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Applying the Food-Energy-Water Nexus approach to urban agriculture: from FEW to FEWP (Food-Energy-Water-People)

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Applying the Food-Energy-Water Nexus approach to urban agriculture: from FEW to FEWP (Food-Energy-Water-People)

Abstract: Many studies examine the correlation between the use of resources such as water, energy and land, and the production of food. These nexus studies focus predominantly on large scale systems, often considering the social dimensions only in terms of access to resources and participation in the decision-making process, rather than individual attitudes and behaviours with respect to resource use. Such a concept of the nexus is relevant to urban agriculture (UA), but it requires customisation to the particular characteristics of growing food in cities, which is practiced mainly at a small scale and produces not only food but also considerable social, economic, and environmental co-benefits. To this end, this paper proposes a new concept for a UA Nexus, together with a methodology for its assessment, that explicitly includes social dimensions in addition to food, energy and water. The paper develops a new conceptual basis, introducing People, together with Food, Energy and Water, as factors of the UA Nexus. A methodological approach for its assessment is presented, aimed at measuring not only resource efficiency and food production but also motivations and health benefits, as well as the ecological awareness of urban farmers. The methodology is based on a combination of methods such as diaries of everyday UA practices, a database of UA activities, life cycle assessment (LCA), and material flow analysis to connect investigations developed at a garden scale to the city scale.

Keywords: Food/Energy/Water Nexus; Urban Agriculture; Urban Metabolism.

Highlights:

- Existing studies on FEW nexus do not consider urban agriculture
- The social dimension of farmers and its impact on resource use is also neglected
- This dimension must be included in a FEW nexus assessment on urban agriculture
- We propose a FEWP (Food/Energy/Water/People) nexus tool for urban agriculture

1. Introduction.

Projections of demographic growth suggest that the global population will reach 9 billion by 2050 (United Nation, 2004). The Food and Agriculture Organisation (FAO) estimates a resulting increase in food demand of approximately 60% (FAO, 2011). It is difficult to imagine how food production can increase without further damaging the planet's supporting systems, which industrial agriculture has already compromised in terms of resource use, biodiversity loss and carbon sink degradation (Bruinsma, 2003), and human health generally (Horrigan et al., 2002). FAO recommends sustainable agriculture intensification to meet this challenge (http://www.fao.org/policy-support/policy-themes/sustainable-intensification-agriculture/en/). Sustainable intensification moves away from practices that damage the environment and promotes an agro-ecological approach, a more rational use of resources and targeted policies as key principles (ibid.).

Agriculture is resource intensive, using 70% of the total global freshwater withdrawn (FAO, 2011). Mueller et al. (2012) show that there are imbalances in fertiliser and water use, with dramatic overuse in China and underuse in Eastern Europe. A proper redistribution of resources would reduce waste and increase yields up to 30% (Pfister et al., 2011) if water use is intensified in regions with insufficient irrigation. Water is also key to energy generation, which in some cases must compete with food production. Yet, in policy and industry, water and energy infrastructure are rarely integrated and rationalised. Similarly, food production is rarely examined in connection with infrastructure such as hydroelectric plants. The optimisation of the nexus between food, water and energy can therefore lead to significant savings and at the same time increase production (FAO, 2014).

Urban Agriculture (UA) is a form of food production on urban and peri-urban land at different scales, using diverse production techniques, economic models and actors. Types of UA include allotments cultivated by individual gardeners, community gardens managed by local groups and social enterprises, cooperatives or commercial farms selling their produce. Benefits generated by UA can include food security, enhanced biodiversity, job provision and opportunities to intensify social interaction (Borysiak et al., 2017; Warren et al., 2015; Cohen et al., 2012;. Hampwaye, 2013; Travaline and Hunold, 2010; Holland, 2004). Potential threats include contamination of produce, mainly linked to soil pollution (Wortman and Lovell, 2013; Romic and Romic, 2003). Cities in the global north are increasingly aware that urban food production can play a pivotal role in global food systems (De Cunto et al., 2014). Just as with conventional agriculture, access to resources is vital (Cohen and Reynolds, 2015). UA can tap into and use urban wastes such as rainwater, greywater, food waste and heat from buildings as resources (Weidner and Yang, 2020) and substantially lower its environmental impact. Conversely, if urban wastes are not used, UA can generate an equivalent or even greater environmental impact than conventional agriculture (Goldstein et al., 2016). Expanding UA requires identifying strategies for low resource use. Frameworks or tools to identify the productivity of UA have been developed, although not from a nexus perspective that correlates production to resource use. Also, these tools have not been comprehensive; they typically measure inputs and outputs related to production, but rarely together with social and ecological benefits, which are fundamental outcomes of UA practices. Frameworks for the assessment and/or implementation of the nexus that have been already developed could be useful to assess UA but they focus on large scale intervention, with only a limited number looking at the urban scale (Zhang, 2013; Newell et al., 2019). A tool for measuring the nexus in UA practices is needed. To address this gap, the FEW-meter project (www.fewmeter.org), has developed a framework that combines qualitative and quantitative indicators of many dimensions of UA. To develop the FEW-meter, the following questions were investigated:

- Is the concept of the nexus, which was developed in relationship to large scale food systems, appropriate for UA practices that are significantly different from industrial food production in scale, quantities produced and purpose?
- What can be learned from existing concept/s of the nexus and how can this be tailored effectively for UA practices?
- Which indicators and analytical methodologies are appropriate to capture the correlation between resource use, production and social benefits?

To answer these questions Section 2 explains the concept of the nexus and Section 3 reviews several nexus frameworks developed to assess UA. In Section 4, we discuss the necessary elements of a nexus for UA and, stemming from it, a framework for its measurement, which includes social benefits as a key component.

2. The Food-Energy-Water Nexus.

Concerns about the sustainability of resource use have been voiced by scientists since the 1960s (Wichelns, 2017). The report 'Limits to Growth' looked at this issue from a complex systems perspective (Meadows et al., 1972). The conceptualisation of a nexus between food, energy, and water, three of the factors most fundamental to the prosperity of society, however, appeared only in the early 1980s, in programmes developed by the United Nations University (Al-Saidi and Elagib, 2017). In 2008 this concept was debated at a policy and industry level, when the World Economic Forum introduced the nexus as a way to investigate the threats that resource scarcity and climate change represent for global food security. The nexus was further discussed and promoted in the World Economic Forum 2011 and in two dedicated conferences in Bonn (2011 and 2014), in which the challenges of implementing nexus policies through effective decision-making processes were discussed (Daher and Mohtar 2015). Despite the ongoing debate, the challenge of managing resource supply systems that have been traditionally designed, operated and governed distinctly is significant (Newell and Ramaswami, 2020). Resources such as water basins are often shared among different jurisdictions, even separate countries, each one with particular policies (Kibaroglu and Gürsoy, 2015), and a lack of cross-sectoral expertise (Bazilian et al, 2011) that is necessary to identify feedbacks between systems.

The nexus is present at many levels in our lives and is embodied in diverse goods and processes, which adds further challenges to the identification of correct approaches to its optimisation. At a national level, it is easy to view the nexus simplistically as irrigation for agriculture, water producing energy and energy deployed for food production, processing and distribution. However, more subtly, the nexus has an impact on elements like the increasing demand for biofuels (energy and food), with its effects on deforestation and carbon sinks (FAO, 2008). It can also impact the distances between food production and consumption, resulting in high food miles and energy intensive produce (Edwards-Jones et al., 2008), or in the demand for and cultivation of water-intensive, rather than water efficient, crops (Allouche et al., 2014). Within the policy realm, some countries provide energy subsidies to agriculture, reducing the cost of pumping for irrigation, thus exacerbating groundwater depletion (Bhaduri et al., 2015). Policies rarely take an integrated approach to all elements of the nexus (Gain et al., 2015).

A review of studies on the nexus demonstrates that there is no unified concept available but rather several interpretations of it (Dai et a., 2018; Galaitsi et al., 2018), each one characterised by a distinct conceptualisation and methodological approach. Broadly, the nexus is a term defining a system within which elements (e.g. food, energy and water) interact through feedback loops. This requires analysing the elements together, rather than in isolation, to understand their interaction for the perpetuation (or sustainability) of the system. Each conceptualisation is shaped by the system's boundaries of the nexus, which can expand or narrow depending on the scope of the issue studied and the particular assessment used for such a study. For example, the EU-funded W4EF project (W4EF, 2015) focuses on water availability and how water is used for energy production, similar to the one developed by Rodriguez et al. (2013). In these assessments, the nexus is conceptualised as a water-energy system in which water used for energy production and energy used for water extraction, processing and distribution have an impact on their availability and optimal usage. Another conceptualisation focuses on the interaction of Climate, Land, Energy and Water (CLEW), applied to a modelling framework that maps flows of resources and particular connections between them, within the production of particular crops (IAEA, 2009). More conventionally, WEF Nexus Tool 2.0 (Al-Saidi and Elagib, 2017) considers water, energy and food.

Table 1 shows a summary of some of the existing nexus studies and tools, indicating their scope of analysis and methodological approach. The table includes a selection of papers reviewed because they are important to the development of the UA Nexus framework. For further reference, Newell et al. (2019) have completed a literature review of nexus frameworks as a whole and for the urban scale, classifying studies based on the conceptual framing and modelling approach. They concluded that quantitative (especially in the field of environmental science) rather than qualitative (social sciences) approaches predominated. Not surprisingly, issues related to institutional structure, governance, equity, resource access, and behaviour were underdeveloped.

TABLE 1 HERE

Defining system boundaries is always complex and often contentious because it excludes some elements to make the analysis manageable. Wichelns (2017), for example, contends that a food/energy/water nexus should also include elements that are fundamental to agricultural production such as land availability and management, and crop selection, which influence water and energy consumption. In their review of macro-level nexus assessment tools, Dai et al. (2018) find that, in the 35 tools examined, seven elements are used in different combinations that attempt to capture the dynamics of interaction between resource use and ecosystems: *water, energy, food, land use, climate, economy and ecosystems*. The number of elements included in each tool varies, with two being the smallest (i.e. energy and water). Five combinations are identified: water-energy (WEN); water-energy-environment (WEEN), water-energy-food (WEFN), water-energy-food-ecosystem (WEFEN), and water-energy-land-climate (WELCN).

As identified by Newell et al. (2019) in their nexus review, the role of humans and social processes in the nexus is an issue that has not been clearly addressed, though researchers have made various attempts to include behaviours and social processes in nexus analyses. For example, a tool developed on behalf of FAO, treats society as an element of the system and therefore includes social variables. MuSiasem (Giampietro et al., 2013) is an assessment tool promoted by FAO, employing a fund-flow framework for socio-ecological system assessment. It is designed to map "flows" of matter and energy, which are metered by "factors" and converted by "funds." Factors can be internal or external, for example a limited supply (external) or a production capacity (internal). Funds are elements which act in system regulation by converting factors. Funds include labour, capital and land.

Despite interest in including social dimensions in nexus models, MuSiasem and a few other assessment tools that consider the livelihood of communities (Biggs et al., 2015) are exceptions; most nexus tools encompass physical rather than social variables. This narrow bounding of the nexus is a significant limitation because human factors have an important role to play in resource consumption. For example, farmers use 92% of the water consumed in the food supply chain (Allan et al., 2015). An estimate of the number of small farms (less than 2 ha) worldwide suggests that 'at least 90% of the world's more than 570 million farms are held by an individual, small group of individuals, or household' (Lowder et al., 2016). Because the farming techniques, and therefore use of resources, in these small farms are likely to be influenced by ecological awareness, culture, local practices, as well as economic and technological variables, social factors are important to include in any assessment. Understanding the interaction between people and their day-to-day attitudes towards food production and resource exploitation is fundamental to a systemic understanding of the nexus.

There is no dedicated methodology devoted exclusively to nexus analysis. Methods have been borrowed from other research areas such as LCA or Value Chain Analysis (Dai et al., 2018). A review of methodologies developed by Zhang et al. (2019) identified eight methods commonly used to model the nexus: 1) Investigations and mathematical statistics; 2) Computable general equilibrium modelling; 3) Econometric analysis; 4) Ecological network analysis; 5) LCA; 6) System dynamics modelling; 7) Agent-based modelling; and 8) Integrated index. Tools can utilise a combination of these methods. For example, Karabulut et al. (2018) combine a matrix through which correlations between elements of the nexus are found, an LCA to complete the initial assessment with an identification of the environmental impact of each resource use and a final experts' consultation to evaluate qualitatively the results of the assessment. Dai et al. (2018) lament that the majority of tools are concerned with quantitative assessments but only a few include the identification of policy and/or governance pathways enabling the effective implementation of nexus policies. Some frameworks to embed the nexus in policy include one developed by Gain et al. (2015), which uses the phase of the policy cycle (i.e. agenda setting, policy formulation, decision-making, implementation and evaluation) to identify local priorities and effective policies. At the core of this framework is an iteration of the cycle, enabling ameliorations identified in each iteration to feed back into management and governance approaches, which in turn become adaptive to necessary changes. Halbe et al. (2015) propose tools for systems thinking such as Causal Loop Diagrams developed through stakeholder engagement. These diagrams map diverse factors and their negative or positive interactions.

This issue of scale of analysis cuts across the issues of boundaries and methods for a robust definition and assessment of the nexus is the issue of scale of analysis. In their review of nexus papers, Newell et al. (2019) concluded that although spatial scale was generally recognized, the operationalisation of multi-scalar interactions was limited. Shannak et al. (2018) identify three scales as interconnected (i.e. national, regional, watershed). Zhang et al. (2018) refine this structure of nested scales by adding cities, spanning the various levels from transboundary, to national, to regional to city level. In a study reviewing 469 papers on the nexus, Zhang et al. (2019) find that nexus studies at an urban scale, although increasing, are scarce compared to those that look at a larger scale. Only some of these urban nexus studies offer a framework of assessment (see Table 1). The urban nexus is mainly analysed using national aggregated data of resource usage, with only a few analyses based on household level data. For example, Cheng (2002) examines the water-energy nexus of households in Taiwan in terms of energy required to use water. Spiegelberg et al. (2017) survey 176 households in the Laguna Lake area, Manila, to identify synergies between fishers and farmers and reach an optimisation of resource exploitation and management. Only one study focuses on UA (Miller-Robbie et al., 2017) utilising a small area in

Hyderabad of 12 m^2 as a case study to identify advantages in terms of GHG emissions when treated wastewater is used for irrigation in UA.

Although these studies indicate that the urban nexus is increasingly attracting interest, the urban scale necessitates further investigation. Water and energy are resources best examined at a regional, national or international level (Biggs et al., 2015), but cities are particularly important because, as population centres, they determine the intensity of global resource flows. Zhang et al. (2019) characterise the urban context in terms of the nexus as one with *resource interdependency* (all sectors are linked and higher usage in one affects the others); *resource provision* (all sectors are based on materials flowing from outside of the urban context); and *system integration* (following on from the above, the identification of the system of flows in which the nexus is located and from which its functioning is affected). Scales are deeply interconnected and the use of resources at a transnational level will cascade to the other levels, but the urban context as conceptualised above requires resources to be imported from the outside, rather than being part of a local ecology. It is also unique because of the integration of networks which make energy, water and food fully available, with the availability resulting in substantial waste, which could be used for food production.

In cities, the nexus can be represented also in terms of urban metabolism, whereby flows of materials 'enter, undergo transformations, and then exit the city.' (Walker et al., 2014). Nexus tools and urban metabolism studies share some methods of analysis (Newell et al., 2019). For example, Wang et al. (2017) use input-output analysis to model the water-energy nexus, which is a methodology often used to identify patterns of urban metabolism. Each tool varies in terms of assessment methods, often combining more than one. It is therefore worth identifying an overarching structure to which tools can conform. FAO Nexus 1.0 (McNamara et. al., 2014) offers one composed of three steps: (1) context analysis (qualitative analysis); (2) quantitative assessment (quantitative analysis, application of input/output tools; assessment of interventions; comparison of interventions); and (3) response options (strategic visions; policies). This overall structure maps well against the one used for urban metabolism, formulated by Zhang (2013), which includes four steps: (1) process analysis; (2) accounting and assessment; (3) modelling structure and function; and (4) optimisation and regulation. There is a conceptual and methodological overlap between these two fields, and urban metabolism shares with the UA nexus the city as the spatial focus of investigation. In fact, the most prominent approach of the urban nexus to date has been urban metabolism modelling, largely in the field of industrial ecology. But this modelling has been rather static, looking at the flows in isolation, while social and economic aspects have been largely absent. The following section will briefly review existing assessment tools for UA, to subsequently build on the review of nexus tools and propose one that is specific for food growing in cities.

3. UA – Tools of Assessment.

UA has been seen as a potentially untapped resource in meeting the food needs of a burgeoning, city-based world population (CoDyre et al., 2015). FAO recognises the importance of urban farming in its recent framework for the Urban Food Agenda (FAO, 2019), mainly for its potential to alleviate food poverty, although it can also be seen as a nature-based solution capable of tackling complex urban challenges such as climate change, food security, biodiversity and ecosystem services, public health and resource efficiency (Artmann and Sartison, 2018; see also Roberts and Shackleton, 2018). Gardens help overcome loneliness and exclusion, and aid development of horticultural skills, feelings of happiness and sense of self-worth (Mourão et al., 2019; Van Tuijl et al., 2018; Armstrong, 2000). They provide spaces and activities to address race, class, and gender inequities, and other forms of inequality (Reynolds and Cohen, 2016). In short, in an urban context, growing food becomes the catalyst for social activities that otherwise struggle to find a space to thrive. In turn, the focus on food can facilitate an ecological knowledge (or memory – the one associated with horticultural practices) that would otherwise be lost for citizens (Barthel et al., 2013). The latter is an important factor because it can shift the attention of those who practice UA to the functioning of ecological systems based on optimal resource usage, therefore moving from ecological knowledge to ecological awareness. In this respect, an understanding of the nexus that includes growing practices (that are themselves informed by knowledge and behaviour, i.e. people as an element), social interactions involved in growing food, and other related practices that occur on urban agriculture sites is fundamental.

Although official figures are not available, UA is expanding and increasingly recognised in urban policies as green infrastructure (Cohen and Wijsman, 2014) and an important part of the larger urban food system. In the extensive literature on UA, studies evaluating its potential to produce significant amounts of food are on the rise, although pointing to mixed results. Garnett (1999) found that land available in London has the potential to supply 18% of Londoners' vegetable intake. Ackerman et al. (2014) estimated that New York City's extended metropolitan area can support between 58 and 89 percent of the city population's demand for fresh produce. A study of urban agriculture production capacity in NYC estimated that vegetable production in existing community gardens would feed an estimated 1700 people per year, but if all available urban vacant lots and other open spaces were used for food production, the amount grown would provide the vegetable consumption needs of 55 million people (Hara et al. 2018). In a study on the availability of ground level and rooftop growing areas in Boston, Saha and Ackermann (2017) estimated that 17.4% of the city's total area can be used to grow food, with the potential to meet the fruit and vegetable demand of the entire city. Other studies focus on very specific quantifications of production. For example, Nadal et al. (2017), suggested that the suitable rooftops in Rubi, Barcelona, if equipped with greenhouses, could produce 50% of the city's expected demand for tomatoes; Ward et al. (2014), quantified the potential of UA in terms of proteins; and Guitart et al. (2015), surveyed gardening practices of 50 community Gardens in Brisbane to assess their 'ecological viability' in terms of fertilisers, pest control soil management and other indicators. In a review on the topic, Weidner et al. (2019) highlighted how the degree of citywide food self-sufficiency that UA can provide depends on the type of area considered, the growing system, the reference value, the estimate of demand, and other variables. The potential for urban agriculture is particularly high in post-industrial or legacy cities such as Detroit, where large tracts of vacant and abandoned land are available. Colasanti et al. (2012) have estimated that Detroit has the potential to produce approximately 75% of its annual vegetable consumption and 40% of its fruit consumption on vacant lots through conventional methods alone.

Gathering data on the food produced in urban agriculture sites can be difficult. Typical UA projects are often small (smaller than small farms as defined above), are generally not managed professionally, but with volunteers with diverse skills involved, which makes the collection and aggregation of reliable data difficult. Whereas nexus studies are often based on secondary data available from national statistics agencies, UA studies need to rely on the help of often untrained farmers and volunteers to gather primary data. A few studies have moved away from simulation and tested data gathering based on citizen science, which, although rather simple in terms of type of data collected, have the merit of being repeatable, easy to implement and therefore likely to be used by other farmers. For example, Codyre et al. (2015) carried out a study of 50 farmers in Guelph, Ontario, to evaluate the productivity of urban gardens in connection with land, labour and capital used. Farmers were asked to compile a diary to track food production and inputs, and this was coupled with a random telephone survey to determine how many people in the city had a food garden to enable scaling up the data. The authors found that farmers produced an average of 1.43 kg of fruit and/or vegetables per m^2 gardened, with a maximum of 4.27 kg per m^2. Pourias et al. (2015) interviewed 23 farmers at the start of the growing season and 14 farmers at the end of the season in a sample of community gardens in Paris and Montreal. Similar to the previous study, farmers were asked to keep a diary over the growing season to record crops and harvests, including what the crop was used for and its final destination. McDougall et al. (2019) developed their study on the basis of the data collected over one year by 13 gardeners in the Sydney area. They found 'mean yields to be 5.94 $kg{\cdot}m^2$, around twice the yield of typical Australian commercial vegetable farms'. This study is particularly interesting for its nexus approach to UA; it attempts to ascertain the effectiveness of production in terms of energy use and labour, thus looking at correlations between food, energy and people. Water was excluded from this study 'as accurate measurement of this was judged to be too onerous for most gardeners' (McDougal et al., 2019 - Supplementary Information, p. 3). Another study measured the nexus potential of UA in Munich, verifying resource efficiency connected to the use of rainwater harvesting for irrigation and energy production through biogas (Gondhalekar and Ramsauer, 2017).

A selection of studies and tools for measuring UA productivity is shown in Table 2. Farming Concrete, Harvest-ometer and MYHarvest are all online tools. Farming Concrete has the widest scope of analysis, taking into account variables such as: the types of crops planted and harvested; how the farm manages waste and the quantity of compost produced; how many volunteers work in the garden, the time worked and number of attendees at events; perceived improvements in mental and physical health as a result of visiting or working in the garden; and economic data on sales of produce and food donated. It was designed as a citizen science project to enable community gardeners to build political support for the gardens by demonstrating their value as sources of healthy food (Gittleman et al., 2012). Harvest-ometer is concerned only with the amount of food produced per garden and the monetary value of that food. MYHarvest is a newer project with no findings to date, but it plans to use data collected on areas planted and volumes harvested of the 40 most popular UK fruit and vegetables to estimate the current levels of UK own-grown fruit and vegetable production, and the extent to which this could be increased if more urban land was made available for own-growing. In addition to these tools, others are available for measuring the health and wellbeing generated by initiatives, which may be relevant to UA. Federation of City Farms and Community Gardens (now Social Farms & Gardens) lists these tools in its 2016 publication, ‘Which tool to use? A guide for evaluating health and wellbeing outcomes for community growing programmes’ (Turner et al., 2016).

TABLE 2 HERE

Other studies are notable for their attempt to measure other benefits of UA that are rather difficult to quantify, such as the ‘ecological viability’ (in terms of gardening practices) of community gardens (Guitart et al., 2015) or, more ambitiously, the ecological, economic and social functions at a city scale (Horst et al., 2017), using an index system (Peng et al., 2015). Goldstein et al. (2016) utilise LCA and material flow analysis to measure the environmental impacts of UA (see also Sanyé-Mengual et al., 2018; Goldstein et al., 2017). Together with the tools mentioned above, these and other studies (Weidner et al., 2019) represent an attempt to generate a systemic view on UA. There are some similarities that can be drawn from the nexus studies, specifically in the attempts to elicit the multidimensional aspects of UA and trace flows of resources. There are also differences, in that people are central in UA studies and assessment frameworks, in terms of practices, ecological awareness, creation of specific knowledge and their involvement in gathering certain types of data. The following section discusses such similarities and differences, while attempting to synthesise a methodological approach to measure a UA nexus.

4. Discussion: Proposing a UA Nexus.

Frameworks to measure and implement the nexus focus predominantly on material resources, leaving out the human dimension. Covarrubias (2019) is one of the few scholars investigating the social and material flows shaping and connecting the sectors of the nexus with the actors facilitating these connections. He argues that material-focused methodologies need to be complemented with a social flows analysis that pays attention to the daily practices, policies, ideologies, networks and socio-cultural meanings that influence resource use. Likewise, in a study of Sydney, Newman (1999) included social factors enabling liveability, such as local leisure opportunities and educational attainments, under the assumption that cities are social organisms. How social factors and social flow analysis can be operationalised and integrated with the material flow analysis, however, is still unclear in the study developed by Covarrubias. Yet, a framework for assessing the UA nexus must include human behaviour because, as noted above, within an urban context composed of small parcels used to grow food, and farmers who often do not prioritise production and rarely have professional training, resource use and crop yields are largely influenced by highly variable behaviours, individual knowledge and social attitudes. While these aspects of the human dimensions of agriculture are also important for conventional agriculture, we argue that the level of variability in experience, training and backgrounds amongst urban farmers and gardeners mark a distinction from traditional forms of non-urban agriculture. Further, as the industrial food system continues to globalize, conventional farmers more often operate with a planned and organised deployment of inputs and practices, many of which are defined by contractual arrangements with buyers or technological requirements. Hence, the nexus for UA can be conceptualised by considering four elements: food, energy, water and people. In this conceptualisation, people are viewed in terms of individual behaviours and practices, social objectives driving individual UA projects, and the involvement of communities within a human-driven system of food growing.

In the conceptualisation of the nexus, the way actors facilitate connections between resources is influenced by the scale of analysis, which spans from nation to neighbourhood. Actors are taken into account in terms of human involvement in broad production systems, the impact of infrastructure on the territory and communities living therein or their interaction with natural habitats. In a UA nexus, people are identified with their actions connected to food growing and its social implications. Generally, urban farmers include in their agendas activities aimed at involving, informing and engaging with local communities (e.g. Keep Growing Detroit, 2019). This is a reflection of a practice that is carried out in an urban realm, and that attempts to use urban nature to improve local social conditions. The identification and quantification of these social activities and related benefits can lead to an understanding of how their attainment can influence production and resource consumption. For example, in a community garden, volunteers carrying out gardening activities and acquiring horticultural skills, will also learn about healthy diets and may change their diets. Once quantified, these social resources and “products” (social goods) can be assessed in parallel with resource flows via traditional nexus and metabolism methods. For example, in addition to energy and water inputs, capital costs and labour can be considered too. Likewise, in addition to produce and waste as outputs, social benefits can be included. This enables explicit integration of material and social flows and allows researchers to highlight trade-offs between resource usage, production and wider benefits to society. Therefore, a UA nexus differs from other frameworks in terms of scale, patterns of resource use and flows analysed.

UA projects vary greatly in physical dimensions, goals and objectives, and scope of activities. The goals may range from spaces for leisure, to providing social benefits, to commercial-scale food production. Patterns of utilisation of resources can change, depending on the particular agenda of each UA project. The UA nexus must therefore take into account these diverse patterns of production and consumption within a network of small projects/farms that can have an influence over the entire system of urban flows. The analysis of the UA nexus at a single farm level can also lead to an understanding of the nexus at a city level. While the aim of a nexus framework is to determine the best options to influence decision-making processes and policy, the UA nexus framework is concerned not only with the urban policies determining resource use but also with measuring the level of agronomic knowledge and ecological awareness of urban farmers to have an impact on their behaviour.

The review of existing tools to measure productivity of UA shows how these put farmers' practices and actions at the core of the evaluation, which is something missing in the nexus frameworks. Yet, these UA measurement tools fail to capture the interconnectedness of the several resources (material and social) utilised in food growing. They are useful in gathering data that are rarely available: the Harvest-ometer, for example, is a database with records of yields of some of the many growing spaces in the UK that can be used to understand the quantity of food produced within the city as well as the variety of plants grown. With methods pertaining to urban metabolism, these data could be used to estimate material and social flows at a city scale and elicit correlations between such flows. As an initial step of the FEW-meter project, a nested scale approach of analysis was identified as appropriate: from farm- to city-level. This entails working with farmers to gather data from each UA case, analysing data collected from a pool of case studies, and using this analysis to perform a material flow analysis at a city scale. The resulting assessment tool is structured around the four steps of the urban metabolism assessment as follows: (1) Process Analysis (identification of the methods and of the indicators representing the four elements of the UA nexus); (2) Accounting and assessment (data collection and analysis); (3) Modelling structure and function (material flow analysis and/or life cycle assessment); and (4) Optimisation and regulation (summarising findings and producing recommendations for urban policies) (see Figure 1).

FIGURE 1 HERE

Some of the tools to appraise productivity in UA use methods such as self-reporting (e.g., diaries). This method can serve multiple purposes of collecting data from a sample of the larger population of food gardens, measuring production, and developing a simulation at a city scale of the UA nexus. Self-reporting can also highlight inefficiencies and prompt behaviour change among participants. To this end, the selected indicators must include those specifically referring to resource use and ecological awareness. Indicators on social benefits will also enable tracking social flows. The diagram below (Figure 2) shows how indicators (characterised as inputs and outputs of a process) are distributed across the four elements of the UA nexus, including four categories of social benefits: health; education; community-building; and economic which have been identified by scanning the vast literature on UA (Artmann and Sartison, 2018; Cohen et al., 2012; Gittleman et al., 2012; Lovell, 2010; Holland, 2004). A list of the indicators for a UA nexus assessment is provided in Table 3.

FIGURE 2 HERE

TABLE 3 HERE

With the UA nexus viewed as flows of inputs and outputs, the infrastructure supporting UA projects needs to be included as part of the assessment. The nexus infiltrates many aspects of lives and practices and it is embedded in the materials used for raised beds and poly-tunnels as much as choices of plants to include in gardens and dietary habits. Life cycle assessment (LCA), a method that has been used in several assessments of the efficiency of UA compared with conventional agriculture, can complement data collected in diaries to generate a broader picture of inputs generating material and social benefits. Goldstein et al. (2016; see also Goldstein et al., 2016b) suggested that the environmental impact of UA can frequently be higher than conventional agriculture. This work found that the high-input strategies required for year-round production in northern climates meant significantly higher impact per unit production than in conventional growing environments. This is largely driven by the carbon-intensity of the grid and the relatively high energy demands of temperature-controlled farming. Others, however, have found that low-input forms of urban agriculture may hold more promise for reducing the environmental footprints of cities' food supplies, including work in Barcelona (Sanyé-Mengual et al., 2015) and Sydney (Rothwell et al. 2016) (warmer climates) as well as London (decidedly northern) (Kulak et al., 2013). If social flows are also considered as part of the outputs, negative environmental effects could be counterbalanced by social benefits. As mentioned above, the nexus UA framework must be able to take into account the diversity of individual projects that greatly differ in size, objectives and intensity of production, and project their patterns of consumption and production at a city scale. This exercise can be developed from different perspectives. For example, material and social flows of particular types of UA can be assessed, although it must be acknowledged that a general typology of urban agriculture is still an object of discussion and debate among scholars (Krikser et al., 2016; Goldstein et al., 2016b). It is possible to identify the nexus at a city scale when considering allotment gardens, in which horticulture is practiced for leisure and generates health benefits, versus urban farms producing food (Morel et al., 2018) for commercial purposes. For this level of assessment, material flow analysis can be used. The resulting methodology is mixed, assembling quantitative and qualitative methods of analysis which include statistical and qualitative analysis of the indicators, and LCA and material flow analysis. A chart illustrating how these methods are linked is shown in Figure 3.

FIGURE 3 HERE

The methodology proposed here has some limitations. For example, diaries may not be filled in accurately because they are compiled by untrained farmers or gardeners, or part-time volunteers who often do not have time to collect data methodically. In order to be reliable, the material and social flows analysis may need to be based on a sufficiently large sample of UA project for each city, which can be problematic, because of the absence of national or local data on UA and the need to develop in-depth large-scale field studies. Nevertheless, the framework proposed here can be a basis for further research.

5. Conclusions.

The aim of this paper was to investigate the structure of a framework to assess UA from a nexus perspective by investigating three key questions: is the conventional concept of the nexus appropriate for UA?; what can be learned from the nexus concept?; and which indicators and analytical methodologies can effectively identify in UA links between resources used, production and social benefits? Our research has demonstrated the importance of addressing the social dimensions and the need for a UA nexus to be a Food-Energy-Water-People (FEWP) nexus. In UA, the social dimension refers to behaviours and policies driving resource use and production as well as to a range of outcomes made possible by using food production as a catalyst for social benefit. Generating social benefits through food production may require UA sites to operate less productively or less efficiently than conventional farms that seek profitability, demonstrating the inextricable nature of social and material flows in UA. The UA nexus needs to capture ‘micro-factors’ related to the agronomical knowledge, ecological awareness and behaviour of urban farmers and the social benefits derived from urban food growing, in order to understand the potential as well as the implications of this practice at a city-scale. The methodology enabling a UA nexus analysis must therefore focus on a nested scale of investigation: 1) looking at single projects in order to best identify indicators connected with the flow of materials, social benefits indirectly generated by these flows and the level of ecological awareness of farmers; 2) subsequently analysing a sample of food growing spaces within a city; and 3) finally using data gathered to model urban social and material flows. Data collected by farmers through diaries, complemented by an LCA of the materials employed by each food growing space, together with a material flow analysis, are the methods and the analytical tools appropriate for this nexus framework. It is expected that, as case studies are developed within the FEW-meter project, the links between social benefits and resource usage will become clearer, thus providing an evidence base on the impact of UA that can support the formulation of resource-efficient and humane UA policies in the global north

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Table 1 – Review of nexus frameworks relevant to UA

Authors	Objective	Nexus	Methodology
Al-Ansari et al., 2015	Assessment for food production, seen as a series of subsystems	Water – Energy - Food	Life Cycle Assessment
Al-Saidi and Elagib, 2017	Evaluation of the nexus frameworks in terms of effective integration into policy	Water-Energy Food	Qualitative analysis – policy and governance for effective implementation of the nexus
Biggs et al., 2016	Connection between resources and the livelihood of local communities	Water – Energy - Food (Nexus Livelihood)	Quantitative analysis - matrix including indicators related to food, energy and water and the impact of their exploitation on the livelihood of local communities.
Daher and Mohtar, 2015	Determining the impact on local resources and land use under different scenarios of food production	Water – Energy - Food (Tool 2.0)	Quantitative analysis / comparative analysis - indicators mirroring the particular energy and water usage and processing necessary for cultivation under 5 different scenarios
Gain et al., 2015	The organisation of a structured process within which the nexus can be examined in policy	Water – Energy - Food	Qualitative analysis – policy and governance for effective implementation of the nexus
Garcia and You, 2018	Framework to assess the production of bioenergy	Food-Water-Energy-Waste	Mathematical model for a bioenergy production from agricultural and organic wastes
Gondhalekar and Ramsauer, 2017	Assessment of urban agricultural production	Water - Energy - Food – Climate	Quantitative analysis - Simulation of wastewater recycling and energy available, resulting in food produced in a district in a district in Munich.
Halbe et al., 2015	Identify optimal nexus strategies using systems thinking tools	Water – Energy - Food	Causal Loop Diagram - data are elaborated and their interconnectedness discussed in a stakeholder engagement workshop
Hang et al., 2016	Assessment of local production systems to plan new towns	Water – Energy - Food	Qualitative analysis – Mathematical model allowing quantification of resource use in all possible interactions between subsystems and types of resource
IAEA, 2009	Nexus determining land availability for particular production and the impact on resources, including land and emissions	Climate – Land – Energy – Water (CLEW)	Material Flow Analysis
Karabulut et al., 2018	Food and energy security against the availability of limited and vulnerable resources such as water, land and ecosystems	Ecosystem-water-food-land-energy	Quantitative and qualitative analysis – matrix of indicators in which LCA is integrated. Expert judgement to evaluate results
Lin et al., 2018	The nexus seen through advantages that anaerobic digestion can yield	Water – Energy – Food - Waste	Comparative analysis of AD and composting technologies, evaluated from a FEW nexus perspective
Martinez-Hernandez et al., 2017	Tool modelling the impact of food production and resource exploitation on the ecosystem	Water – Energy - Food – Ecosystem (NexSym)	Quantitative analysis – dynamic modelling of flows
Mayor et al., 2015	Develop guidelines for the implementation of the nexus	Water - Energy - Food	Qualitative analysis – policy and governance for effective implementation of the nexus.
Nie et al., 2019	Framework identifying trade-off in land use for food production	Water – Energy - Food - Land	Qualitative analysis – Framework for FEW nexus modelling in relationship to land allocation scenarios.
Vanham et al., 2016	Study on the impact of diets in Dutch city on water usage levels	Water - Food	Qualitative analysis – Study on typical diets in Dutch cities and their impact on water availability
W4EF, 2015	Identify levels of resource usage between two factors of the nexus	Water - Energy (W4EF)	Qualitative analysis – Framework enabling the quantification of the impact of energy production sites on local water environments.
	Nexus assessment frameworks at an urban scale		
Chen and Chen, 2016	Beijing is used as a case study in which energy consumed directly and for water infrastructure, as well as water consumed directly and for energy production are identified.	Water - Energy	Network model with quantitative analysis

Fang and Chen, 2017	Beijing as a case study in which the nexus identified by analysing the impact in different sectors of water-energy consumption at a territorial scale.	Water - Energy	Linkage analysis – quantitative analysis
Miller-Robbie et al., 2017	UA case study in Hyderabad, looking at the GHG emissions in relationship to wastewater treatment for water used for irrigation, compared to those generated by the use of water from the grid	Water-Energy-Food-Health	LCA
Ramaswami et al., 2017	New Dehli is used as a case study to analyse external and internal aggregated flows of water – energy - food	Water-Energy-Food	Quantitative analysis of aggregated data at a city level
Walker et al., 2014	London as a case study to examine flows of materials and their best employment in order to reduce their carbon footprint. Urine as a fertiliser is considered.	Water-Energy-Food	Multi-Sectoral Systems Analysis (material flow analysis and sensitivity analysis)

Table 2 – A selection of the existing tools to measure UA outputs

Category	Name/reference	Data collection	Category of indicators	Subcategories of indicators/metrics
Existing tools	Farming Concrete (https://farmingconcrete.org/toolkit/) see also (Gittleman et al., 2012)	Data recorded in a diary Citizen Science	Food production	Crop count
				Harvest count
			Environmental data	Landfill waste diversion
				Compost production
				Rainwater harvesting
			Social data	Number of volunteers
				Number of participant hours per task
				Number of person hours per project (e.g. building a fence)
				Skills and knowledge sharing
				Reach of programs
			Health data	Changes in attitude to fruit and vegetables
				Good moods in the garden
				Healthy eating
				Mood of the community about the garden
			Economic data	Market sales
				Food donations
	Harvest-ometer (https://www.capitalgrowth.org/the_harvestometer/)	Online tool	Food production	Weight for each crop
				Value for each crop
	MyHarvest (https://myharvest.org.uk/)	Online tool	Food production	Weight for each vegetable or fruit
				Growing area for each vegetable or fruit
Participative study	Harvest Notebook (Pourias et al., 2015)	Data recorded in a diary	Food production	Weight for each crop
				Frequency of harvest
				Type of preparation (food processing)
				Destination of food
				Annotation on practice

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Table 3 – List of indicators used for the FEW-meter assessment framework

	CATEGORY	INDICATOR	UNIT	COLLECTED BY
Water	Irrigation	Water (mains)	L	Farmer
		Water (groundwater)	L	Farmer
		Water (rainwater harvest)	L	Farmer
Energy	energy	Electricity	kWh	Farmer
		Renewable energy production	kWh	Farmer
		Fuel	L and type	Farmer
		Trips to garden	km/week and mode of transport	Research team
		Trips to deliver food	km/week; mode of transport and fuel	Research team
Food	crops	Harvest per crop	kg	Farmer
		Destination per crop	(e.g. farmer, friend, sold, uneaten…)	Farmer
		Cost per crop	Local currency	Farmer
	supplies	Fertiliser	kg and type	Farmer
		Herbicide	kg and type	Farmer
		Pest control / Insecticide	kg and type	Farmer
		Compost produced locally	kg	Farmer
		Animal feed	kg and type	Farmer
		Surface area of the project	m²	Research team
	Machinery	Surface area for cultivation	m²	Research team
		Inventory of tools/machinery	Number	Research team
		Inventory of timber, metal, plastic, glass used for fencing, raised beds, poly-tunnels, irrigation, greenhouses and sheds	Volume x each material	Research team
	Soil Health	Soil toxicity	Soil analysis	Research team
		Soil composition	Soil analysis	Research team
People	Social	Educational activities	Type and N of events and participants divided by age group (under 12 / 12-18 / 19-64/above 64)	Research team
		Community activities	Type and N of events and participants divided by age group (under 12 / 12-18 / 19-64/above 64)	Research team

		Socio-demographic profile of farmers and volunteers	Age, employment, salary, education etc.	Research team
		Physical and mental health	Hours spent gardening, motivations for gardening, Moods	Research team
		Diets	Increase in fruit and veg consumption; increase in number meals prepared at home etc	Research team
	Economy	Average salary (local currency/year) of FTE paid employees	Local currency	Research team
		Staff	N and FTE of farmers, people and volunteers	Research team

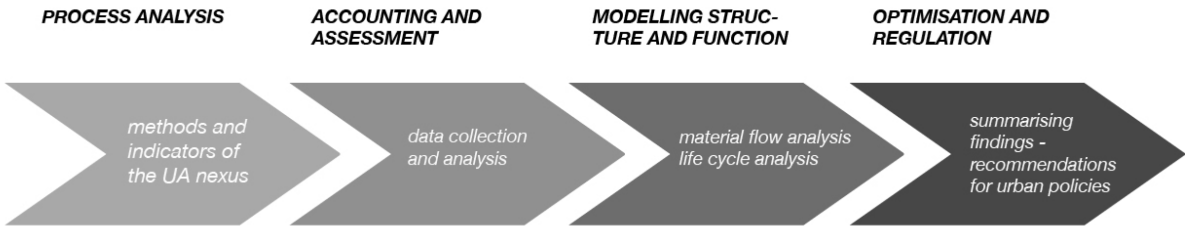

Figure 1 – Structure of the UA nexus assessment process

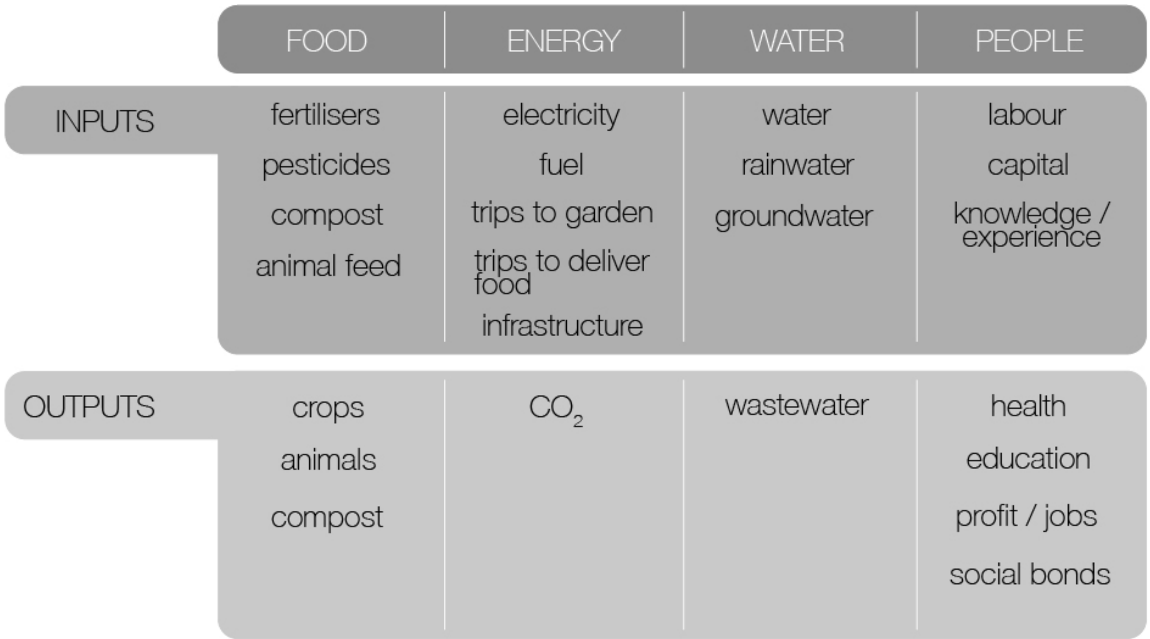

Figure 2 – Main categories of indicators for a UA nexus framework of assessment.

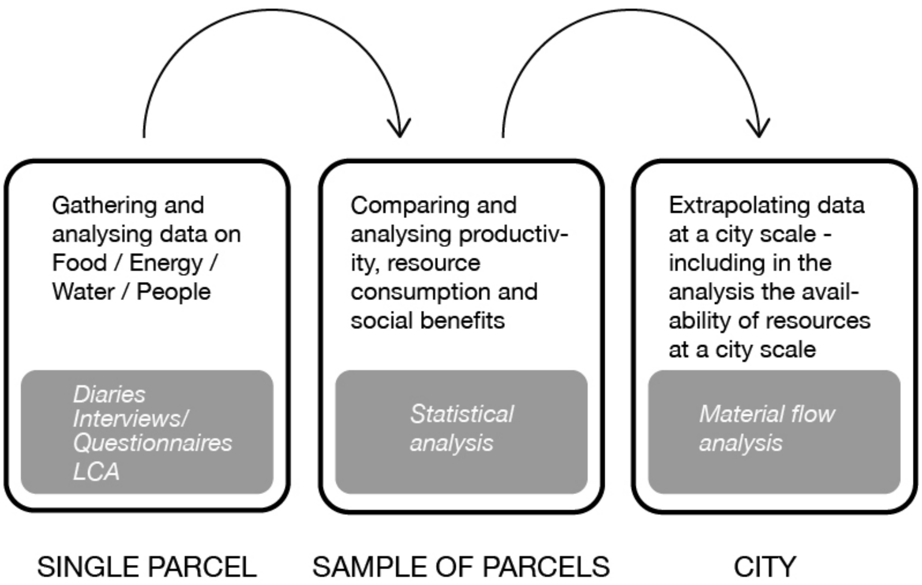

Figure 3 – Nested scales of analysis of the UA nexus. In the grey boxes, methods of investigation at each particular scale are indicated