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Optimizing productive green roofs for urban food self-sufficiency in Amsterdam

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ABSTRACT

Fulfilling urban dietary demand often hinges on importing food from rural areas, leaving the local food supply chain and food security vulnerable to disruptions. Productive green roofs have the potential to partially address this challenge by supplying food locally and therefore mitigating sudden disruptions in the urban food supply chain. However, increasing urban food self-sufficiency requires an understanding of urban food production potential and the optimal planting structures for crop rotation planning. In this study, we modeled various crop rotations spatially and temporally to assess the potential for urban productive green roof food production to meet the local dietary demand of specific crop groups. We estimated urban food self-sufficiency considering average productive green roof crop yields and climatic variability (2003–2021) within the city of Amsterdam. We find that Amsterdam's potential productive green roofs can achieve urban food self-sufficiency of 52 % for selected crops (41–54 % when accounting for climatic and spatial variability). When optimizing the planting structure, this number rises to 71 % (50–71 %). Our results highlight that productive green roofs in Amsterdam have the potential to strengthen the local food supply chain, especially if a strategic approach to the planting structure is adopted.

1. Introduction

Urbanized areas rely heavily on importing food from rural areas to meet the dietary needs of their densely populated communities (Satterthwaite et al., 2010; Toboso-Chavero et al., 2023). Producing food in urban areas can connect people to food and give them a better understanding of all the requirements and efforts to grow food (Seto & Ramankutty, 2016; Specht et al., 2014). Urban agriculture mainly includes ground-based agriculture (e.g. community gardens, vacant land), vertical farming, and rooftop agriculture (Eigenbrod & Gruda, 2015). With rapid urbanization and a rising number of urban buildings worldwide, rooftop spaces present a promising opportunity for agricultural production (Yang et al., 2024). Furthermore, producing urban food on green roofs can have important environmental benefits: fostering urban biodiversity (Orsini et al., 2014), cutting transport and its associated environmental impacts (e.g., less air pollution) (Goldstein et al., 2016), mitigating the urban heat island effect (Wang et al., 2022), countering the urban sprawl at the cost of agricultural land (Bren d'Amour et al., 2017), building short food supply chains (Weidner et al., 2019), and improving water and waste management (Paithankar & Taji, 2020; Weidner & Yang, 2020). Rooftop agriculture also provides social benefits by providing educational opportunities, fostering social cohesion, improving mental health, and increasing social equity (Appolloni et al., 2021; Specht et al., 2017; Stefani et al., 2018). These positive aspects warrant an exploration of strategies that can promote urban food self-sufficiency and enhance local food security (Hume et al., 2021; Kriewald et al., 2019). In this context, the concept of productive green roofs emerges as a compelling solution, representing a form of building-integrated urban agriculture that holds the potential to produce food locally (De Simone et al., 2023; Calheiros & Stefanakis, 2021; Song et al., 2022; Xie et al., 2024).

Food self-sufficiency based on productive green roofs has been the subject of various studies. Here, food self-sufficiency refers to the capacity to meet local demand with local food supply. Productive green roofs focus on food production of edible crops, while other green roofs prioritize ecological or aesthetic functions of non-edible plants (Dong et al., 2024). Song et al. (2022) estimated a 3 % food self-sufficiency of leaf vegetable consumption for Singapore's high-rise residential

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buildings. In Cerdanyola del Vallés, Barcelona, Toboso-Chavero et al. (Toboso-Chavero et al., 2023) calculated a range of 28–78 % vegetable self-sufficiency while considering various urban morphologies. According to De Simone et al. (2023) the city of Berlin, Germany, could supply up to 11 % of the demand for vegetables through productive green roofs. Orsini et al. (2014) suggest that productive green roofs in Bologna, Italy, could potentially produce 12,000 t of vegetables annually, which could satisfy 77 % of the city's population's vegetable requirement. Saha and Eckelman (2017), by identifying possible green roof areas and appropriate grounded patches, predicted that productive green roofs could provide an additional 30 % of the country's fruit and vegetable needs in Boston, USA. In a region north of Barcelona, Zambrano-Prado et al. (2021) calculated that productive green roof areas could yield 210 % of the consumption of tomatoes and 21 % of the consumption of lettuce. These studies evaluated bulk categories (e.g., vegetables) and/or limited specific crops to assess productive green roof potential. However, few studies use planting structure optimization that involves spatial planning and crop rotations to spatially and temporally allocate potential green roof areas to various crop mixes. Research on urban agriculture in Amsterdam has looked at different aspects including its socioeconomic impacts (Oost, 2013), policy integration (Labee, 2021), smart city implementations (Berger & Goos, 2024), planning challenges (Farhangi et al., 2020), and rooftop design (Nelli, 2022). However, no study has focused on quantifying urban food self-sufficiency through productive green roofs in Amsterdam, considering crop rotation planning. Although Xie et al. (2024) have explored food production potential for mixed produce based on productive green roofs, they combined crop yields and potential roof areas without addressing spatial and temporal allocation for crop rotations. Thus, the extent to which productive green roofs can satisfy the local consumption dietary requirements when considering optimized crop distribution and seasonal rotations remains unexplored.

In this study, we quantify urban food self-sufficiency for a range of local climate conditions experienced in Amsterdam over the past decade with optimized crop rotation plans. We use Sequential Least Squares Programming to optimize planting structures for crop rotations on productive green roofs to meet the city's food demand. With this study, we provide a strategic framework for integrating productive green roofs into urban food systems.

2. Methods

2.1. Study area

Amsterdam was selected as an ideal location to investigate urban food self-sufficiency through productive green roofs, based on several key factors: (i) Suitable weather for urban rooftop agriculture: The winters in Amsterdam seldom fall below 0 °C, while the summers rarely exceed 30 °C (KNMI, 2022). The city's average temperature in the period 2003–2021 is 10.7 °C, while the average annual precipitation during the period is 904 mm (Cornes et al., 2018a). (ii) Supportive policy initiatives: Amsterdam's Food Strategy Implementation Agenda (2023–2026) emphasizes increasing local food production and raising awareness about food production to reduce food waste through urban agriculture, including rooftop farming (Gemeente Amsterdam, 2023a). The Amsterdam Urban Farming Foundation (Stichting Stadslandbouw Amsterdam) (Amsterdam Urban Farming Foundation, 2024a) has actively promoted urban agriculture and shorter food supply chains. Since 2023, it has organized the annual Amsterdam City Farming Day, aiming to meet 25 % of the city's local food demand by 2030 and increase resident participation and awareness to 20 % by 2026 within urban agriculture (Amsterdam Urban Farming Foundation, 2024b). (iii) Extremely urbanized: On average, over 80 % of The Netherlands' population lives in urban areas (European Investment Bank, 2018). Notably, Amsterdam stands out with a population density of 4880 persons per km^2 (CBS, 2024a), categorizing it as extremely urbanized (>2500 persons per km^2) by Dutch standards (CBS, 2025). (iv) Urban productive green roofs potential: Amsterdam occupies an area of 219 km^2 including green areas of 8240 ha (61 % of public outdoor space, ~90 m^2 per capita), and rarely produces vegetables and fruits within its agricultural landscape (Fig. 1) (Gemeente Amsterdam, 2023b). Despite having limited vegetable and fruit production within its agricultural zones, the city has significant potential for productive green roof food production, with approximately 396 hectares on flat roofs suitable for food production on public and commercial buildings, excluding industrial and residential buildings (Fig. 1) (Xie et al., 2024; BAG, 2024). The 396 hectares represent unused rooftop areas on potential productive green roofs, excluding existing green roofs dedicated to supporting plants, animals, and fungi, as well as other rooftop functions like water harvesting, energy production, and spaces for recreation and leisure (Gemeente Amsterdam, 2023c).

2.2. Estimating crop production potential on productive green roofs

We employed the framework developed by Xie et al. (2024) to quantify Amsterdam's productive green roof crop productivity for specific crop types with an open-air agriculture system including lettuce, cabbage, onion, pea, leek, strawberry, spinach, cauliflower, bean, and broccoli. The selection of crop types was guided by two main considerations: (1) crops need to be shallow-rooted due to the lightweight soil layer, which is limited to 20 cm in depth to align with typical rooftop load-bearing capacities (not exceeding 2 kN m^{-2}) (Xie et al., 2024); and (2) the crops should be locally produced. The chosen ten crop types represent 82.5 % of the total open-air vegetable production, including strawberries, classified as a vegetable type by Statistics Netherlands (Xie et al., 2024; CBS, 2024b). We collected data on climate including maximum temperature, mean temperature, minimum temperature, radiation, relative humidity, wind, and precipitation (Cornes et al., 2018b), soil (Ledesma et al., 2022), crop (Xie et al., 2024), full irrigation amount to achieve maximum crop yield potential (Xie et al., 2024), and potential green roof areas (Xie et al., 2024). We adopted the climate conditions between 2003 and 2021 and average crop parameters (e.g., harvest index, and canopy cover) (Xie et al., 2024) to calculate average yields on productive green roofs between 2003 and 2021 (Table S1). The average year 2008 (determined by average yearly precipitation between 2003 and 2021) (Fig. S2) served as a baseline scenario, while other years between 2003 and 2021 were examined to assess how the optimized planting structure determined for the year 2008 performed under varying climate scenarios, including drier and wetter conditions. Considering that effective utilization of water resources is crucial for maintaining the sustainability of agricultural production, we determined the irrigation amount for each crop type at their maximum water use efficiencies, quantified as the ratio of yield to actual crop evapotranspiration during the crop growth period (Table S2). Maximum water use efficiencies were obtained by simulating green roof crop yields and actual crop evapotranspiration by changing irrigation values (increasing by 1 mm intervals until full irrigation amount). The potential productive green roof areas in Amsterdam were assumed as 396 ha considering productive green roof criteria including available roof area (Xie et al., 2024), building height (Saha & Eckelman, 2017), roof types (Zambrano-Prado et al., 2021), roof area (Zambrano-Prado et al., 2021), building functions (Shao et al., 2021), and construction year (Silva et al., 2017) (Table S3). We evenly allocated productive green roof areas to 14 planting methods (considering different crop rotations that are strategically timed according to the distinct growth periods of each crop (Fig. S1, Table S4)).

2.3. Quantifying urban food self-sufficiency

Annual urban food self-sufficiency (UFSS) for the 10 crop types was quantified by matching food demand (FD, in tons) with food production (FP, in tons; Eqs. (1)–(3)), as follows:

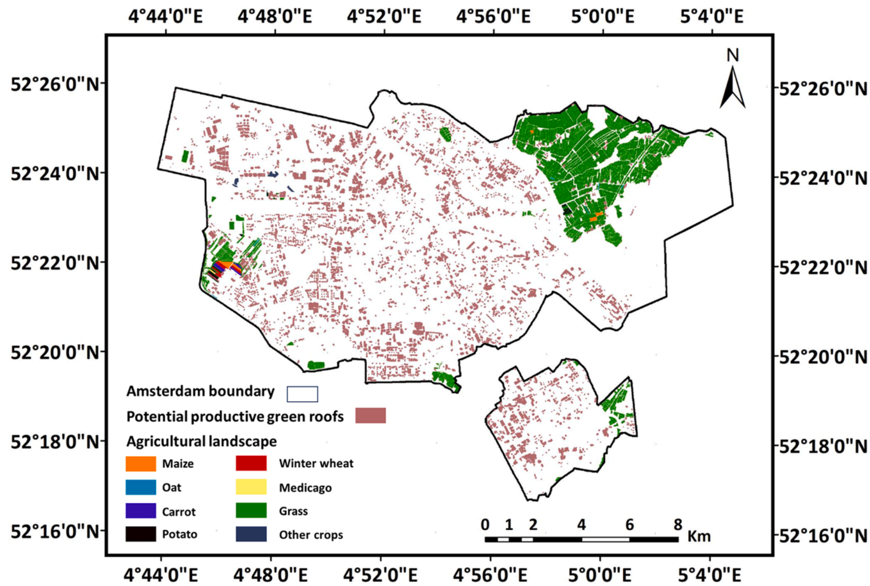

Fig. 1. Study area, potential productive green roofs, and crop map in Amsterdam.

$$UFSS = \sum_{i=1}^{10} \min(FP_i, FD_i) \Big/ \sum_{i=1}^{10} FD_i \tag{1}$$

$$FP_i = Area_i Yield_i \tag{2}$$

$$Area_i = \sum_{k=1}^{n} Area_{j_k} \tag{3}$$

where, i is the crop, representing bean, broccoli, cabbage, cauliflower, leek, lettuce, onion, pea, spinach, and strawberry (1, 2,..., 10); j is the crop planting method, representing onion - spinach$_b$, leek, lettuce$_a$ - bean - spinach$_b$, cauliflower, lettuce$_a$ - broccoli, strawberry - spinach$_b$, pea - cabbage$_b$, pea - spinach$_b$, cabbage$_a$ - spinach$_b$, cabbage$_a$ - cabbage$_b$, lettuce$_a$ - lettuce$_b$ - spinach$_b$, lettuce$_a$ - cabbage$_b$, spinach$_a$ - lettuce$_b$, and spinach$_a$ - cabbage$_b$ (1, 2,..., 14; *a, b* represent different growth periods for the same crop); n is the total number of occurrences of crop i within different crop combinations of *j; k* represents each occurrence; *Area* (ha) refers to the planting areas on productive green roofs, *Yield* (t ha^{-1}) is the green roof crop productivity.

FD was calculated assuming that local diet data for the 10 selected produce in Amsterdam follow those of the Netherlands and considering the food waste at the household level (18.9 %) following Navarre et al. (2022). These 10 produce are consumed at 70 g/day per person, representing 44 % of the total vegetable consumption (158 g/day per person) in The Netherlands (Table S5) (van Rossum et al., 2011). Information regarding local dietary patterns for targeted crop types in The Netherlands was sourced from the report by the National Institute for Public Health and the Environment (Table S5) (van Rossum et al., 2011).

A UFSS value of 100 % indicates a perfect match between FP from urban productive green roofs and the city residents' FD (Zasada et al., 2019), thereby minimizing the overproduction of crops that might go unused. Thus, to check whether there are potential food surpluses, we calculated the food production surplus ratio as the ratio between FP and FD for specific crop types (Hiç et al., 2016).

2.4. Optimizing planting structure

We used the Sequential Least Squares Programming (SLSQP) mathematical optimizer to maximize UFSS on productive green roofs with crop planting areas of 14 crop planting structures (as described for j in Eq. (3)) as the independent variable (Kraft, 1988). Optimizing planting structures on productive green roofs is essential for developing sustainable urban food systems, by making efficient use of otherwise limited city resources (Davis et al., 2017). To allocate green roof areas effectively for crop rotations, optimization models are often applied to determine the best crop distribution and timing (Dury et al., 2012). Pontes et al. (2024) conducted a review of 46 papers that analyzed six methods: Linear Programming, Non-Linear Programming, Heuristic, Evolutionary Algorithms, Dynamic Programming, and Stochastic Dynamic Programming. Among the optimization models for crop rotation planning problems, Linear Programming is the most frequently applied method due to its straightforward approach, particularly when addressing linear objectives such as maximizing profit, reducing carbon emissions, enhancing crop yields, or minimizing irrigation needs (Pontes et al., 2024). For more complex scenarios where objectives have non-linear dependencies, Non-Linear Programming, such as SLSQP, is more suitable to offer a stable solution (Kraft, 1988). The algorithm chooses the best planting structure based on 396 ha of potential green roof areas (Eqs. (4)–(6)).

$$Maximize\ (UFSS(FP_i, FD_i)) \tag{4}$$

Subject to:

$$\forall j \mid Area_j \rangle 0, \sum_{j=1}^{14} Area_j \leq 396\ ha \tag{5}$$

$$\forall i \mid FP_i \leq FD_i \tag{6}$$

where, i is the crop (as described in Eq. (1)); j is the crop planting method (as described in Eq. (3)).

2.5. Sensitivity analysis

We used Eq. (1) to quantify UFSS considering climate variability between 2003 and 2021 with/without the optimized planting structures (based on the average year 2008) obtained from Eq. (2). We thus checked the influence of climate variability on UFSS. To this end, we optimized the planting structure each year for different climate situations and estimated the corresponding UFSS.

3. Results

3.1. Urban food self-sufficiency

Our results reveal a UFSS of 52.2 % and a food surplus of 30.5 %, caused by the overproduction of cabbage when allocating green roof areas evenly among the 14 planting methods in the average year 2008 (Fig. 2a, b). By optimizing planting structures, UFSS rises to 70.7 %, highlighting the benefit of optimized planting structures, which allocated fewer areas to cabbage, peas, spinach, and strawberry (Fig. 2b). While cabbage production exceeds the actual demand, peas, and spinach have very low simulated crop yields on productive green roofs (Tables S1 and S2). Therefore, peas and spinach become low-priority options when optimizing crop rotations based solely on yield and sequence planting, and excluding soil quality or other environmental aspects. The changes in self-sufficiency under different planting structures highlight the strong competition between crops for growth periods within a crop rotation (Fig. S1).

3.2. Planting structure choices

After the planting structure has been optimized for urban food self-sufficiency, only 6 cropping patterns (including leek, cauliflower, cabbage, and 3 crop rotations) were selected among the potential 14 planting methods (Table 1). Notably, the crop rotation of lettuce and broccoli occupies the largest area of productive green roofs at 101.5 ha, whereas $cabbage_a$ and $cabbage_b$, utilize the smallest area at 24.6 ha.

As for each specific crop type, only cabbage and lettuce (both occupy 169.7 ha) can satisfy local demand with food production surplus ratios of 355 % and 100 %, respectively. The ratios of other crops lie between 9 % and 94 % before opimization (Table 2, Fig. 2b). This means there is a significant over-production of cabbage and different planting structures could significantly improve UFSS. We also found that spinach growth in Amsterdam (from September to October) is fully covered by local precipitation without the need for additional irrigation (Table 2) and thus acts as a rain-fed crop.

After optimizing for productive green roof areas and crop rotations, we found six types of crops, namely onion, lettuce, leek, cauliflower, cabbage, and broccoli, match well with the dietary requirements of Amsterdam's residents (Table 3, Fig. 2b). Lettuce occupies the largest potential green roof areas of 173.2 ha, whereas pea and strawberries are excluded from green roof production. Specific crops also have varying potential according to their rotation. For instance, $lettuce_a$ has a lower crop yield than $lettuce_b$, however, $lettuce_a$ (173.2 ha) can compete with $lettuce_b$ (0 ha) because the crop rotations including $lettuce_a$ (e.g. $lettuce_a$ - bean - $spinach_b$ for 35.8 t ha^{-1} and $lettuce_a$ -broccoli for 36.4 t ha^{-1}) have more crop productivity than the crop rotations including $lettuce_b$ (e.g. $spinach_a$ - $lettuce_b$ for 26.2 t ha^{-1}) (Table S1).

Table 1
Original planting structure and optimal planting structure.

Planting ways	Area (original planting structure)	Area (optimal planting structure)
onion-$spinach_b$	28.28	69.29
leek	28.28	29.93
$lettuce_a$-bean- $spinach_b$	28.28	71.69
cauliflower	28.28	98.23
$lettuce_a$ -broccoli	28.28	101.49
strawberry- $spinach_b$	28.28	0
pea-$cabbage_b$	28.28	0
pea- $spinach_b$	28.28	0
$cabbage_a$- $spinach_b$	28.28	0
$cabbage_a$ - $cabbage_b$	28.28	24.59
$lettuce_a$ - $lettuce_b$ - $spinach_b$	28.28	0
$lettuce_a$ - $cabbage_b$	28.28	0
$spinach_a$-$lettuce_b$	28.28	0
$spinach_a$ - $cabbage_b$	28.28	0

Note: a and b represent different growth periods. Potential productive green roof areas (396 ha) were assumed to be evenly allocated to 14 planting methods for non-op situations.

3.3. Sensitivity analysis

UFSS ranged from 41 % to 54 % without optimized planting structures in varying climates (2003–2021), and 50–71 % with the optimal planting structure for the year 2008 in varying climates (2003–2021) (Fig. 3, Table S6). These broad ranges reflect climate variability affecting food productivity and, in turn, UFSS. The year 2008 reported the largest UFSS value of 71 % with the optimized planting structure. This is because the planting structure is optimized for the 2008 climate, and the optimized planting structure may not be as suitable for climates that deviate from this year. When optimizing planting structures on a yearly basis (from 2003–2021), UFSS achieves a slightly higher range of 60–74 % (Fig. 3, Table S6), further highlighting the added value of optimizing planting structures according to the specific climatic

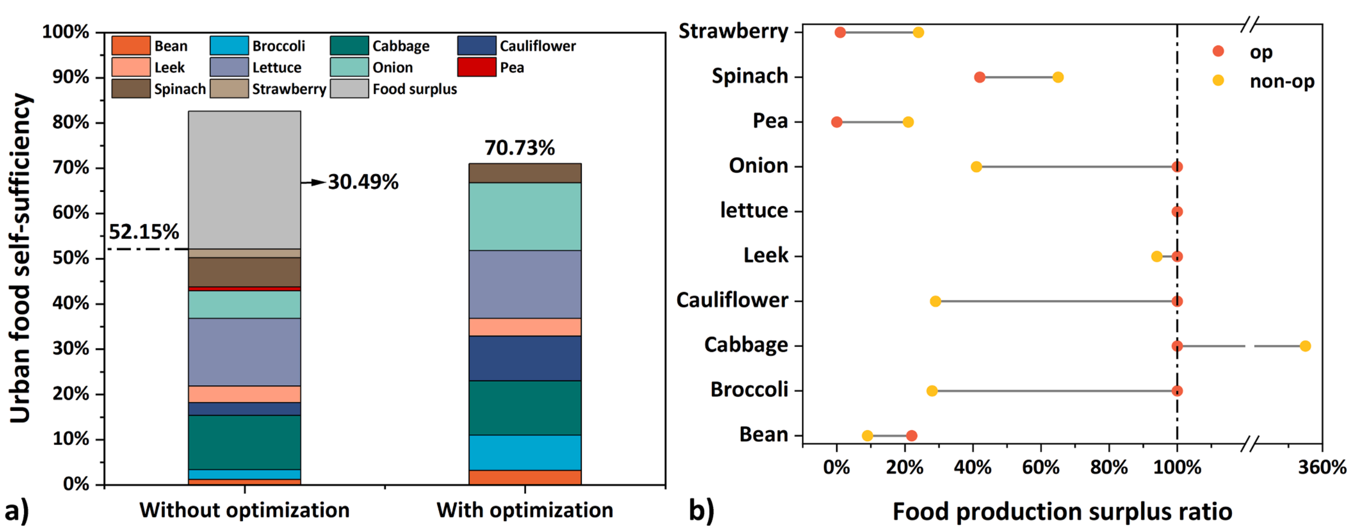

Fig. 2. (a) Urban food self-sufficiency for the specific crops on productive green roofs. (b) Food production surplus ratio for each type of produce. With optimization (op) represents planting structures that are optimized to match the diets of mixed produce. Without optimization (non-op) represent equal areal distribution of the 14 planting approaches. The dashed line represents food production matches well with food consumption without over-production.

Table 2
Original planting structure and associated food production surplus ratios of individual crops.

Crops	Area (ha)	Yield (t/ha)	Food production (t)	Food demand (t)	Food production surplus ratio	Irrigation (m^3)
Bean	28.28	9.86	278.84	3229.43	9 %	24,038
Broccoli	28.28	17.09	483.31	1734.5	28 %	35,632.8
$Cabbage_a$	56.56	49.78	2815.56	2676.82	355 %	56,560
$Cabbage_b$	113.12	59.08	6683.13			33,936
Cauliflower	28.28	22.47	635.45	2207.25	29 %	33,936
Leek	28.28	28.92	817.86	865.65	94 %	52,318
$Lettuce_a$	113.12	19.33	2186.61	3347.62	100 %	199,091.2
$Lettuce_b$	56.56	20.46	1157.22			91,627,.2
Onion	28.28	48.31	1366.21	3347.62	41 %	46,379.2
Pea	56.56	3.39	191.74	907.18	21 %	113,685.6
$Spinach_a$	56.56	5.75	325.22	2207.25	65 %	24,320.8
$Spinach_b$	169.68	6.57	1114.80			0
Strawberry	28.28	15.42	436.08	1852.69	24 %	75,224.8

Note: a and b represent different growth periods.

Table 3
Optimal planting structure and associated food production surplus ratios of individual crops.

Crops	Area (ha)	Yield (t/ha)	Food production (t)	Food demand (t)	Food production surplus ratio	Irrigation (m^3)
Bean	71.69	9.86	706.86	3229.43	22 %	60,936.5
Broccoli	101.49	17.09	1734.46	1734.5	100 %	127,877.4
$Cabbage_a$	24.59	49.78	1224.09	2676.82	100 %	24,590
$Cabbage_b$	24.59	59.08	1452.77			7377
Cauliflower	98.23	22.47	2207.22	2207.25	100 %	117,876
Leek	29.93	28.92	865.57	865.65	100 %	55,370.5
$Lettuce_a$	173.18	19.33	3347.56	3347.62	100 %	304,796.8
$Lettuce_b$	0	20.46	0			0
Onion	69.29	48.31	3347.39	3347.62	100 %	113,635.6
Pea	0	3.39	0	907.18	0 %	0
$Spinach_a$	0	5.75	0	2207.25	42 %	0
$Spinach_b$	141.65	6.57	930.64			0
Strawberry	0	15.42	10.33	1852.69	0 %	0

Note: a and b represent different growth periods.

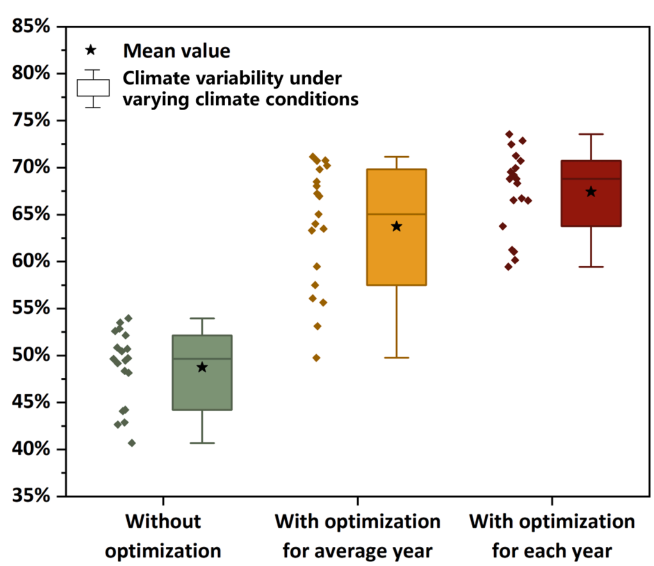

Fig. 3. Urban food self-sufficiency for the specific crops on productive green roofs considering climate variances between 2003 and 2021 under three scenarios (without optimization represents equal areal distribution of the 14 planting approaches, with optimization for average year means planting structure is optimized to match diets of mixed produce based on average year, and with optimization for each year means that the planting structure is optimized to match diets of mixed produce based on each year between 2003 and 2021).

conditions.

4. Discussion

Our study quantifies the potential urban food self-sufficiency achievable by cultivating a wide variety of crops on productive green roofs. We go beyond previous studies by demonstrating the benefits of optimizing crop rotation strategies suitable for productive green roof food production. Our model of productive green roof crop production accounts for many factors key to estimating urban food self-sufficiency on productive green roofs, including potential green roof areas, crop types, and crop productivity. For starters, potential productive green roof areas depend on criteria defining roof areas suitable for productive green roofs, such as available roof areas (Xie et al., 2024), building height (Saha & Eckelman, 2017), roof types (Zambrano-Prado et al., 2021), and roof area (Zambrano-Prado et al., 2021), building functions (Shao et al., 2021), and construction year (Silva et al., 2017) (Table S2). For example, Song et al. (2022) primarily focused on residential buildings and ignored potential productive green roof areas in other types of buildings (such as public buildings), and hence estimated a much lower urban food self-sufficiency of 3 %. Furthermore, given the weight limits imposed by the load-bearing capacities, shallow-rooted crops are more suitable to be planted on a productive green roof. De Simone et al. (2023) estimated vegetable self-sufficiency for productive green roofs of 11 %, when considering an average vegetable requirement (including all vegetable types) of around 100 kg $person^{-1}$ yr^{-1}. Our results show that when restricting food production to shallow-rooted vegetables, the potential to match local diet requirements is much higher, highlighting the importance of considering only suitable crops for productive green roofs. Lastly, crop productivity varies for different planting technologies on productive green roofs. We adopted conventional agricultural planting for our model. However, Saha and Eckelman (2017) showed that when adopting hydroponic rooftop-based gardening, crop yield could be three times higher, i.e., 195 t ha^{-1} yr^{-1} compared to 65 t ha^{-1} yr^{-1} modeled in our study. The urban food self-sufficiency of productive green roofs in Barcelona (78 %) (Toboso-Chavero et al., 2023) and Bologna (77 %) (Orsini et al., 2014) are comparable to current research in Amsterdam (71 %), primarily due to the favorable temperatures during the growing seasons that support crop growth. As European cities, Barcelona and Bologna experience lower rainfall compared to Amsterdam, but these limitations are effectively mitigated through the use of rainwater harvesting systems in Barcelona and hydroponic techniques in Bologna (Toboso-Chavero et al., 2023; Orsini et al., 2014).

Fresh vegetables and fruits have a relatively short shelf life, typically lasting only a few weeks when refrigerated (Jafarzadeh et al., 2021). The consumption of these items normally follows a seasonal pattern that aligns with the crop harvesting period (Bonuedi et al., 2022). Given the lack of daily intake data to capture seasonal variations in the consumption of fresh vegetables and fruits, we assumed average yearly consumption for the year 2010 (van Rossum et al., 2011). This implies that our UFSS calculations effectively assume that the seasonal variations in productive green roof food production will be mirrored by consumption.

There are several potential limitations in, or potential improvements for, this study: (1) We structured crop rotations directly based on the temporal succession of crop growth periods (Fig. S1). This approach excluded long-season crops, such as cauliflower and leek, from crop rotation plans. However, integrating crops like spinach after harvesting cauliflower or leek, even under suboptimal weather, could still be feasible with acceptable yield reductions, allowing for better use of available productive green roof space. (2) The yield of each type of produce on productive green roofs can vary significantly due to various environmental factors, including irrigation strategies (Van Mechelen et al., 2015), nutrient use (D'Ostuni et al., 2023), soil composition (Eksi et al., 2015), climatic conditions (Walters & Stoelzle Midden, 2018), and plagues and diseases (Md Meftaul et al., 2020). In our study, we employed an optimized deficit irrigation strategy to determine the volume of required irrigation, with the objective of maximizing water use efficiency. Yet, irrigation estimates should also consider locally available water resources and local water use policies (Hilaire et al., 2008). (3) The model we used lacks a nutrient management module. Crop rotations can be designed and modeled accounting for nutrient use efficiency. Proper nutrient management can benefit crop yields and reduce the danger of nutrient loss into the environment (Benincasa et al., 2017). (4) Due to limited data for targeted crops (only available for 2010) (van Rossum et al., 2011), we could not consider the effects of changing dietary patterns on urban food self-sufficiency in Amsterdam. (5) Our method to allocate planting structures to potential green roof areas can be further developed to incorporate additional perspectives (e.g. maximizing rainwater retention capacity) using a more effective multi-objective optimization model like NSGA (Nondominated Sorting Genetic Algorithm) (Deb et al., 2000).

5. Conclusion

Taking Amsterdam as a case study, the UFSS on productive green roofs was estimated according to the food requirements of residents through planting structure optimization of different crop rotations. This research quantifies UFSS by matching diets of mixed produce with/without optimized planting structures in varying climate situations. It further evaluates UFSS based on the planting structure optimized for each year.

There are five main findings in the current research. (1) Optimal planting structures can improve the UFSS on productive green roofs in Amsterdam from 52.2 % to 70.7 %. (2) Six cropping patterns including three single crops (leek, cabbage, and cauliflower) and three crop rotations (onion -spinach, lettuce - bean - spinach, and lettuce - broccoli) provide the optimal configuration for productive green roof planting when aiming to improve urban food self-sufficiency in Amsterdam. (3) Onion, lettuce, leek, cauliflower, cabbage, and broccoli production on productive green roofs have a good match with food demand in Amsterdam under the optimized planting structure. (4) Optimized results assign the lettuce - broccoli rotation to the largest potential green roof production area (101.5 ha), and, for single crops, lettuce to the most extensive possible productive green roof area (173.2 ha). (5) UFSS ranged from 60 to 74 % in varying climates when selecting optimized planting structures for different climate ranges, slightly higher than the one ranging from 50 to 71 % when directly applying the optimized planting structure for 2008 to different years.

Our results show that productive green roofs offer a valuable contribution to local food security by providing an alternative shorter supply chain that enhances the self-sufficiency of urban areas. Further research could explore how to allocate productive green roof areas to maximize food self-sufficiency in various cities by following key steps from this study: (1) selecting suitable crop types and designing crop rotation plans, (2) framing the crop rotation optimization problem, (3) simulating crop growth potential, (4) optimizing the planting structure, and (5) evaluating urban food self-sufficiency. Our model is equipped to incorporate different climate patterns, so it could be extended over very large metropolitan areas, or even at national levels. Additionally, future research could engage various stakeholders—residents, governments, businesses, and educational groups—in designing productive green roof systems to address broader goals, such as offering healthier food options, retaining rainfall to reduce urban flooding, generating economic benefits and job opportunities, and increasing awareness of food production to minimize food waste (Appolloni et al., 2021). This study provides a framework for optimizing the spatial and temporal allocation of crop rotations on productive green roofs combined with varying climate conditions. Further exploration could incorporate a circular economy approach to maximize the sustainability of productive green roofs by promoting efficient reuse of water and nutrients within urban ecosystems.

CRediT authorship contribution statement

Pengxuan Xie: Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **José M. Mogollón:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jan Willem Erisman:** Writing – review & editing, Supervision. **Valerio Barbarossa:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that there is no conflict of interest exists in the submission of this manuscript.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2025.106284.

Data availability

Data is available upon request.

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