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Monitoring the contribution of urban agriculture to urban sustainability: an indicator-based framework

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ABSTRACT

In an increasingly urbanized world, urban agriculture and community gardening are promoted as lever for sustainable urban development. Urban agriculture contributes to food security, provides health benefits for the population, fosters social inclusion and enhances perceived wellbeing. At the same time, from a planning perspective, urban agriculture also provides a valuable resource for urban regeneration. However, depending on prevalent farming practices urban agriculture may also have social and environmental externalities. While several of these aspects have been extensively tackled in the literature, others, in particular governance and planning aspects, are still unaddressed. Moreover, a comprehensive outline for the evaluation of urban agriculture performance from an urban sustainability perspective is still lacking. In this work we present a novel indicator-based evaluation framework for urban agriculture that captures the contribution of gardening practices to urban sustainability in a consistent, transparent and systematic way. We further illustrate the usability of our framework by testing it in Fællesgartneriet Brabrand, a community garden located in the city of Arhus, Denmark.

1. Introduction

Urban agriculture is increasingly promoted as a tool for sustainable urban development (Zasada et al., 2020) and agri-food sustainability (Caputo et al., 2020). Community gardening is a particular type of urban agriculture where farming objectives are coupled with well-being and resilience goals on multiple levels: individual, social group, and natural environment (Okvat and Zautra, 2011). Urban agriculture is perceived as having manifold social and environmental benefits for city dwellers, combatting the negative environmental, social and health externalities associated with prevalent production and consumption patterns often linked to city life (Menconi et al., 2020; UN General Assembly, 2016). Among other things, urban agriculture is perceived as contributing to reinforced food security (Edmondson et al., 2020; Ma et al., 2020), improved health outcomes (Brown and Jameton, 2000), enhanced wellbeing (Mayer and Frantz, 2004), and social inclusion (Batitucci et al., 2019), as well as making a significant contribution to the Sustainable Development Goals (Russo and Cirella, 2019). Moreover, urban agriculture is also considered as an important tool for urban regeneration and as promoting social innovation at city level (Sanyé-Mengual et al., 2019).

At the same time, urban agriculture has also been linked to a number of undesired effects and externalities. These mostly relate to environmental risks linked to aspects of gardening practices, particularly irrigation, fertilization, and weed and pest control. A number of studies have found problematic concentrations of organic toxins, including microbial contamination, and inorganic pollutants, like pesticides and heavy metals, in plants, soil and irrigation waters (Graefe, Buerkert, & Schlecht, 2019; Perrin, Basset-Mens, & Huat, 2014; Taylor & Lovell, 2014). These poor agricultural practices are generally due to a lack of knowledge of safe gardening practices. From a social perspective, some studies have pointed out problems with vandalism (Lee et al., 2019), while others have raised concern about so-called 'green gentrification' (Davidson, 2017).

These undesired effects anticipate trade-offs at various levels, including those between policy goals and sustainability spheres. As urban agriculture is highly contextual, the nature of these trade-offs is likely to vary across geographies and implementations. In high-income settings, urban agriculture is typically oriented towards personal and collective well-being and eco-conscious lifestyle and consumption; in low-income areas, food security and urban renewal are more likely to be a priority (Håkansson, 2019; McClintock et al., 2016). Despite growing research attention, systematic and, at the same time, flexible approaches to measuring the impacts of urban agriculture in different cultural

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contexts are lacking (Kingsley et al., 2019). Similarly, a structured conceptual analyses of urban sustainability benefits, including the operationalisation of the various domains impacted by urban agriculture practice, remain scarce (Zasada et al., 2020).

In response to this deficit, we present a novel multidimensional, indicator-based, sustainability assessment framework for urban agriculture that has been designed to be adaptable to any cultural setting and all types of urban agriculture, from community gardens to rooftop agriculture. The framework is rooted in scientific research and concepts, particularly the ecosystem services framework (Bolund & Hunhammar, 1999; Costanza, D'Arge, & De Groot, 1997), and builds on agreed frameworks at global level, like Sustainable Development Goals, SDGs (Sachs et al., 2020). The framework is supported by an extensive list of indicators covering the various dimensions of urban sustainability and is operationalised by a transparent and adaptable scoring system, which are provided as supplementary materials to this paper. Through comprehensive and transparent design, the framework can be relevant for and accessible to a broad range of potential users, including researchers on the built environment, city planners and developers, alongside a variety of actors operating at community levels, comprising urban farmers. A key novelty of our approach is that it covers aspects of sustainable urban design that have been neglected by most previous frameworks.

The paper begins by laying out the theoretical design of the tool, based on a review of the most relevant contemporary literature on the topic. This is followed by a detailed description of the data model and scoring system. The paper goes on to report briefly on a 'test case' in Fællesgartneriet Brabrand (*English translation: Community Garden Brabrand*), located in the peri-urban area of Aarhus, the second largest city in Denmark. It concludes by eliciting the main advantages and disadvantages of the framework, proposing areas for future research on the contribution of urban agriculture to urban sustainability.

2. Theoretical design

Since the introduction of sustainable development as a concept in the 1980s, a range of metrics and indicators have been used in an attempt to evaluate the sustainability of urban systems (see, e.g. Verma & Raghubanshi, 2018, for a relatively recent review). Researchers, planners and sustainability experts have advocated the adoption of systemic (Frank et al., 2017), nested (Mori and Christodoulou, 2012) and multi-dimensional perspectives (Klopp and Petretta, 2017). From a methodological standpoint, most of these assessments stem from two broad families of performance evaluation methods. The first includes the development of indicator-based decision-support tools such as panels, dashboards and scoring systems (Huang et al., 2015). The second builds on metrics adapted from environmental sciences like urban metabolism, emphasising comprehensiveness and precision by looking at cities as complex systems (Kennedy et al., 2011). Notably, both approaches can be used to analyse a set of possible options such as investment or design alternatives (i.e. supporting ex-ante decision-making processes) or to focus on the evaluation of already implemented solutions.

The advantage of indicator-based approaches to urban sustainability analysis is their ability to simplify otherwise complex information. Scoreboards, rankings and similar tools make information accessible, even for those lacking specialised knowledge. As such, indicator-based approaches can facilitate public participation in sustainable urban design, while at the same time providing a solid foundation for decision-making at all governance levels (Hiremath et al., 2013). Used alone or in combination with 'harder' metrics pertaining to sustainability science, indicators and frameworks for sustainable development contribute to the design of sustainable systems that integrate urban development and environment protection (Singh et al., 2009). However, since there is no long-standing consensus on which indicators are more 'suitable' or 'relevant' to assess sustainability (Diaz-Sarachaga et al., 2018; Hák et al., 2016), not even at the urban level (Klopp and Petretta, 2017), urban sustainability indicator frameworks abound, and so do their known conceptual and methodological limitations (Huang et al., 2015; Sharifi, 2021).

The contributions of urban agriculture to urban sustainability have been assessed through manifold methods and tools. These include, inter-alia, in-depth interviews, participant observation (Taylor & Lovell, 2015), surveys (Lee et al., 2019; Menconi et al., 2020; Mourão et al., 2019; Zasada et al., 2019), landscape metrics (Anderson et al., 2019; Zhao and Zhang, 2019), life cycle assessment (Fisher and Karunanithi, 2014; He et al., 2016; Pérez-Neira and Grollmus-Venegas, 2018) and footprint metrics (Guo et al., 2019; Martinez et al., 2018), and agricultural monitoring (Perrin et al., 2014). Also, substantial efforts have been invested to explore and quantify the ecosystem services provided by urban agriculture (Clinton et al., 2018; Gren and Andersson, 2018; Liu and Russo, 2021). A major limitation has been the inability of any one assessment method or tool to capture the multidimensional nature of urban agriculture. This challenge has been addressed by recent works by Caneva et al. (2020) and (Gómez-Villarino and Ruiz-Garcia, 2021), who developed frameworks to design and evaluate urban agricultural practice in space. While both frameworks are promising in terms of their multidisciplinary approach and procedural mechanisms, the monitoring and evaluation components include indicators that require significant levels of technical knowledge and may be challenging to collect in a real world setting.

The scope of our tool was defined based on a comprehensive literature review which prioritised research papers addressing: (1) conceptual developments regarding the implications of urban agriculture for sustainability; (2) methods and tools used to evaluate outcomes; (3) specific indicators included in the monitoring schemes, also considering the measured impacts or benefits of urban agriculture. The literature review was initially performed in May 2020 and updated in December 2020 using the Scopus abstract & citation database. The search string was: "TITLE-ABS-KEY (("urban agriculture" OR "community garden*" OR "green infrastructure*") AND (evaluat* OR assess* OR monitor*) AND (impact* OR benefit*) AND indicator*)". A total of 96 papers were initially found by applying this research strategy. Complementary searches focusing on seminal works and cross-citing papers were also performed. This increased the number of documents included in our review by a factor of four.

We classified the papers according to how they evaluate the implications of community gardening on urban sustainability. By analogy with the terminology used in the life cycle assessment literature (Finkbeiner, 2015), we looked in particular at: (1) the *sustainability endpoints*, that define the broad sustainability domains affected by urban agriculture, like natural environmental resilience or social wellbeing; (2) the *sustainability midpoints*, or specific mechanisms affecting urban sustainability, both negatively, like potential soil pollution, and positively, like food production, and; (3) the specific indicators used by each work to characterise these aspects, if any. For the sake of simplicity, we decided to use the term 'sustainability pillars' when referring to the endpoints, and 'sustainability dimensions' to denote the midpoints. This resulted in a framework derived from four main contributing pillars of urban agriculture to sustainable urban development. Three of these pillars are closely linked to the well-established social, economic and environmental dimensions of sustainability, and include: *Environmental resilience and resource efficiency; Food security and income generation*, and; *Inclusive society*. The fourth pillar focuses on *Sustainable urban design*, as a key aspect that mediates and enables the remaining pillars in the urban context.

2.1. Environmental resilience and resource efficiency

Urban agriculture presents a range of environmental benefits. Energy efficiency can be realised through reducing food miles and the need for product packaging (Hallett et al., 2016), as well as by integrating agriculture into buildings, also known as zero-acreage farming (e.g., rooftop gardens and greenhouses, edible green walls, and indoor farming operations). With respect to climate regulation, the captive capacity of vegetation is highest during the growth phase meaning that urban agriculture can capture much more CO_2 per surface area than in natural systems like tropical forests as plants are continuously in the primary production phase (Kulak et al., 2013). Urban agriculture can also help ameliorate the urban heat island effect by modifying the distribution and morphology of urban green space at the local level (Liu et al., 2021). The diverse nature of the vegetation can also result in higher levels of biodiversity than other green areas in the city (Clucas, Parker, & Feldpausch-Parker, 2018; Lin, Philpott, & Jha, 2015).

Urban agriculture can also contribute to improved soil and water management. Soil quality, productivity and stormwater infiltration can be enhanced through the use of natural fertilisers, such as organic waste and green manure, as well as by mixing and rotating the types of crop grown (Beniston et al., 2016; Tuğrul, 2019). The recycling of organic waste also presents a great opportunity to increase the circularity of urban systems (Weidner and Yang, 2020). Urban agriculture contributes to urban water management both directly through the use of recovered wastewater (Dalla Marta et al., 2019; Pollard et al., 2018), and indirectly by providing permeable surfaces that allow rainwater and runoff to drain through the soil. These surfaces also help ameliorate the urban heat island effect.

Growing food in cities also presents challenges from an environmental standpoint. Potentially contaminated soil and water, as well as chemical fertiliser and animal manure, can negatively impact the environment and pose health problems for urban dwellers (Hallett et al., 2016). The potential for contamination as repeated applications of an excessive amount of compost can result in soil phosphorus accumulation and negatively impact water quality (Rudisill et al., 2015). Moreover, if organic fertilisers, especially those containing animal manures, are not composted properly before application, fruits and vegetables can be contaminated with pathogens that may cause gastrointestinal illness in humans (Beuchat, 2006).

2.2. Food security and income generation

Food security refers to a situation 'when all people at all times have physical, economic and social access to a sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life' (FAO, 1996). Although the role of urban agriculture as a successful macro-level food security strategy has been questioned (Badami and Ramankutty, 2015; Crush et al., 2017; Davies et al., 2020), many studies emphasise its contribution to food security at the local level in both the Global South (Chiappe Hernández, 2019; Khumalo and Sibanda, 2019; Moucheraud et al., 2019; Tasciotti and Wagner, 2015) and the Global North (Edmondson et al., 2020; Hume et al., 2021; Orlando et al., 2019).

However, the contribution that urban agriculture can make to food security goes beyond the quantification of per-unit area yields and production potentials. Aspects such as the stability food prices are relevant determinants of food security. For instance, at the global level, Ma et al. (2020) show that the countries with the most changeable levels of food production are those showing greater levels of food insecurity. FAO's Committee on World Food Security Round Table on hunger measurement, developed a methodology to assess food security that reflects the various components of food insecurity, namely *availability, access, stability* and *utilisation* (FAO, 2020). The FAO methodology has been regularly updated since it was initially launched under the Millennium Development Goals framework (MDG indicator 1.9). The last modification was introduced in 2014 (Wanner et al., 2014).

Urban agriculture can also make a relevant contribution to household finances, particularly in low-income areas (Batitucci et al., 2019). For instance, Victor et al. (2018) showed that urban agriculture initiatives in Kinondoni Municipality (Tanzania) can generate sufficient revenue to keep a household of six members above the monetary food poverty line. On a different context, CoDyre et al. (2015) estimated that the commercial value of the products from a commercial garden in a mid-sized Canadian city would be worth \$6.56 USD/m^2 per year. Moreover, urban agriculture initiatives typically involve a range of complementary activities that can generate substantial income streams for some or all participants. Examples include floriculture (Manikas et al., 2020; Recasens and Alfranca, 2018), as well as the provision of training and other services (Gregory et al., 2016; Holland, 2004). These often attract other economic activities, creating synergies that can boost local economies, particularly in low-income or degraded areas (Hatchett et al., 2015). Even if direct impacts are highly localised, spillovers spread to the economy as a whole in the form of *indirect* income and jobs.

2.3. Inclusive society

Urban agriculture is often considered as an enabler of new forms of social engagement, providing an arena for challenging stereotypes, exchanging knowledge and dismantling social barriers (Corcoran & Kettle, 2015; Davidson, 2017). Despite this, numerous studies have found that the make-up of urban agriculture participant groups often fails to mirror the diversity of the neighbourhoods in which urban agriculture initiatives occur (Christensen et al., 2019; Kingsley & Townsend, 2006). Depth of engagement can also be important, as those responsible for the leadership of the urban agriculture initiatives have been found to be more socially active than other participants (Glover, Parry, & Shinew, 2005; Glover, Shinew, & Parry, 2005). Further, collective decision making contributes to the viability and sustainability of urban agriculture initiatives (Kingsley & Townsend, 2006; Teig et al., 2009).

The development and maintenance of social connections within and between different groups have received considerable attention in the literature (Audate et al., 2019; Christensen et al., 2019; Firth et al., 2011; Kingsley and Townsend, 2006; Shostak and Guscott, 2017; Svendsen, 2009). Though these connections generally begin through a shared enjoyment of gardening, they have also been found to deepen over time, with fellow gardeners becoming a source of social support (Kingsley & Townsend, 2006; Teig et al., 2009; Veen et al., 2016). The development of networks that extend beyond the gardens themselves appear to be less common (Kingsley and Townsend, 2006), except in circumstances where strong relationships already exist between participants (Veen et al., 2016).

Urban agriculture also contributes to societal inclusion by creating or enhancing connectedness to place. Svendsen (2009) studied over 300 community garden groups in New York City, and found wellbeing benefits associated with a range of aspects including pride in the space, contributing something positive to the neighbourhood, satisfaction with the ability to grow one's own food, and a place to relax and centre oneself. Interestingly, while the original motivation to join the garden group was generally personal, the outcome almost always included individual and collective benefits. This is consistent with the work of Romolini et al. (2012), who found that, regardless of the organisational form it took, a common expectation of environmental stewardship was that benefits would extend beyond the bounds of a particular site or project. Urban agriculture has also been found to be highly valued by immigrant communities, providing a way to connect with and share aspects of their country of origin, as well as a connection to their new home (Shostak & Guscott, 2017; Svendsen, 2009; Taylor & Lovell, 2015).

2.4. Sustainable urban design

In addition to the previous three, well-established, sustainability pillars, the literature on urban agriculture and urban morphology also focuses on sustainable urban design as an additional dimension through which urban agriculture may indirectly contribute to urban sustainability. In urban morphology, the physical structure of the city is a result

Table 1
Overview of the performance matrix.

Sustainability Pillars	Dimensions	Relevance	Links to SDGs	Ecosystem services
Environmental resilience and resource efficiency	Climate regulation and energy balance	(Caputo et al., 2020; Cortinovis and Geneletti, 2019; Habeeb, 2017; Hallett et al., 2016; Kulak et al., 2013; Nowak et al., 2006; Weidner and Yang, 2020)	11, 13, 15	Regulating: climate and water. Supporting: soil
	Soil conservation, restoration and reclamation	(Carlet et al., 2017; Hallett et al., 2016, 2016; Lin et al., 2015; Schwarz et al., 2016; Tuğrul, 2019; Van der Wiel et al., 2019; Wielemaker et al., 2019)	3, 6, 11, 12, 15	
	Water management	(Dalla Marta et al., 2019; Pollard et al., 2018)	6, 11	
	Reduction of food packaging	(Hallett et al., 2016)	11.12	
	Green technology innovation	(European Commission, 2017)	9	
Inclusive society	Community engagement and participation	(Christensen et al., 2019; Davidson, 2017; Glover, Parry, et al., 2005; Glover, Shinew, et al., 2005; ioby, 2018; Kingsley and Townsend, 2006; Teig et al., 2009)	3, 11, 12, 16	Cultural: Mental & physical health; Provisioning: Recreation
	Social capital: diversity, interactions and relationships	(Audate et al., 2019; Christensen et al., 2019; Corcoran and Kettle, 2015; Davidson, 2017; Firth et al., 2011; Kingsley and Townsend, 2006; Teig et al., 2009; Veen et al., 2016)	5, 10	
	Wellbeing: connection to culture and environmental stewardship	(Hawkins et al., 2011, 2011; Romolini et al., 2012, 2012; Shostak and Guscott, 2017; Svendsen, 2009, 2009; Taylor and Lovell, 2015; Van Den Berg et al., 2010, 2010)	3, 11, 13	
Food security and income generation	Food provision	(Chiappe Hernández, 2019; Dixon et al., 2007; Edmondson et al., 2020; Furness and Gallaher, 2018; Hume et al., 2021; Khumalo and Sibanda, 2019; Lynch et al., 2013; Moucheraud et al., 2019; Orlando et al., 2019; Poulsen et al., 2015; Sanyé-Mengual et al., 2018; Tasciotti and Wagner, 2015)	2, 12	Provisioning: food, and other tradeable resources (e.g. flowers)
	Food safety	(Aboagye et al., 2018; Audate et al., 2019; Gallaher et al., 2013; Graefe et al., 2019; Igalavithana et al., 2017; Perrin et al., 2014; Prudic et al., 2019; Taylor and Lovell, 2015)	3, 14, 15	
	Financial resilience and jobs	(Bohm, 2017; Haberman et al., 2014; Hashimoto et al., 2019; Holland, 2004; Manikas et al., 2020; Moustier, 2014; Victor et al., 2018; Zezza and Tasciotti, 2010)	1, 10	
Sustainable urban design	The garden as an element of the urban structure	(Andrade et al., 2018; Bokalders and Block, 2014, 2014; Davies et al., 2008; Eizenberg et al., 2019; Krafta, 1994, 1996; Mougeot, 2000; Piorr, 2018; Thomaier et al., 2014)	11	Regulating: air quality, noise Cultural: Spiritual and aesthetic values
	The garden in relation to other elements of the urban structure	(Arama et al., 2019; Borges et al., 2019; (Bowman, 2009); Deelstra et al., 2001; DeKay, 1997; Eggermont et al., 2015; Eizenberg et al., 2019; Fernandez Andres, 2017; Heather, 2012; Horst et al., 2017; Krafta, 1996; La Rosa et al., 2014; Lopez and Souza, 2018; Mougeot, 2000; Olofsson et al., 2011; Opitz et al., 2016; Peschardt, 2014; Piorr et al., 2018; Poulsen et al., 2017; Van Renterghem et al., 2012)	11	
	The garden from an institutional perspective	(Casazza and Pianigiani, 2016; Davies et al., 2020; Lohrberg et al., 2016; Martin and Wagner, 2018; Opitz et al., 2016; Taylor and Lovell, 2015; Teitel-Payne et al., 2016; Viljoen et al., 2015; Voicu and Been, 2008; Wekerle and Classens, 2015)	11	

of the articulation between different morphological elements, like e.g. open spaces, buildings, roads and public and private areas (Hillier, 1996; Krafta, 1994). The way these elements interact with each other results in different spatial configurations that can enforce barriers or create accessibilities (Weibul, 1976). Both, barriers and accessibilities, influence social behaviour and can, for example, enhance social integration or segregation (Vaughan, 2007), make urban spaces safer (Çamur et al., 2017) or encourage anti-social behaviour (Armitage, 2011; Friedrich et al., 2009).

Following this argument, the physical characteristics of the urban agriculture garden, such as the size of the plot or built area (Khan et al., 2018), the topography, the transition between the garden to the surrounding public space, like the presence of fences (Andrade et al., 2018), and how it contributes to delivering mixed neighbourhoods (Deelstra et al., 2001), are important aspects to consider. These contribute to estimate the 'potential' that the garden has to influence the dynamics of the public spaces (e.g., social interaction, mobilities in public areas, urban economies), thereby impacting key spheres of urban sustainability.

The relationship the garden/plot has with other elements of the urban structure is also important. For example, its location in relation to the city, e.g. intra-urban or peri-urban spaces (Opitz et al., 2016; Piorr et al., 2018), whether the garden is located on marketable (e.g. competing uses) or non-marketable land with little public utility has an influence on the scale and type of urban agriculture undertaken (Horst et al., 2017; La Rosa et al., 2014). Connectedness to the urban surroundings, such as distance to public transportation can reveal levels of physical accessibility (Olofsson et al., 2011) and closeness to busy roads may contribute to the reduction of urban pollution and noise (Van Renterghem et al., 2012) but at the same time increase contamination risks in agricultural products (Beuchat, 2006). Based on its morphological characteristics, the garden can also contribute in various ways and degrees to alleviate urban density, reducing urban heat islands (Arama et al., 2019; DeKay, 1997) and provide ecosystems services such as opportunities for recreation to people who could not easily access other green areas (Eggermont et al., 2015; Gren and Andersson, 2018).

From an institutional perspective, land tenure and ownership (Taylor & Lovell, 2015; Viljoen, Schlesinger, & Bohn, 2015), top-down policies and mechanisms that safeguard or incentivise the implementation of gardens in the city (Casazza and Pianigiani, 2016; Lohrberg et al., 2016) and bottom-up initiatives that promote urban agriculture practices (Teitel-Payne et al., 2016) are also relevant, as these aspects may potentially constrain the widespread of urban gardens.

2.5. Data model and scoring system

Our evaluation framework is operationalised by means of a performance matrix. The performance matrix groups all the domains, subdomains and criteria considered in the scheme, as well as related indicators. It hence provides an overview of the relevant analytical dimensions included in the framework and classifies and organises the information required to perform the assessment. Moreover, the matrix can also be used as a basis for discussion and consensus generation among experts and participants in urban agriculture initiatives. By design, the indicators included in the performance matrix enable a flexible application of the framework. Virtually all these indicators can be replaced by alternative measures or proxies. This ensures transferability of the framework to contexts with limited data availability and/or technical constraints. Table 1 provides a simplified version of the performance matrix, showing the pillars, the main dimensions or topics covered, and the links of these aspects to specific SDGs and ecosystem services. The relevance of the various components is reflected through peer-reviewed publications. A full version of the performance matrix including all the indicators identified in this review is provided as supplementary material to this paper.

A total of 87 indicators across the four pillars were identified and articulated according to this framework. This sample of indicators is expected to exemplify how the dimensions can be characterized. Still, the selection of the specific indicators to apply is case-specific. Any number of these can be utilised in combination to perform a particular assessment. Determinations about which indicators to use can be made in consultation with relevant stakeholders in line with the specific aims of the urban agriculture initiative, based on data availability and processing capacity, or in response to place specificities driven by physical or cultural characteristics.

With respect to scoring, our main objective was to develop a transparent and easy to use model. As such, we have deliberately avoided the use of synthetic scores or multidimensional indices where the variables are combined in a weighted average to give the resulting value of the composite indicator. We have instead opted for a visual approach to aggregate the information, which allows for a comprehensive and synthetic overview, yet consistent interpretation of evaluation results. This decision was taken on the grounds that typical data aggregation methods used in multi-criteria evaluations lead to a trade-off between the interpretability of the results and the numerical robustness of the metric. In general, simpler methods based on linear or geometric aggregation models, like the arithmetic mean used in the SDG scheme (Sachs et al., 2020), bring about compensability issues, whereby the decline in one criterion or component of the construct may be totally or partially offset by progress in another one (Munda, 2012). Conversely, more robust aggregation approaches, like pairwise and outranking methods, tend to be less intuitive and hence difficult to interpret by the average person (Greco et al., 2019). These limitations may be worsened by the use of weighting schemes. These not only tend to be unstable and subject to mutable value choices, but may also lead to further misconceptions and challenge the interpretation of the aggregated scores (Becker et al., 2017).

In our scoring framework, side-by-side comparisons of sustainability dimensions are facilitated using a simple linear transformation that adjusts indicator values individually, basing on reference minimum and maximum values.

$$v_i' = \frac{x_i - \min x_i}{\max x_i - \min x_i} \tag{1}$$

The transformed indicator score v_i' gets a value ranging from 0 to 1 based on a theoretical minimum ($\min x_i$) and maximum ($\max x_i$) score. In this setting, a higher score represents higher performance (increasing utility; beneficial direction in our performance matrix).

To account for decreasing utility situations (detrimental direction in our performance matrix), the normalisation formula (1) was reversed as follows:

$$v_i' = \frac{\max x_i - x_i}{\max x_i - \min x_i} \tag{2}$$

where a lower score represents higher performance (declining utility).

Following these transformations, all indicators become a-dimensional, ranging from 0 to 1, where higher scores are preferable than smaller ones. This approach is similar to that used in the most recent editions of the Sustainable Development Report that couples the production of index scores (based on a simple and hence fully compensable arithmetic mean that we avoid here) with a range of visuals including dashboards, dispersion indices, radial plots, as well as background indicators (Sachs et al., 2020).

3. Framework application: Fællesgartneriet Brabrand

The framework was tested in the Fællesgartneriet Brabrand, a relatively large garden established in 2014 in a peri-urban area in the city of Aarhus, Denmark. The garden includes two greenhouses (80 beds) and some open space (85 beds), covering a total area of 11 000 m^2. Each bed is $50m^2$ and the majority of the 100 members rent more than one lot. Fællesgartneriet Brabrand is run by a board made up of six members elected by the garden membership.

3.1. Data collection

Data about Fællesgartneriet Brabrand were collected between October and December 2020 using a combination of methods. An online semi-structured interview was held with the garden leader to elicit general information about the garden. The garden leader then disseminated an online survey to the other garden participants. The survey covered a range of themes including demographic background, participation in the garden (e.g., motivations, travel to the garden, interactions with other gardeners), information about their specific plot (e.g., type of garden, fertilisers used, watering methods), details about the food they grow, economic inputs and outputs, and opinions about the specific benefits of the garden. Responses were received from 48 of the 100 garden members. GIS analysis, including photo interpretation, was employed to calculate the area and land cover (e.g., sealed soil, pavement), estimate the population density, and conduct accessibility analysis (e.g., distance to the city centre, public green areas, busy roads, and public transport). Online semi-structured interviews were conducted with planners from Aarhus Municipality to investigate how local planning documents address (or not) urban agriculture.

4. Results

The sustainability performance assessment of Fællesgartneriet Brabrand is based on a selection of 24 headline indicators (see Table 1). All indicators where calculated using an increasing utility function, with the exception of food waste generation and fees and maintenance costs. A full version of the scoring system is provided as supplementary material to this paper.

The overall performance suggests a relatively even contribution to urban sustainability across the four pillars (see Figure 1). There is, however, substantial variation evident within each pillar.

From an environmental resilience perspective, the strongest performance is on soil conservation. Crop rotation is a widely used organic farming method in the garden and the use of pesticides and herbicides is prohibited. All the respondents reported using fertilizer of some sort, with animal manure the most common (61%). The garden also contributes to significant food-related GHG emission savings compared to conventional production and supply methods (65% lower). At the other end of the scale, Fællesgartneriet Brabrand performs poorly on water management and soil sealing. Wastewater is neither treated nor recycled, and there is a considerable proportion of the garden occupied by impermeable areas such as greenhouses and other on-site amenities.

With respect to food security and income generation, the assessment suggests minimal food waste generation and an average performance in terms of both food production stability and food self-sufficiency. Almost a third of gardeners report satisfying all of their fruit and vegetable

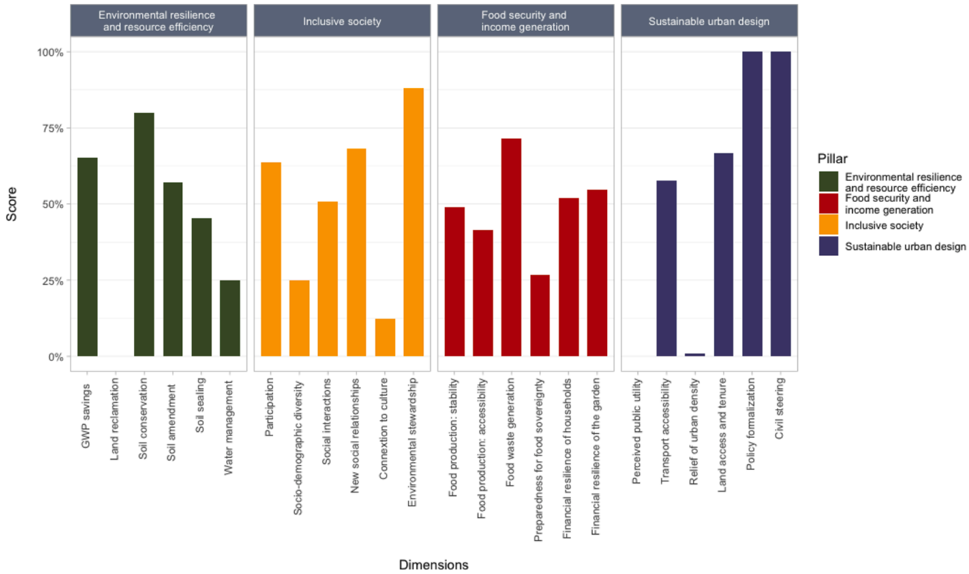

Figure 1. Performance of Fællesgartneriet Brabrand in Aarhus (Denmark), by urban agriculture sustainability pillar (data for 2020).

needs through their garden and around half described their yields as 'very' or 'quite' predictable. This is relatively high considering the broad range of motivations reported by the gardeners, many of which were of social or environmental matrix. In financial terms, participants do not report any major expenses resulting from garden participation and the financial sustainability of the garden as a whole is relatively good. Membership fees range from DKK 450 to 1 850 per year. This revenue covers the annual costs (leasing the space, supplies, maintenance), leaving a 10% surplus on garden finances. Formal training mechanisms were not frequent, resulting in a low score on the active learning indicator (27%).

Table 2

From a social inclusion perspective, environmental stewardship is the highest performing indicator, with the majority of gardeners reporting a strong sense of pride in their garden, both at the individual plot and neighbourhood level. Members also report spending a considerable amount of time in the garden, with most visiting once a week (44%) or more (50%) and visiting for 1-2 hours (44%) or more (48%). The development of new social relationships is fairly common, as are social interactions between gardeners. Demographic diversity within the garden is limited, with gardeners more likely to be older, educated and female than members of the general population of Aarhus Municipality. Cultural or religious expression are not a strong motivator for gardeners at Fællesgartneriet Brabrand.

On the sustainable urban design indicators, Fællesgartneriet Brabrand performs somewhat unequally. The bottom-up approach to its establishment, alongside engagement in the 'Taste Aarhus program' and other community and research initiatives result in a strong performance of the civil steering indicator. Similarly, acknowledgement of allotment gardens as vital to the urban structure within the municipal land-use plan resulted in a top score on policy formalisation. Low scores in relation to accessibility and relief of urban density can largely be explained by the garden's peri-urban location. Although the majority of the survey participants (58%) reporting travelling to the garden by bicycle, a significant number still use private cars (35,4%). Land access and tenure are based on a formal agreement that is renewed on an annual basis. While this does offer some security, the private ownership of the land is still perceived with concern. This is exemplified by the low score on perceived public utility, which highlights the precariousness resulting from a combination of private land ownership and location in an attractive development area.

5. Conclusions

We have presented an indicator-based framework for the evaluation of urban agriculture contribution to urban sustainability. The framework provides a structured scheme to assess the benefits and potential externalities of urban agriculture in a comprehensive and systematic way. The approach considers not only beneficial impacts but also potentially detrimental or negative consequences of urban agriculture initiatives on urban sustainability and can be applied in any cultural setting to analyse the impacts by the different types of urban agriculture initiatives, regardless of the gardening methods and technologies used. The framework is anchored in established scientific and sustainability appraisals, in particular to the SDGs and ecosystem services narratives. Our framework is operationalised by means of a performance matrix that builds on a comprehensive and well-documented set of indicators. By design, the framework has great flexibility of adaptation to specific contexts, while keeping a balanced structure. The indicators have been proposed by adopting a flexible practice-oriented perspective. This takes into consideration data requirements in terms of availability, complexity and accuracy, enabling overall comparability of the evaluations while at the same time providing enough flexibility to accommodate various perspectives, interests and skill levels among potential users, which makes the framework relevant and potentially appealing to a range of researchers and practitioners interested in the design and deployment of sustainable urban agriculture initiatives. The framework has been conceived to be applicable at garden level, but it could be easily adapted to be applied at the city level or other relevant scales.

The framework can support local governance processes for sustainable urban design. It has been primarily developed for the monitoring and evaluation purposes. However, the approach can also be used to support decision making processes at other stages of the policy cycle. Thus, the framework may have manifold applications, ranging for strategic urban planning and urban design, to self-monitoring by the communities participating in the agriculture schemes. The framework is also expected to contribute to on-going academic debates about the role of urban agriculture for increased environmental and community resilience, about the significance of the various expressions of urban innovation for 'sustainable city making', as well as about the challenges surrounding the monitoring and evaluation of sustainability goals by means of indicator-based evaluations.

The test application in the Fællesgartneriet Brabrand garden prove that the framework can be consistently applied to address simultaneous

Table 2
Results of the evaluation of the Fællesgartneriet Brabrand garden

Pillars	Dimensions	Indicators	Units	Data source	Score (percent)
Environmental resilience and resource efficiency	Climate regulation: GWP savings	Estimated global warming potential (GWP) savings, according to the products cultivated in the garden	Percentage (weighted share)	Literature & survey	65.3%
	Land reclamation	Area of previously vacant or idle land utilised for urban agriculture (e.g. abandoned lands, brownfields, etc.)	Percentage	Interviews	0.0%
	Soil conservation	Share of plots that adopt organic farming methods aimed at soil conservation - crop rotation	Weighted score	Survey	80.0%
	Soil amendment	Type of fertilisers used by garden participants in urban agriculture	Weighted score	Survey	57.2%
	Soil sealing	Share of land covered by permeable material or bare soil	Percentage	GIS & interviews	45.5%
	Water management	Main water sources in urban agriculture: Groundwater, irrigation channels or pipelines, reticulated mains water, rainwater, recycled-, grey- or stormwater	Weighted score	Interviews	25.0%
Inclusive society	Community engagement: participation	Overall time spent in the garden (during growing season) including number and duration of visits	Average hours per day	Survey	63.8%
	Social capital: diversity	Extent to which the socioeconomic composition of the garden is similar to that of the city	Weighted score	Surveys & NSI	25.0%
	Social capital: interactions	Extent to which garden participants report interactions of any kind with other gardeners	Weighted score	Survey	50.9%
	Social capital: relationships	Number of new relationships developed through participation in the garden	Weighted score	Survey	68.1%
	Wellbeing: connection to culture	Extent to which the garden supports cultural and/or religious expression	Weighted score	Survey	12.2%
	Wellbeing: environmental stewardship	Extent to which the garden promotes environmental stewardship	Weighted score	Survey	88.0%
Food security and income generation	Production of food: stability	Predictability in the annual/seasonal production of food, considering diversity of products: (1) Energetic crops: cereals, roots and tubers; (2) Vegetables, all kinds; (3) Fruits, all kinds; (4) Products of animal origin: milk, eggs, meat, fish	Percentage (accumulated share)	Survey	48.9%
	Production of food: accessibility	Share of total annual household consumption of food obtained from own production, considering diversity of products: (1) Energetic crops: cereals, roots and tubers; (2) Vegetables, all kinds; (3) Fruits, all kinds; (4) Products of animal origin: milk, eggs, meat, fish	Percentage (accumulated share)	Survey	41.4%
	Food waste generation	Share of participants in community garden initiatives that declare to throw food produced in the urban agriculture, at production, transport, storage or consumption stages	Percentage	Survey	71.4%
	Preparedness for food sovereignty	Participation in formal and informal urban agriculture education schemes targeting food production practices	Weighted score	Survey	26.9%
	Financial resilience of households	Total amount of money spent by participants on garden-related activities per year, including fees, services, supplies, and other production costs	Weighted score based on monetary units	Survey	51.9%
	Financial resilience of the urban agriculture initiative	Income balance last year: garden's capacity to generate enough income to cover ordinary costs and generate surplus to cover future investments or unexpected expenses	Percentage (surplus over total budget)	Interviews	54.5%
Sustainable urban design	The garden as an element of the urban structure: perceived public utility	Type of land (e.g., marketable or non-marketable) in which the garden is located. It is a proxy of competing uses for land in cities.	Weighted score	Interviews	0.0%
	The garden in relation to other elements of the urban structure: transport accessibility	Means of transport vs travel time to reach the garden	Weighted score	Survey	57.6%
	The garden in relation to other elements of the urban structure: relief of urban density	Population density in the area where the garden is based (1sq km grid)	Persons/km^2	GIS-Analysis	1.1%
	The garden from an institutional perspective: land access and tenure	Access to land via formal documents (e.g., lease or property contracts)	Weighted score	Interviews	66.7%
	The garden from an institutional perspective: policy formalization	Degree of recognition of urban agriculture initiative in city planning documents (strategic plans, urban city plans, etc.)	Weighted score	Interviews	100.0%
	The garden from an institutional perspective: civil steering	Type of role of civil society organisation's role in driving the urban agriculture initiative	Weighted score	Interviews	100.0%

needs at city and community level. Moreover, we showed that the framework can be reliably applied to the analysis of smaller gardens and in situations where severe data constraints may apply. The testing also aroused some of the limitations of indicator-based evaluations, emphasising the need for assuring redundancy in the data model and for acquiring contextual knowledge on the assessed urban agriculture initiative. Both aspects are an absolute requirement for proper interpretation of results. This step requires further research. Ad-hoc tools for bringing the information together in an interpretable way and to manage trade-offs between sustainability priorities are needed. This remains a key challenge for most multi-dimensional sustainability frameworks and appraisals, including the one presented in this work. Last but not least, the framework should be tested in other urban contexts, remarkably in the Global South, where different community priorities, urban-agricultural systems and data situations prevail.

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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.

Supplementary materials

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