Life cycle assessment of eight urban farms and community gardens in France and California

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Abstract

Urban agriculture (UA) is often positioned as an environmentally sustainable food supply for cities. However, life cycle assessments (LCA) measuring environmental impacts of UA show mixed results, because of inconsistent application of LCA and reliance on hypothetical case studies. To address these shortcomings, we performed an LCA of eight urban farms and community gardens in Paris, France and San Francisco, California, USA. We collected primary data from sites representing diverse growing systems (low-intensity open-field to open-air hydroponics) and motivations (education, civic engagement, and commercial production). We found that medium-tech farms, with minimum social engagement had the lowest impacts using a kilogram-based functional unit, but socially-oriented farms had the lowest impacts with an area-based functional unit. Most impacts came from infrastructure (irrigation pipes, hydroponics structures), irrigation, compost, and peat for seedlings. Our findings can help LCA practitioners perform UA LCAs more completely/consistently, and help urban farmers/gardeners target high-environmental-impact practices to optimize.

Keywords: agriculture, food, vegetables, climate change, life cycle assessment, urban agriculture, environmental impacts

Highlights:

- Calculated environmental impacts of 8 urban farms/gardens using life cycle assessment
- Collected primary data and aimed for complete, transparent assessment
- Vertical, outdoor, professional farms had largest impacts by area; not by mass of crop
- Most impacts came from infrastructure, irrigation, compost, and peat from seedlings
- Results were highly sensitive to system modeling choices, such as compost parameters

Preprint published in the Resources, Conservation & Recycling journal:

doi: 10.1016/j.resconrec.2023.106921

1 Introduction

Interest in urban agriculture (UA), the growing of food in and around cities, is on the rise among researchers, policymakers, and citizens (Mok et al., 2013; Pinheiro et al., 2020). In the Global North, UA is recognized as a mostly multifunctional activity where growing food is one of several objectives and benefits, alongside education, community development, recreation, climate change mitigation, urban biodiversity improvements, and organic waste recycling (Kirby et al., 2021; Siegner et al., 2020; Weidner et al., 2019). Still, the agricultural function remains a top priority in the context of food security, food justice, revenue generation, and access to fresh produce (Kirby et al., 2021; Pourias et al., 2016; Siegner et al., 2020). Agriculture's contributions to many environmental issues are well-documented, such as climate change, water depletion, energy use, land degradation change and degradation, eutrophication, and biodiversity loss (Campbell et al., 2017). As researchers and local leaders call for expanding UA in cities in support of sustainable urban food systems, it is imperative that the practice provides environmental benefits (Armanda et al., 2019; Mohareb et al., 2017).

Life cycle assessment (LCA) has helped clarify the environmental impacts of rural agriculture and conventional food systems. LCA is a standardized method to estimate environmental impacts of a product or service throughout its life cycle, from "cradle to grave" (ISO 14040, 2006). After decades of applying LCA to rural agriculture, generating ~2,000 studies of fruits and vegetables and tens of thousands of grains (Poore and Nemecek, 2018), the method is generally considered robust and mature for agricultural applications (Andersson et al., 1994; Notarnicola et al., 2017). LCA results converge across the entire body of literature, allowing for some generalizations regarding impactful processes, typical ranges of values, and relative performance of different farming methods (Parajuli et al., 2019; Seufert and Ramankutty, 2017).

Such consensus has not been achieved for UA. In a recent review and meta-analysis, we showed that it was difficult to draw generalizations on UA's environmental performance because of *how* the LCAs were done, and *what systems* were studied (Dorr et al., 2021a). We identified challenges in three areas:

1. System modeling decisions and reporting introduced variation into results and hampered interpretation. For example, important elements such as post-farm transport and avoided emissions were inconsistently included, and reporting of results used varied terminology and breakdowns of processes into life-cycle stages.
2. Data were often not representative of UA. Many case studies relied on secondary data from rural agriculture (a handful were even categorized as "hypothetical" production sites), and studied research-oriented or innovative systems.
3. Most studies used a small sample (about 65% of papers in the meta-analysis only worked with one farm/garden, and about 85% worked with 3 or fewer), meaning that there were few replicates for each type of UA system and set of LCA modeling decisions.

In response to these shortcomings, we proposed a general methodological guideline for performing LCAs of UA (Dorr et al., 2022a [under review]). The main tenets of the guideline are reliable primary data, appropriate compost and substrate system modeling, careful choice of compost emission factors, nuanced downstream system boundary (product delivery) definitions, and general transparency in system and results descriptions. We also propose practical questions that UA LCAs may answer, and future research directions. Following these guidelines allows for consistent and robust application of LCA to UA which will improve inter-comparability of studies and enhance our understanding of the environmental performance of UA.

We demonstrate these guidelines through an LCA of a diverse set of eight urban farms and gardens in Paris, France and San Francisco, California. In doing so we address the various gaps in the existing literature. Namely we included a large sample size of functioning urban farms/gardens covering two regions and climates and then assessed their environmental performance using robust primary data and a consistent, transparent modeling approach. The overall objectives of this study were twofold. The first goal was to perform a comprehensive LCA of diverse UA, based on primary data, to contribute to the knowledge around its environmental performance. In particular, we seek to explain the relative environmental performance of diverse types of UA. The second goal was to simultaneously inform and demonstrate methodological guidelines to support more systematic and consistent LCAs of UA. This was developed through an iterative process where the guidelines were informed by work with case studies (presented here), and the case studies here adhered to the guidelines.

We found that infrastructure and irrigation had large contributions to several impact categories, followed by compost production and peat from seedlings. Professional, vertical, open-air farms were efficient at growing lots of food with low impacts per unit of crop, but had high impacts on an area basis. Conversely, farms with more social objectives or communal management had lower impacts on an area basis, and displayed examples of both high and low impacts per kilogram of produce grown. Adhering to the UA LCA guidelines allowed us to perform a comprehensive and transparent LCA, with consistent results. Our findings indicate which processes urban farmers should focus on to reduce their environmental impacts, and highlight which types of UA may incur the least environmental tradeoffs for different objectives.

2 Methods

Here we describe the case study farms and gardens, data collection, and the LCA method, including goal and scope definition, life cycle inventory, and impact analyses.

2.1 Geographic context

Four farms were in Paris and its bordering cities (Aubervilliers and Rosny-Sous-Bois), and the other four farms were located in the San Francisco Bay Area (cities of San Francisco, Berkeley, and El Sobrante). These locations were chosen because of their different population densities (affecting the physical form of cities and therefore farms/gardens, and post-farm delivery modes), climate, and context of UA (i.e., its history and main orientation), which are detailed for each location in the Supplementary Material. UA is an established practice in both locations, going back hundreds of years in Paris and at least to World War II in San Francisco, with interest from local researchers, governments, and practitioners (APUR, 2017; Barles, 2007; Glowa, 2014; Lawson, 2014).

2.2 Description of the farms

The coded names and main characteristics of the farms/gardens are presented in Table 1, including their physical attributes and some primary data collected during this study. All sites are open-air farms, because we were unable to successfully collaborate with any indoor farms (see details in Section 2.1 of the Supplementary Material). Additional details on the physical setup, motivations, management, growing practices, mass of each crop harvested, and selection criteria of the cases are included in the Supplementary Material. Typically, for UA, “farm” indicates a commercial site and “garden” denotes a non-commercial site (Reynolds and Darly, 2018). For brevity, we refer to all sites as farms in the rest of this paper.

The degree of social engagement – interaction with local communities – was defined by the researchers through site visits. Low-engagement farms were not usually open to the public or did not hold events that brought in the public, few people (mostly employees) did the farming, and food sales were important. Medium-engagement farms welcomed specific outside groups—usually students—and farming was done mostly by employees and with the help of volunteers. High-engagement farms encouraged participation from the public, were farmed roughly equally by both employees and volunteers, and stressed food donations more than sales. As shown in Table 1, high engagement farms tended to be in the US and low engagement farms tended to be in France, which was not surprising given the current orientation of UA in both locations (see detailed descriptions in Section 1 of the Supplementary Material).

		FR1	FR2	FR3	FR4	US1	US2	US3	US4
Description	Data collection period	Sept. 2019-Aug. 2020	Jan. 2020-Dec. 2020	Jan. 2019- Dec. 2019	May 2019-Apr. 2020	Jul 2020- Jun 2021	Jan. 2020- Dec. 2020	Jul. 2020-Jun. 2021	Jul. 2020- Jun. 2021
	Position	Rooftop, substrate, vertical	Rooftop, hydroponic, aeroponic	Rooftop, substrate	Rooftop, substrate	Ground, soil	Ground, soil	Ground, built up soil	Ground, built up soil
	Main goal(s)	Commercial, food production	Commercial, food production	Job training, food production	Education	Community building, education	Research, food production	Commercial, education	Education
	Degree of social engagement	Low	Low	Low	High	High	Medium	Medium	High
Area	Total farm area (m^2)	2600	1490	700	1791	6336	854	3541	2390
	Green area (m^2)	253*	298	397	248	880	610	635	554
Food	Annual harvest (kg)	6924	7999	1771	475	2117	741	922	312
	Yield (kg/m^2)	27.4	26.8	4.46	1.92	2.41	1.21	1.45	0.56
	Number of crops	23	18	36	39	47	14	129	19
Water	Water use by crop (m^3/kg)	0.24	0.24**	1.17	0.45	0.96	0.51	1.17	2.63
Compost	Compost (kg/m^2)	0.00	0.00	3.02	17.3	9.24	11.1	10.6	12.1

Table 1 Food production, water use, and compost use data are annual measures for 2019-2021 (with different 12-month periods among the farms). *FR1 grows in vertical structures. This area refers to the ground area covered by those structures, not the surface area of the facades. **FR2 had no data available regarding water use. We assigned the same water use per m^2 as FR1, since they also used precise, low-consumption drip irrigation in vertical structures.

2.3 Data collection

Data collection methods varied at each farm, but can generally be characterized as either 1) using data that farms already collected (minority of the data), and 2) working with farmers to define data collection methods to track their practices (majority of the data). Details of these data collection methods, plus secondary data sources, are available in the Supplementary Material. For all farms, data collected represent one year of operation, but different 12-month periods between 2019 and 2021 were used. Before accepting to use data from 2020 that may have been unrepresentative due to the COVID-19 pandemic, we were assured by farmers that operations were not affected.

2.4 Life cycle assessment

2.4.1 Goals

The goals of this LCA were to 1) quantify the environmental impacts of diverse types of UA in different locations with different motivations; 2) to find what explains the relative environmental performance of diverse types of UA, by looking at trends, hotspots, system modeling decisions, and sensitive inventory data.

2.4.2 Scope

The system boundary for this LCA includes everything needed to grow fruits and vegetables on the farm, and the distribution step directly after the farm. In most cases this was to the consumer, but some farms sold some of their produce through small neighborhood grocery stores. The included processes are shown in the process diagram in Figure 1. We included two functional units in our analysis, which is important to account for the multiple functions of agriculture:

- 1 kg of produce, and
- 1 m^2 of area under food production for one year.

We provide impacts in the Supplementary Material for additional functional units:

- 1 m^2 of total farm area for one year and
- 1 m^2 of green area for one year (i.e., area for food production plus ornamental or native plants).

We used the LCA database Ecoinvent version 3.5 for background life cycle inventory data, and SimaPro version 9.0 software for LCA computation.

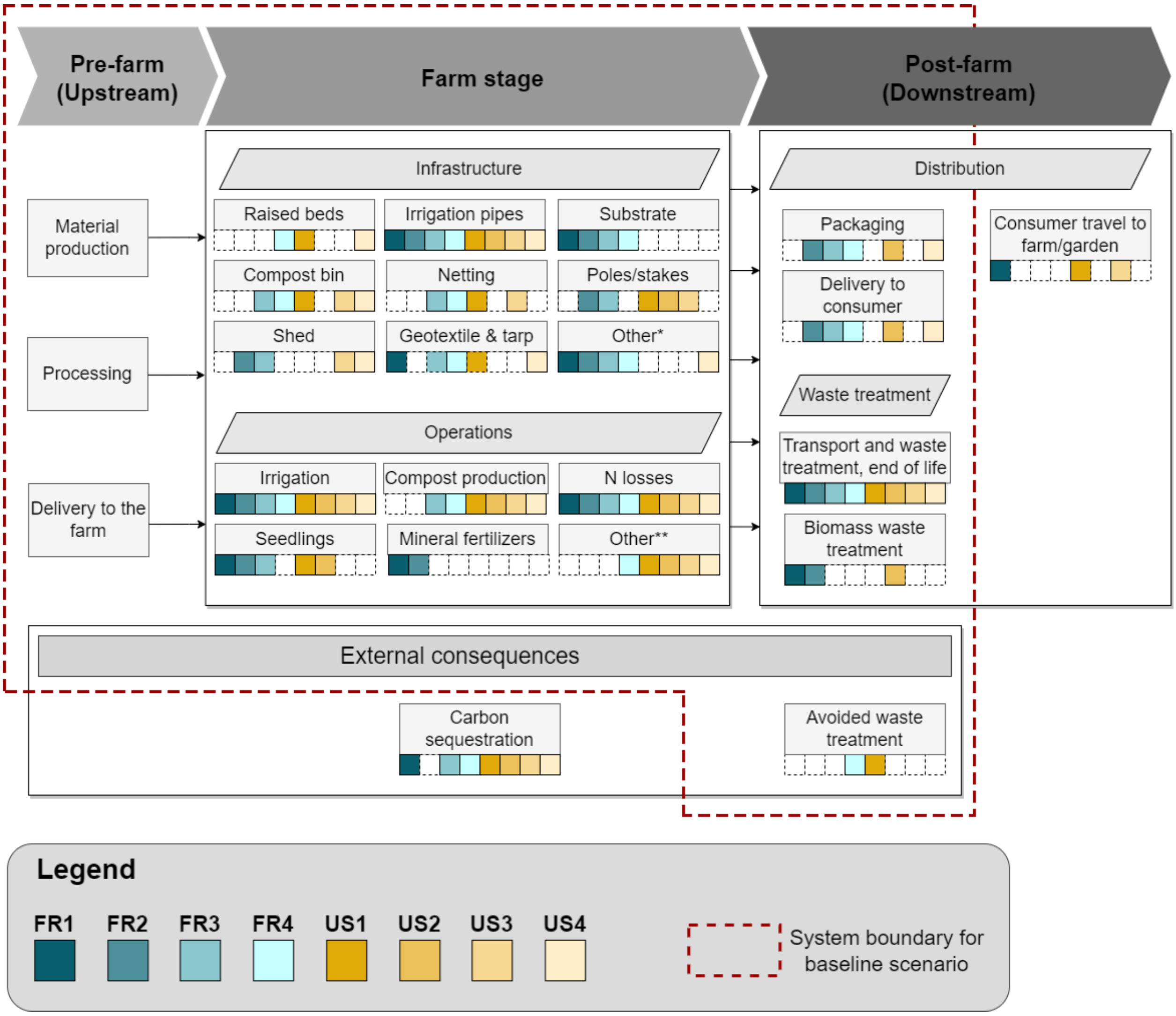


Figure 1 The process diagram shows what was included in the system boundaries of the LCA for each farm. Colored squares placed below a process indicate that the process was included for that farm, and a white square indicates that it was not relevant for that farm. Processes outside the red dashed line—carbon sequestration and customer travel to the farm—were accounted using sensitivity analyses. *Other infrastructure and **Other operations inputs are detailed in the main text in section 2.4.3.

2.4.3 Life cycle inventory

The processes and inputs at all farms varied, but we categorized them into consistent categories to help interpret the results. The categories included substrate, infrastructure, delivery of inputs, compost, other supplies, nitrogen losses, irrigation, seedlings, delivery of product, packaging, avoided municipal biowaste treatment, and waste treatment of inedible biomass. Lifetimes for infrastructure were determined based on the expected lifetime of either the material or the object, depending on which is shorter. For example, the lifetime of drip tape is limited by the durability of the object rather than the integrity of the plastic. Impacts of infrastructure were amortized to the single year of use covered in the LCA. A detailed description of the categories and what they included, and of how they were measured or calculated, are in section 10 of the Supplementary Material.

Figure 1 shows which processes were considered for which farm. Other infrastructure for FR1 was steel frames for vertical growing structures. FR2: hydroponics plastic structure, aeroponics plastic towers, large vat for fertigation mixing, steel tables, and weight distributing tiles. FR3: cables and sand bags. FR4: greenhouse. US4: greenhouse, wood tables. Other supplies for FR4 were beer brewing residues, mushroom compost, and straw. US1: mushroom compost. US2: fuel for a tractor, crushed oyster shells, and feather meal. US3: wood chips, crushed oyster shells, feather meal, alfalfa meal, and kelp meal. US4: manure, pesticide (Sluggo©), fish emulsion, kelp meal, feather meal.

2.4.4 Life cycle impact assessment

We used the Product Environmental Footprint (PEF) impact assessment method, version 2.0 (European Commission, 2017). We included six impact categories that are particularly relevant for agricultural production: climate change (kg CO_2 equivalent), water scarcity (m^3 of water deprived), land degradation (Pt, a dimensionless soil quality index, combining measures of erosion resistance, mechanical filtration, physicochemical filtration, groundwater regeneration, and biotic production (Bos et al., 2016)), energy demand (MJ), marine eutrophication (kg N eq.), and terrestrial eutrophication (mol N eq.) Results for other impact categories and other impact assessment methods (ReCiPe 2016, TRACI 2.1, CML-IA baseline V3.05, and ILCD 2011 V1.10) are available in the Supplementary Material to support comparisons with future studies.

2.4.5 Sensitivity and uncertainty analyses

We performed sensitivity analyses to test the impact on the results of modeling decisions that we identified as important in our recent literature review of UA LCAs (Dorr et al., 2021a) as well as other important decisions identified here. These scenarios were:

- transport of consumers to farm;
- carbon sequestration from compost;
- avoided waste treatment from compost (for farms that didn't collect waste);
- increasing the lifetime of infrastructure and substrate, giving fewer of their impacts to the one year of the study;
- all composting impacts given to compost (no economic allocation), and
- variations in the parameters and emission factors for compost.

2.5 Creation and demonstration of methodological guidelines

Because the of the varied methods and decisions in available UA LCAs, we developed methodological guidelines to support more consistent and complete UA LCAs (Dorr et al., 2022a [under preparation]). Many similar methodological reflections and adaptations have been done to improve LCAs of rural agriculture (Audsley et al., 1997; Caffrey and Veal, 2013; Notarnicola et al., 2017), but none have been dedicated to UA.

We created these guidelines iteratively and in parallel to the present work, where this LCA both informed and demonstrates the guidelines. We present the challenges, review the many ways they have been overcome, and recommend how to deal with them in the future. Our literature review of UA LCAs (Dorr et al., 2021a) and firsthand experience with these farms allowed us to identify these challenges. The challenges and recommendations include:

- High crop diversity: functional units can be chosen that incorporate production of all crops, allocate between crops, or are unrelated to crop production (i.e. based on land degradation, revenue, social outcomes…). When the functional unit is a mix of crops, a breakdown of which crops are grown should be provided.
- Data (un)availability: primary data should be collected with the help of farmers and gardeners. We provide recommendations for how many types of data can be measured and tracked.
- Compost system modeling: compost made on the farm with leftover biomass should be modeled differently from compost made off the farm and purchased. All emissions from on-farm composting should go to the farm. For off-farm composting, compost

becomes a recycled product, and impacts should be allocated between the waste generator and the user of the recycled product.

- Compost emission factors: greenhouse gas emissions from compost are highly variable, so it is difficult to find generic values and apply them to case studies. Commonly used singular sources of compost emissions in UA LCAs have high variability. We recommend using average values, using specifically representative values, a range or distribution of emission factors.
- Carbon sequestration: use of organic or bio-based inputs is common in UA, and can have the benefit of sequestering carbon in soil/substrates. This is especially relevant for compost since it is high in organic carbon. Since little is known about the long-term fate of soil carbon sequestration from compost, carbon credits (in the form of avoided climate change impacts) should be excluded from main LCA results.
- Substrate: a unique input in UA is substrate to cultivate crops in, since growing in soil is often not an option. We frame substrate as a type of infrastructure, and recommend possible lifetimes and waste treatment options. We also summarize system modeling decisions for the often recycled or organic by-products that are most often used to create substrate.
- Transport and delivery: since a main characteristic and proposed benefit of UA is reduced food miles, UA LCAs should include post-farm delivery steps. Delivery is often directly to the consumer, so care must be taken to ensure that comparisons to conventional rural agriculture also include transport all the way to the consumer.
- Variability and uncertainty: changing practices and incomplete data collection mean that variability and uncertainty may be especially high in UA. Parameters with high uncertainty/variability can include infrastructure and substrate lifetime, compost emission factors, and delivery logistics. These can be accounted for using sensitivity analyses, calculating impacts across ranges or distributions of values, or collecting data over multiple years.

3 Results

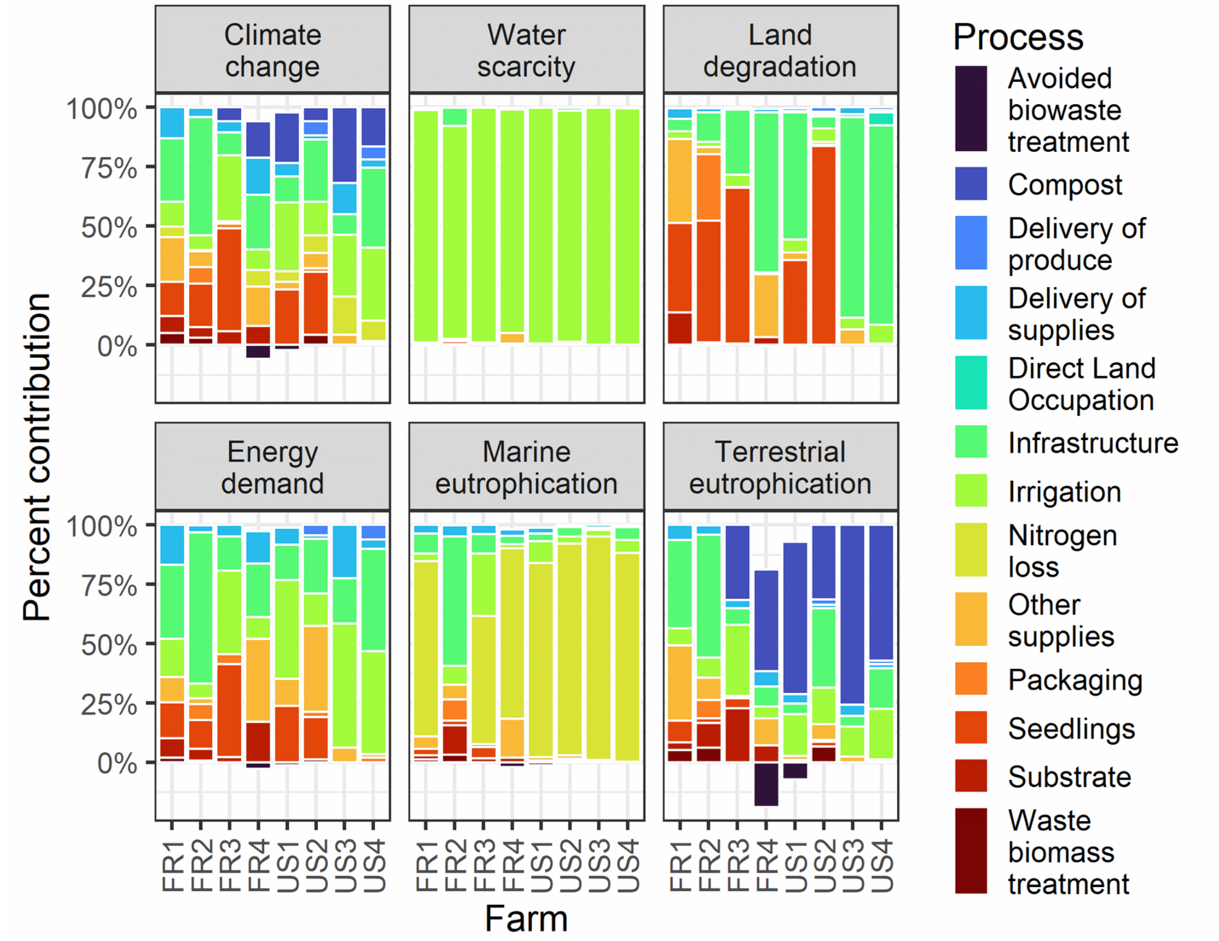


Figure 2 The relative contribution of each process category to each impact category is presented. More details on what is included in each category are provided in the Supplementary Material.

The next section presents a process contribution analysis, detailing which inputs and processes accounted for large impacts. The following section describes general trends in impacts among the farms. Raw results, including values for all assessed impact categories, are presented in the Supplementary Material.

3.1 Process contribution analysis

Figure 2 shows the percent contribution of each process category for all farms.

3.1.1 Infrastructure

Infrastructure had the largest average contribution to land degradation with an average of 43% (mostly related to wood use), and for climate change it contributed an average of 24%. It was especially impactful for FR2, where it accounted for 50% of climate change impacts and 64% of energy resource use. Impacts in these categories for FR2 were driven by the significant amounts of plastic for the hydroponic structures and the aeroponic towers. US4 also had large infrastructure impacts, mostly due to the shipping container they used as a shed. Of note is the importance of this single piece of infrastructure, even though it was severely discounted for the farm, with a long lifespan of 50 years and half of the impacts since it was reused. At US4, infrastructure contributed to 34% of climate change, 84% of land degradation, and 43% of energy use.

3.1.2 Irrigation

Water scarcity impacts were dominated by irrigation, with a contribution ranging from 90 to 99%. Irrigation was the largest contributor to energy use for US1, US3 and US4. It contributed on average 19% of climate change impacts, but this was as high as 26-31% for US1, US3, US4, and FR3. It contributed 27% to energy resource use on average, and this was 52, 44, and 43% for US1, US3 and US4, respectively. Irrigation included both tap water (delivered from a city water treatment plant) and on-farm electricity for pumping, but the majority of impacts for most impact categories came from tap water. This points to the potential benefits of substituting energy intensive municipal water sources for alternatives, such as harvested rainwater.

3.1.3 Compost

Compost production was the largest source of terrestrial eutrophication impacts and the fourth largest source of climate change impacts on average. Among the six farms that used compost amendments, it contributed an average of 57% to terrestrial eutrophication and 17% to climate change impacts. For farms using little compost these contributions could be as low as 6%, and for those with large volumes applied this could be as high as 32%. Many parameters with uncertainty were involved in modeling compost, and the importance of these was evaluated with sensitivity and uncertainty analyses (Sections 3.4 and 3.5).

3.1.4 Nitrogen losses

Nitrogen losses from nitrate leaching drove marine eutrophication, and contributed between 54 and 94% of impacts (on average 80%). This was excluding FR2, which we assumed had no nitrate leaching due to recirculation of the fertigation water. There was large uncertainty here regarding the actual fate of leached nitrate in urban wastewater systems and the emission factor of leached nitrate. We used a standard emission factor based on the amount of nitrogen applied, which is a rough approximation for rural agriculture, and is surely more uncertain for UA substrate conditions (IPCC, 2019).

Nitrous oxide, N_2O, is a potent greenhouse gas with approximately 300 times the radiative forcing over carbon dioxide over a century. N_2O emissions were responsible for 0.5% to 16% of climate change impacts, with an average of 6.4%. The largest contributions were from US3, where emissions from compost and chicken feathers contributed almost equally. Chicken feathers have high nitrogen content (about 16% of dry matter), compared to 0.9% for compost assumed here. Indirect N_2O emissions from leaching of nitrogen and subsequent volatilization were responsible for about 30% of these emissions, and direct emissions were responsible for 70%.

3.1.5 Seedlings

For the five farms that purchased seedlings, seedling production was important for land degradation (average 55% contribution), climate change impacts (25%), and energy use (22%). Peat moss is typically the main substrate for the seedlings according to Ecoinvent and our own observations at the farms, and its production was responsible for most of the impacts from seedlings in all of these categories. For the three farms that started seedlings onsite, we were not able to disaggregate the compost and water used for seedlings, but they were accounted for in the farm-level totals.

3.1.6 Delivery of supplies and materials

Delivering supplies and materials to the farms contributed an average of 9% of energy demand and 8% of climate change impacts. This process was most impactful at FR1, FR4, and US3. For FR1, seedlings represented 75% of the delivery amounts (measured as weighted-distance, or kilograms transported multiplied by distance). They purchased seedlings from two suppliers 215 and 360 km away, 17 times per year. For US3, most of the delivery amounts came from compost delivery (78%), and for FR4 this was delivery of compost amendments (62%) and substrate for the initial application (28%). These contributions were especially large because compost was delivered from rather far away for these two farms: 56-58 km, compared to other farms with an average of 17 km.

On average, transporting supplies and materials was much more impactful than distributing food products, which suggests that there may be a tradeoff in the hyper-local positioning of UA: proximity to the consumer led to low distribution impacts, but this was at the expense of difficulty and distance for delivering agricultural inputs to farms located inside cities.

3.1.7 Other supplies

The ‘Other supplies’ category was particularly impactful for FR4 and FR1. For FR4, this was partly from the spent mushroom substrate purchased from an urban mushroom farm, evaluated in an LCA by Dorr et al. (2021b), who used economic allocation to distribute impacts between mushrooms and their leftover substrate. This substrate accounted for 35% of FR4’s total energy use and 14% of climate change impacts. Straw for mulching was the other main input and accounted for 20% of land degradation at FR4. At FR1, impacts from other supplies came from organic fertilizers used in the precise fertigation system. Producing these fertilizers accounted for 19% of total climate change impacts, and 37% of land degradation impacts. FR2 also used liquid mineral fertilizers, but smaller amounts: 0.002 kg N/kg crop, compared to an average of 0.050 kg N/kg crop for all farms (details in Supplementary Material section 8.1). Consequently, fertilizers did not contribute large impacts to FR2.

3.1.8 Substrate

Substrate contributed an average of 12% of terrestrial eutrophication impacts, 8% of energy use impacts, and 7% of climate change impacts. It contributed the most to impacts at FR4, with 9% of climate change and 12% of terrestrial eutrophication impacts. These impact categories were strongly affected by compost, which composed the bulk of the substrate. Substrate impacts from FR1 and FR2 were relatively small, with 5-7% contribution to climate change and 3-10% to terrestrial eutrophication. This was because their substrate was mostly composed of coconut fiber which had no allocated production impacts since it is a waste material.

3.1.9 Remaining processes

It is also important to note the process categories that were not very impactful here because the farms may have optimized these processes and demonstrate low-impact options, or the processes may be consistently low impact in UA LCAs and require less attention. These included avoided waste treatment from composting, delivery of the final product, direct land occupation by the farm, packaging, and waste treatment of nonedible biomass. Results from these processes are detailed in the Supplementary Material, section 4.

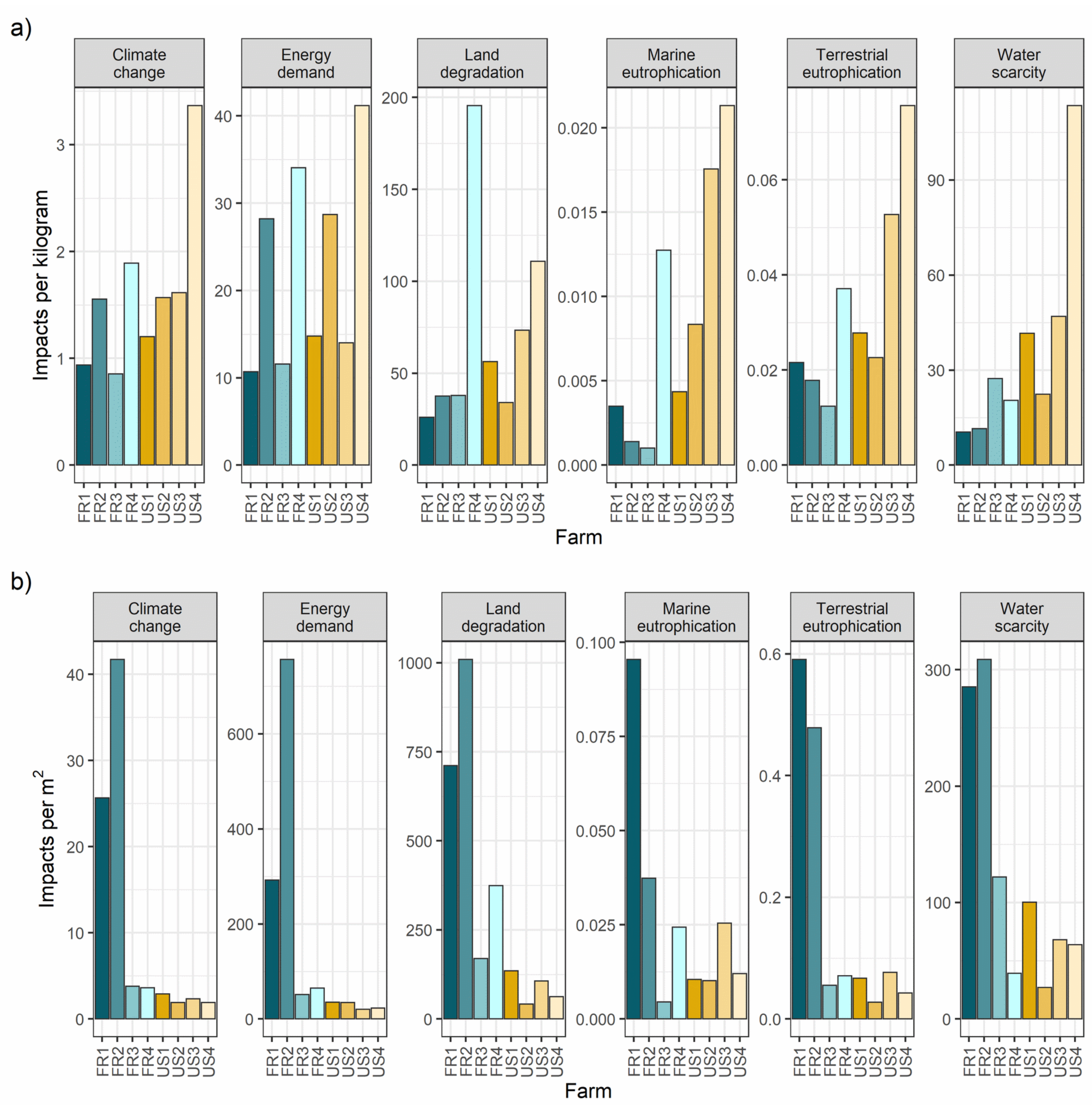


Figure 3 Results are shown for eight impact categories with a functional unit of a) kilograms of crop grown and b) m2 of food growing area occupied per year. The six impact categories considered were: climate change (kg CO2 eq), water scarcity (m3 deprived), land degradation (Pt), energy use (MJ), marine eutrophication (kg N eq), and terrestrial eutrophication (mol N eq).

3.2 Explaining the relative performance across diverse forms of urban agriculture

	FR1		FR2		FR3		FR4		US1		US2		US3		US4	
	kg	m²	kg	m²	kg	m²	kg	m²	kg	m²	kg	m²	kg	m²	kg	m²
Climate change	7	2	5	1	8	3	2	4	6	5	4	7	3	6	1	8
Water scarcity	8	2	7	1	4	3	6	7	3	4	5	8	2	5	1	6
Land degradation	8	2	6	1	5	4	1	3	4	5	7	8	3	6	2	7
Energy demand	8	2	4	1	7	4	2	3	5	5	3	6	6	8	1	7
Marine eutrophication	6	1	7	2	8	8	3	4	5	6	4	7	2	3	1	5
Terrestrial eutrophication	6	1	7	2	8	6	3	4	4	5	5	8	2	3	1	7

Table 2 The ordered ranking of impacts across farms is shown for both functional units: kilogram of crop grown and m^2 of area cultivated. The farm with the largest impacts for a given impact category has a rank of 1, and the one with the lowest has a rank of 8. It is clear that for some farms the performance changes drastically based on the functional unit, and some have more consistent performance.

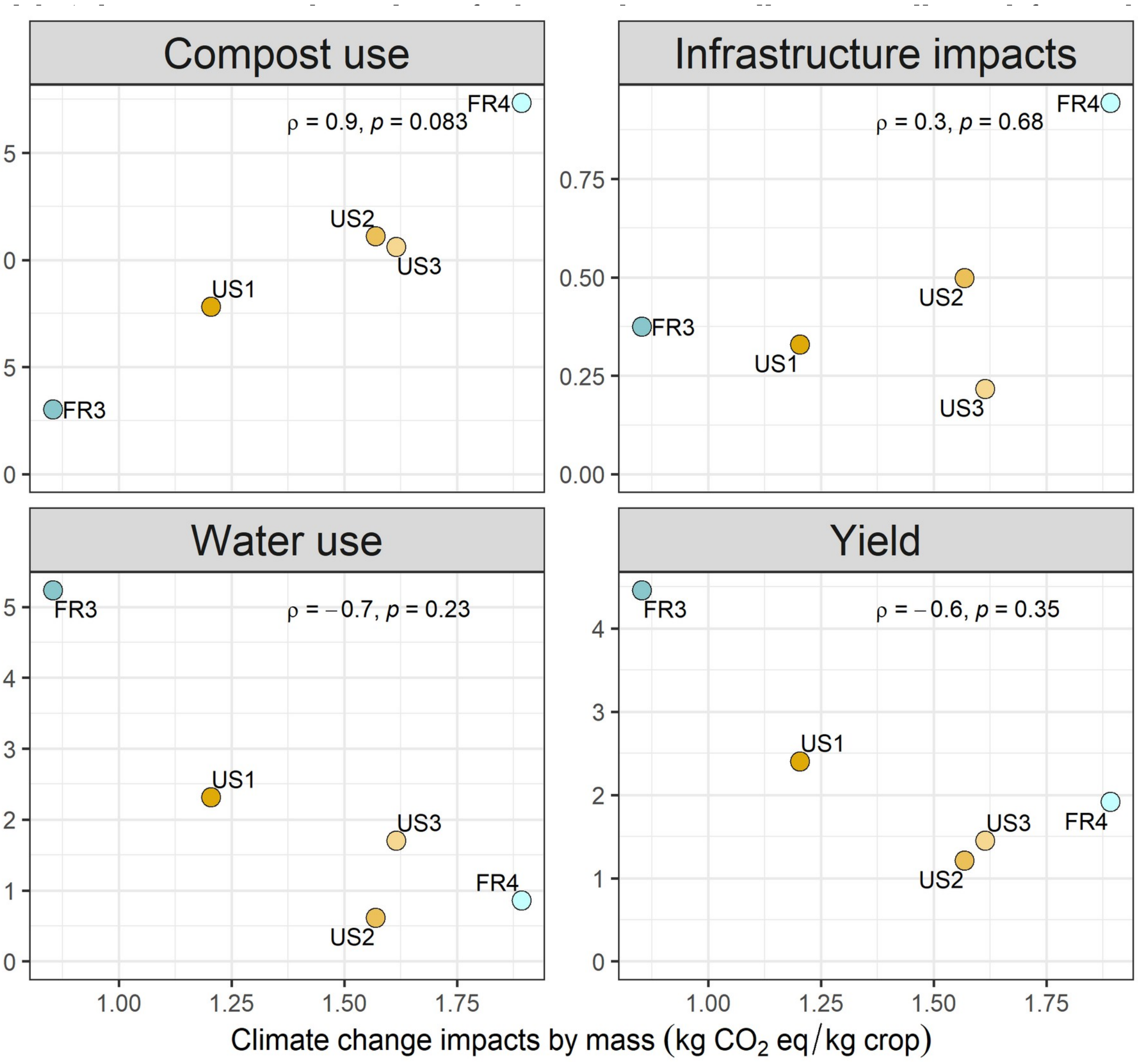
We noticed striking differences in the relative performance of the farms depending on the choice of functional unit. Results per kilogram of food were typically within one order of magnitude across the farms. For instance, climate change impacts per kilogram of crop ranged from 0.85 to 3.4 kg CO_2 eq., with a mean and standard deviation of 1.6±0.79 kg CO_2 eq. (Figure 3a). Energy demand ranged from 11 to 41 MJ/kg, with a mean and standard deviation of 23±12 MJ/kg. Notable exceptions were water scarcity which ranged from 10 to 113 m^3, and marine eutrophication which ranged from 0.001 to 0.021 kg N/kg. The relative performance of the farms shifted based on indicator, but US4 had the most environmentally intensive food production across five of six indicators because of its low level of food production (Table 2). FR4 was the most intensive for land degradation because of their large use of land-based inputs such as wood for raised beds and straw for mulch.

Conversely, there were orders of magnitude differences across most impact categories when using an area-based assessment. FR1 and FR2 had significantly higher impacts than the other farms because these two farms intensively used space with vertical growing structures to increase yields (Figure 3b). For example, climate change impacts per m^2 of food cultivation area were 26 and 42 kg CO_2 eq./m^2 for FR1 and FR2, and the other farms had a mean and standard deviation of 2.7±0.84 kg CO_2 eq./m^2. As explained below, yield primarily explains the jump in environmental impacts for these farms when switching between functional units.

3.2.1 Yield, water use, compost use, and infrastructure intensity

Yield was highly influential in determining the relative performance of some farms. For instance, high-yield farms FR1 and FR2 (both commercial rooftop farms had yields of 27 kg/m^2), had low environmental impacts per kilogram but extremely large impacts per m^2 due to the use of vertical space (with tall structures filled with substrate or aeroponic towers) and subsequent intensive material inputs per unit of floor space. The high productivity at these farms counterbalanced their resource intensity. This effect was also visible for the school garden US4. Here, the farm had a very low yield of 0.56 kg/m^2 compared to an average of 2.0 kg/m^2 for the other non-vertical farms in our sample. So even though the material inputs per m^2 were moderate, the low outputs from this area led to very high impacts per kilogram.

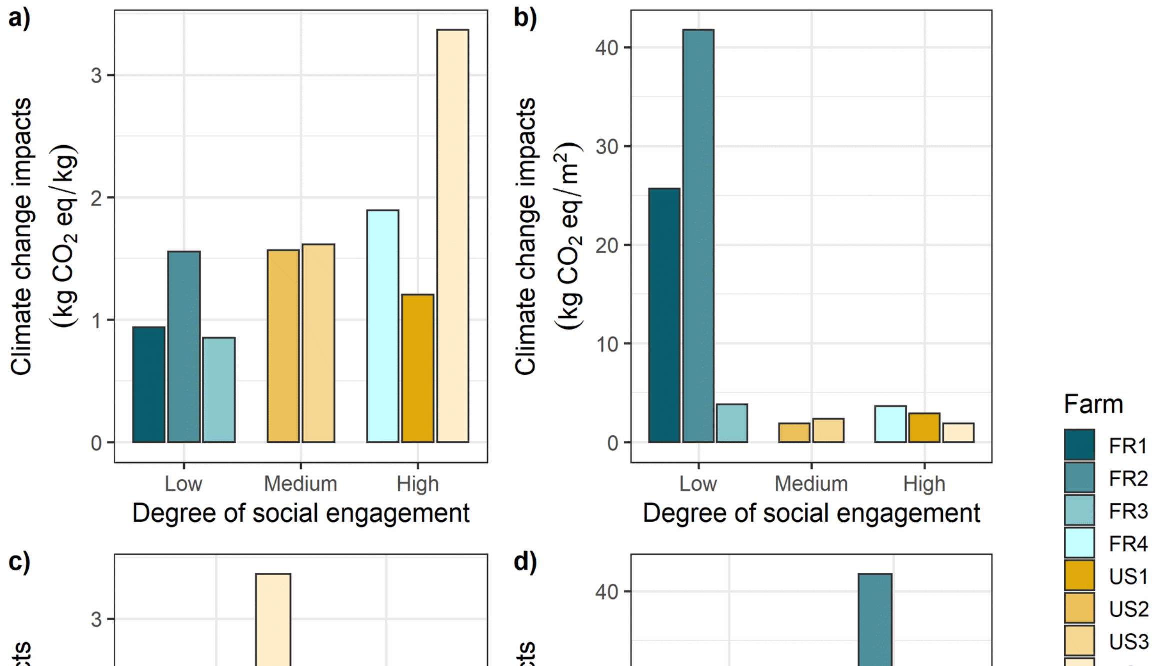
The other five farms had intermediate yields, similar to rural agriculture and other open-air UA (1.2-4.5 kg/m^2) (Dorr et al., 2021a), and had variable rankings in environmental impacts related more to inputs and practices than yield. For example, FR4 had the highest land-use impacts with a mass-based FU, mostly due to their use of wood for raised beds and straw for

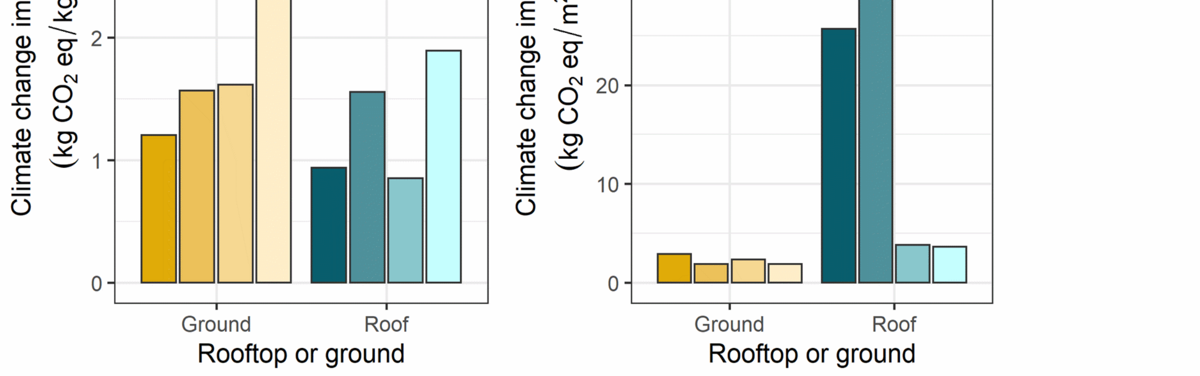


reliance on infrastructure. The two school farms with high social engagement, US4 and FR4,

Figure 4 Scatter plots show climate change impacts compared to other annual measures for each farm with intermediate results. a) compost use in kilograms per m2 b) climate change impacts of infrastructure only, in kilogram CO2 eq./m2, c) water use in m3/m2, d) yield in kilograms of crop grown per m2. The area refers to farm area in food production.

Farms with higher social engagement may have had larger impacts per kilogram due to less attention paid to growing food. Instead, farmers dedicated large amounts of time to educational programming, managing volunteers, or other activities. In addition, there may have been trade-offs between efficiency/environmental performance, and farm





or compost, and have lower impacts per kilogram.

Figure 5 Climate change impacts were compared between farms' social engagement level (a and b), and their rooftop or ground placement (c and d). High engagement farms had performed well using an area-based functional unit (b), but had large impacts per kilogram (a). Rooftop farms had larger impacts than ground-based farms considering an area-based functional unit, but this was driven by two of the four farms (FR1 and FR2). Ground-based farms tended to have larger impacts per kilogram.

location, cultivation setup (e.g. hydroponic vs. soil-based), motivation, and compost application rates. On the one hand, ground-based farms (in urban soils or creating urban soils on top of an impermeable surface) needed to apply large amounts of compost to create fertile soils, which is a common concern for UA (Edmondson et al., 2014). On the other hand, all rooftop farms had to import substrate, such as expanded clay, which contributed moderately to impact categories sensitive to compost for FR4 and FR3. No rooftop farms studied here made structural modifications to the buildings, therefore avoiding large infrastructure burdens seen in other studies (Goldstein et al., 2016). Their rooftop position led to weight load constraints, resulting in the lightweight substrate at FR1 and weight-distributing tiles for heavy fertigation tanks at FR2, but these did not contribute significantly to impacts. Ultimately, the placement on a building did not explain environmental performance.

3.3 Sensitivity analysis

Sensitivity analysis was performed to test the effects of our system modeling choices. The scenarios were chosen mainly on recommendations from the guidelines we developed for doing UA LCAs, and are presented in the Methods section 2.4.5. These scenarios test the inclusion of additional processes with the potential to influence the results, but are not recommended for inclusion in baseline scenarios because of uncertainty in the necessary data or calculations, or because they are atypical modeling methods. The relative changes from the baseline scenario for each farm are shown in Figure 6a for climate change impact, plus the average relative change.

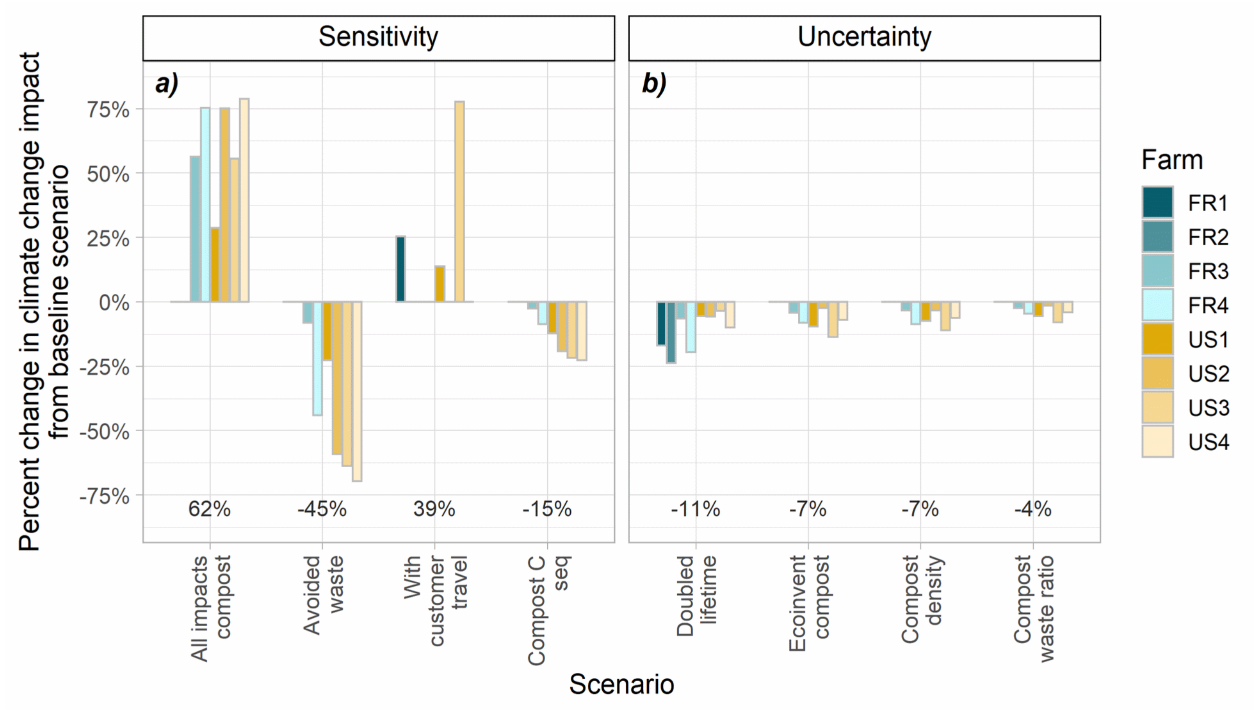


Figure 6 a) Sensitivity and b) uncertainty analyses were done to test the effect of different system modeling decisions and parameter values. Bars show the percent change from the baseline scenario's climate change impacts for each farm, and the value shown above the x-axis is the average percent change for that scenario.

The largest changes in impact came from the scenario where purchased compost was given 100% of the impacts of composting, as is frequently done in agricultural LCAs, rather than 7% based on economic allocation in the baseline scenario (Adewale et al., 2016; Bartzas et al., 2015). Climate change impacts increased an average of 62%, and compost contributed to an average of 40% of climate change impacts. In the next scenario, we subtracted environmental impacts of municipal waste treatment of the organic waste that was used to make off-farm compost. Typically, in such a farm-level LCA the farm would not receive these credits, but we wanted to explore the extent of its importance because this is a major proposed benefit of UA. Climate change impacts were reduced by an average of 45% for the six farms that used compost, and the hydroponics system FR2 emerged with largest impacts per kilogram. The next scenario included customer travel to the farm to purchase or harvest produce, and was not included in the baseline scenario due to high uncertainty in customer travel behaviors. Climate change impacts increased by 14%, 25%, and 78% for the three farms considered, and varied based on the assumed mode of transportation and distances traveled. The last sensitivity analysis included the potential offsets in climate change impacts thanks to carbon sequestration from annual compost amendments and resulted in reductions of 12-23% for the four US farms and 3-9% for the two French farms using compost. A more detailed presentation and interpretation of the sensitivity analyses are in the Supplementary Material, section 5.

3.4 Uncertainty analysis

Uncertainty analysis was done to test the effect of uncertainty in inventory data and parameters. Similar to sensitivity analysis, these tests were done by rerunning the models with changes in the inventory data. Relative changes to the baseline scenario for each farm are shown in Figure 6b, plus the average relative change.

Because impacts of infrastructure and substrate are directly related to their estimated lifetimes, we modeled a scenario where their lifetimes were doubled. This reduced climate change impacts by up to 24% for FR2, and FR1 became the farm with the lowest climate change impact per kilogram of produce. Land degradation impacts decreased 21% on average. The remaining uncertainty analyses were related to compost production, due to the high uncertainty in its parameters and inventory data. First, we modeled a scenario using emission factors for compost production from the Ecoinvent database (a common source of compost inventory data in LCA studies), which resulted in decreases in climate change impacts of 2-14%. Next, we performed a Monte Carlo simulation with 1,000 runs to test uncertainty in emission factors of methane and nitrous oxide from compost production, compost density, and the mass balance of organic waste input to compost output. With modest amounts of uncertainty in the distributions for these four parameters, the overlapping 95% confidence intervals suggest that several farms can be considered to have the same level of potential impacts (Figure 7). More details from the uncertainty analysis are in section 6 of the Supplementary Material.

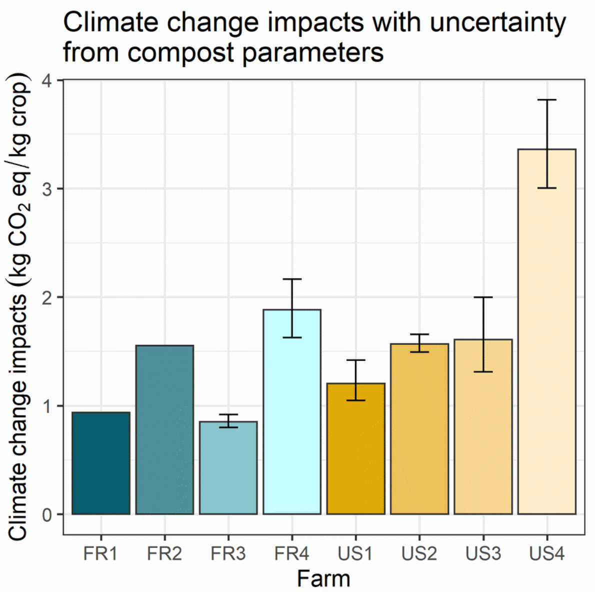


Figure 7 We performed Monte Carlo simulations to test the uncertainty of four compost parameters: density, the waste-to-compost ratio, CH_4 emission factors, and N_2O emission factors. The figure shows the climate change impacts of the baseline scenario with error bars representing the 95% confidence interval. Overlapping error bars suggest that farms can be considered to have the same impacts.

4 Discussion

4.1 Comparison to other studies

Most of the yields found here were within the ranges found in other UA LCAs (Table 3) (Dorr et al., 2021a). FR1 and FR2, with intensive vertical growing systems, were exceptionally productive. FR3 had high yields compared to similar types, likely because of its commercial nature and focus on food production. US4 had very low yields, which could be attributed to several factors: the farm manager was new and mostly experienced with ornamental production; the site was in San Francisco, which is notoriously cloudy, even compared to nearby cities; slow replanting after harvest cycles; and growing food was secondary to educational activities.

Our comparison presents direct irrigation water use (i.e., blue water) rather than the LCA impact category of water scarcity. This is because there are few studies that use the same impact assessment method that we did (AWARE, included in the PEF guidelines), and because the “scarcity” aspect of our results was not very accurate because we lacked appropriate local characterization factors (see section 10.8 in the Supplementary Material for details). Water use for all farms studied here was larger per kilogram and per m^2 than rural agriculture in France and California growing similar vegetables (Table 3). UA in other studies also shows lower water use than what we measured in the case studies, although there is large variability.

Climate change impacts per kilogram for our farms were comparable to the averages from the literature for UA, although on the high end (Dorr et al. 2021a). The average impact of the seven open-air, soil-based farms was 1.6 kg CO_2 eq/kg of crop, compared to an average of 1.2 kg CO_2 eq/kg for similar farms in the literature (Table 3). The only outlier was US4, with a climate change impact of 3.4 kg CO_2 eq/kg of crop. Regarding the open-air hydroponics farm FR2, impacts per kilogram were lower than similar farms summarized in the literature, which had an average of 2.1 kg CO_2 eq/kg. FR2 also used aeroponics, which may have lowered impacts by efficiently using small amounts of sprayed fertigation. Climate change impacts per kilogram for all farms were on average four times larger than the averages for similar baskets of rural-grown vegetables summarized in the review by Clune et al. (2017). The coefficient of variation was 1.45 for the meta-analysis sample of intra-urban, soil-based, open-air systems, and 0.37 for our case studies. This indicates that there was less variation within our set of results, where farms were still very diverse, than there was between values in the literature. On an area basis, FR1 and FR2 had much higher impacts than other UA systems, but the other six farms had impacts within the expected range. In contrast to other open-air, soil-based UA, our farms had relatively large climate-change impact contributions from infrastructure (which was typically more impactful for indoor farms), and small contributions from delivery of crops (due to the prevalence of delivery by walking or bicycling) (Dorr et al., 2021a). We found similarly high impacts from delivering supplies to farms, such as compost and soil amendments, further highlighting this as a process to pay attention to.

There were few comparable results available for energy demand, but our case studies had larger values than the average found in the literature.

We should note that these comparisons, along with the comparisons between the farms we studied, are cursory since each farm grew a different mix of crops. Considering both the mass and area-based functional units, different functions were technically fulfilled, since different vegetables were produced. We found no suitable method to allocate inputs/impacts among crops at any farm due to the large number of crops grown, and the fact that many crops were interspersed within the same parcel and shared inputs. Distributing impacts across the entire basket of crops produced at urban farms is common practice given the paucity of ideal allocation methods (Boneta et al., 2019; Pérez-Neira and Grollmus-Venegas, 2018; Sanyé-Mengual et al., 2018).

Measure	System type	Average	St Dev	Range	Sample size
Yield (kg/m^2)	**Case study- low tech[1]**	**2.0**	**1.4**	**0.6-4.5**	6
	Case study- medium tech[1]	**27**	**0**	**27**	2
	Open air UA[2]	4.2	4.0	0.62-16	32
	Open air UA[3]	1.9	1.4	0.17-6.7	72
Water use (m^3/m^2)	**Case study- California[1]**	**1.3**	**0.58**	**0.61-2.0**	4
	Case study- France[1]	**4.7**	**2.7**	**0.78-6.5**	**4**
	Open air UA[3]	0.12	0.21	0.01-1.3	72
Water use (m^3/kg)	**Case study- California[1]**	1.3	0.92	0.51-2.6	4
	California rural ag[4]	0.27	0.10	0.08-0.51	13
Energy demand (kWh/kg)	**Case study- soil-based [1]**	6.1	3.4	3.0-11.4	7
	Case study- hydroponics + aeroponics[1]	7.8	0	7.8	1
	Open air, soil-based UA[2]	1.8	2.6	0.32-10	13
	Open air, hydroponics UA[2]	10	7.1	2.6-20	6
Climate	**Case study- soil based[1]**	**1.6**	**0.85**	**0.85-3.4**	7
	Case study- hydroponics +				

Table 3 Our results (in bold text) are compared to averages from the literature for urban and rural agriculture. [1]Case studies presented in this paper, [2](Dorr et al., 2021a), only intraurban agriculture, [3](Dorr et al., 2022b [in press]), [4](Stone et al., 2021), [5](Clune et al., 2017), considering only lettuce, tomato, cucumber, zucchini, squash, pumpkin, strawberry, onion, carrot, and apple. In our case studies, medium-tech farms include FR1 and FR2, and all other farms are low-tech.

4.2 Lessons for doing UA LCAs

Our experience of adhering to the guidelines in performing a detailed LCA of eight diverse UA sites can provide lessons/insight for future LCAs (Dorr et al., 2022a [under review]). We identified processes that were important and should be regularly included with high-quality primary data (infrastructure, irrigation, compost, and peat-containing seedlings), and processes containing considerable uncertainty. Compost emerged as a sensitive and potentially important input, which has been inadequately studied in existing UA LCAs (or agriculture LCAs in general). Aspects that would be better considered with a city-scale or territorial LCA were identified, such as benefits from composting as an alternative waste treatment, or customer travel to the farm. Our results reiterated the importance of using multiple functional units to highlight strengths of different types of farms and farming practices, as found in other agriculture LCAs (van der Werf et al., 2020). Overall, following the guidelines strengthened this LCA, but further improvements could be made. More rigorous data collection that tracked inputs per crop would allow for crop-level results, which would be more comparable to produce from conventional, rural agriculture. Furthermore, our comparisons to conventional food products were limited compared to the guideline recommendations, because we excluded transport to the consumer (i.e. “last mile”) and seasonality for conventional products which can influence results (Plawecki et al., 2014). As mentioned in the guideline, accounting for these requires complex modeling and large assumptions, which were outside the scope of this work.

Our study also highlights some of the practical difficulties of collaborating with urban farms. A major difficulty in data collection was the dynamic nature of UA: farm layouts were frequently changing, new cultivation areas were created, and new farming practices were tested. This made it difficult to capture representative practices over one year. Indeed, where we have data from multiple years, yield varied by up to 50% annually. There was a high turnover rate among the farmers and managers, who were our main partners for the studies. For half of the farms, the main farmer or point-person for data collection left during the 1-2 years of collaboration. This raised issues of inconsistency in farming practices, data collection methods, and motivation/willingness to participate in the study. Another difficulty was incomplete record keeping: it was not uncommon for data on harvest or supplies to go unrecorded. Farmers were often not used to collecting such information, and this was manual and intensive data collection which required substantial coaching and support by researchers. Difficulties in data collection with UA have been widely reported in studies aiming to characterize the agricultural practices of UA, let alone perform LCAs (McDougall et al., 2019; Whittinghill and Sarr, 2021). We recommend outlining data collection expectations with farmers/gardeners in the beginning of the project, and adapting to whatever type and quality of data can be collected. More recommendations for primary data collection are included in the guidelines. Using these adaptable measurement methods and regularly checking in with farmers allowed us to obtain a satisfactory quality of data, despite the challenges.

4.3 Lessons for improving environmental performance of urban agriculture

For urban farmers, our results suggest how to manage and design farms to reduce environmental impacts (although we acknowledge that efficiency may not be a main priority or objective for farmers). Overall, our study showed which processes to prioritize, as they are consistently impactful, and which processes may not be worth as much effort. For a simple interpretation, farmers/gardeners should focus on infrastructure and irrigation because they were found to be consistently impactful across farms and impact categories. For infrastructure, farmers should prioritize using recycled or reused materials (either through direct reuse or purchasing items made from recycled materials) and using infrastructure for as long as possible. For irrigation, the type of water can be changed to collected rainwater or treated wastewater, which comes with less impacts than municipally-treated tap water (Qin and Horvath, 2020). The amount of water may also be reduced by avoiding wasted water through leaks (Stokes et al., 2013), using timed drip-irrigation settings (and adapting these settings based on weather and crops), and avoiding irrigating bare areas that have not been replanted (or replant bare areas). Other impactful processes that farmers could optimize are compost and seedling procurement. For compost, farmers can adjust the amount used to ensure they do not use more than is necessary, purchase compost from facilities that prioritize reducing or capturing fugitive greenhouse gas emissions, and source compost locally to reduce transport of such a large input. Finally, seedlings should be started with a minimum amount of peat.

For policy makers, the environmental performance of different farms can profile which types of UA to promote based on different objectives: if food production is the goal, for example, to improve food security of a city, then medium-tech farms (such as FR1 and FR2) or professional farms similar to the ones we included can optimize growing food with lower impacts per kilogram. If food production is less important than education or social benefits, then low-tech farms are better to minimize impacts per m^2 per year regardless of how much food is grown. The importance of infrastructure in our results suggests that implementing UA as a transitional land degradation can impart high environmental costs. Temporary urban farms should use minimal infrastructure or use recycled or reused/repurposed material as much as possible. Finally, our results suggest that UA uses substantial amounts of water, although it must be evaluated how important this water use would be compared to what the whole city consumes.

5 Conclusion

Existing LCAs have provided mixed conclusions about the environmental performance of UA, due to inconsistent application of the method; use of secondary data; lack of functioning, representative case studies; and a small number of studies. We worked with a diverse set of eight urban farms and gardens across two regions, collected essential primary data, performed LCA, and identified which processes and decisions were essential and must be improved for more robust studies in the future. By adhering to strict guidelines for doing LCAs of UA we showed that it is possible to comprehensively, transparently, and consistently model UA using LCA.

Infrastructure and irrigation emerged as impactful for many impact categories. Compost, which is not usually focused on in other LCAs and seen as an innocuous, climate-neutral input, was important for climate change impacts for five of the eight farms, even when severely discounted through economic allocation. This highlights the importance of managing composting operations to minimize greenhouse gas emissions. Following this finding, we explored sources of sensitivity and uncertainty for compost, and found that small changes in parameters changed climate change impacts by up to 14%, and a different system modeling decision increased climate change impacts by 62%. Using two functional units, based on mass of food produced and area cultivated, resulted in very different rankings of the farms. Extremely high or low yield was a determining factor of relative impacts for three farms, but the five farms with more intermediate yields had a mixed performance. Generally, the medium-tech farms (i.e., open-air hydroponics, vertical substrate structures) and the professional farms performed best using the amount of food grown as a functional unit, suggesting that this type of UA may be better for efficiently growing food and alleviating food insecurity. Inversely, they had the largest impacts on an area basis, where the low-tech farms and gardens with more social objectives tended to perform better with an area-based functional unit. Yields and climate change impacts were generally similar to averages from other UA and rural agriculture studies, but water use was much higher.

This work provides valuable insight into how we can do LCAs of UA, and demonstrates the application of a consistent set of guidelines for improved UA LCAs. It also contributes to the growing field of research on the environmental performance of UA, which can help evaluate UA's position in cities and design UA to optimize its environmental objectives.

Acknowledgments

The researchers express their deep gratitude to the farmers and gardeners who volunteered to collect primary data for this study. E.D, C.A, and B.Gabrielle gratefully acknowledge financial support of lab recherche environnement VINCI ParisTech. A.H gratefully acknowledges the support of the National Science Foundation under Grant No. 1739676. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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