintain plant health, especially for non-professional gardeners.

4.3 Further research: Social benefits and site-specific evaluations of urban agriculture

To improve urban sustainability, several strategies can be applied to urban areas. Liu et al. [30] optimized the arrangement of low-impact developments, photovoltaic systems, and urban agriculture in a densely populated region in Taipei; their results indicated that urban agriculture is not preferable because of its high environmental impacts. However, among the three practices, only urban agriculture provides additional values that involve citizens.

The benefits of urban agriculture evaluated in most studies have emphasized provisioning and regulating services. However, cultural services, such as providing environments for agri-food education, entertainment and recreation, and the improvement of citizen social networking that benefit mental health [31, 32], are the main reasons for the Taipei government promoting urban agriculture. The social benefits of urban agriculture should not be ignored in further research.

In addition, based on the city-scale plans delivered by the proposed assessment framework, local communities can follow the suggested strategies to implement practical solutions. At this stage, detailed site-specific evaluations can be conducted, considering factors such as human operation, pesticide use, fertilization, water usage, and local environmental concerns like flood control and building safety.

5 Conclusions

This study developed a systematic approach, including land use classification, discrete design generation, and quantitative assessment, to understand the impacts of possible urban agriculture plans on the city scale. Using Taipei, the capital city of Taiwan, as a case study, we demonstrate that urban agriculture can considerably increase cultivation area and production compared to the current status of the city.

Improving the use of non-green areas, such as rooftops and walls, based on the requirements of a city, can add additional value to a city. Our results revealed that food production and heat-island reduction also carry environmental impacts. Quantitative assessment through LCA approach can be used to identify hot spots of planting scenarios and planning strategies that minimize associated impacts and improve production efficiency.

Urban agriculture in well-developed cities may not be commercial and may have to rely on the participation of citizens. To put it into practice, the government can apply different strategies to different regions based on their land use and land cover. For example, public rural areas can be outsourced with commercial farming; green areas in the central city can be open to citizens; seeds or equipment could be provided to encourage citizens to grow plants on their private properties or rooftops.

The proposed integrated framework is particularly applicable to well-developed cities with limited space for urban agricultural planning. The factors considered in the framework are flexible and can be tailored to the characteristics of the target cities, with indicators selected based on the specific environmental issues of interest. This framework enables systematic analysis of urban agricultural scenarios through quantitative assessments, helping to avoid negative impacts and providing efficient plans to enhance urban sustainability.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42834-025-00241-5.

Supplementary Material 1.

Authors' contributions
Zih-Ee Lin: Conceptualization, Methodology, Validation, Writing-Original Draft, Writing-Review & Editing, Visualization; Yin-Chi Lin: Methodology, Formal analysis, Investigation, Writing-Original Draft, Visualization; Mengshan Lee: Methodology, Validation, Writing-Review & Editing; Pei-Te Chiueh: Conceptualization, Validation, Resources, Writing—Review & Editing, Supervision, Funding acquisition; Chun-Wei Wu: Resources, Writing-Review & Editing; Yu-Sen Chang: Resources, Writing-Review & Editing.

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Data availability
All data generated or analyzed during this study will be made available on request.

Declarations

Competing interests
The authors declare they have no competing interests.

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