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¹ Life cycle assessment of eight urban farms and ² community gardens in France and California

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10 Abstract

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

20 Highlights:

- 21 Calculated environmental impacts of 8 urban farms/gardens using life cycle assessment
- 22 Collected primary data and aimed for complete, transparent assessment
- 23 Vertical, outdoor, professional farms had largest impacts by area; not by mass of crop
- 24 Most impacts came from infrastructure, irrigation, compost, and peat from seedlings
- 25 Results were highly sensitive to system modeling choices, such as compost parameters
- 26
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30 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., 31 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 32 and benefits, alongside education, community development, recreation, climate change mitigation, urban biodiversity improvements, and organic waste 33 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 34 security, food justice, revenue generation, and access to fresh produce (Kirby et al., 2021; Pourias et al., 2016; Siegner et al., 2020). Agriculture's 35 contributions to many environmental issues are well-documented, such as climate change, water depletion, energy use, land degradation change and 36 degradation, eutrophication, and biodiversity loss (Campbell et al., 2017). As researchers and local leaders call for expanding UA in cities in support of 37 sustainable urban food systems, it is imperative that the practice provides environmental benefits (Armanda et al., 2019; Mohareb et al., 2017). 38

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:

- 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.
- 51 2. Data were often not representative of UA. Many case studies relied on secondary data from rural agriculture (a handful were even categorized 52 as "hypothetical" production sites), and studied research-oriented or innovative systems.
- 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 60 doing so we address the various gaps in the existing literature. Namely we included a large sample size of functioning urban farms/gardens covering 61 two regions and climates and then assessed their environmental performance using robust primary data and a consistent, transparent modeling 62 approach. The overall objectives of this study were twofold. The first goal was to perform a comprehensive LCA of diverse UA, based on primary 63 data, to contribute to the knowledge around its environmental performance. In particular, we seek to explain the relative environmental performance of 64 diverse types of UA. The second goal was to simultaneously inform and demonstrate methodological guidelines to support more systematic and 65 consistent LCAs of UA. This was developed through an iterative process where the guidelines were informed by work with case studies (presented 66 here), and the case studies here adhered to the guidelines. 67

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.

74 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.

77 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;

83 Glowa, 2014; Lawson, 2014).

84 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

87 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

⁸⁹ "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/m²)	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 m² as FR1, since they also used precise, low-consumption drip irrigation in vertical structures.

103

104 2.3 Data collection

Data collection methods varied at each farm, but can generally be characterized as either 1) 105 using data that farms already collected (minority of the data), and 2) working with farmers to 106 define data collection methods to track their practices (majority of the data). Details of these 107 data collection methods, plus secondary data sources, are available in the Supplementary 108 Material. For all farms, data collected represent one year of operation, but different 12-month 109 periods between 2019 and 2021 were used. Before accepting to use data from 2020 that may 110 have been unrepresentative due to the COVID-19 pandemic, we were assured by farmers that 111 operations were not affected. 112

113 2.4 Life cycle assessment

114 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.

119 2.4.2 Scope

120 The system boundary for this LCA includes everything needed to grow fruits and vegetables 121 on the farm, and the distribution step directly after the farm. In most cases this was to the 122 consumer, but some farms sold some of their produce through small neighborhood grocery 123 stores. The included processes are shown in the process diagram in Figure 1. We included two 124 functional units in our analysis, which is important to account for the multiple functions of 125 agriculture:

- 126 1 kg of produce, and
- 1 m² of area under food production for one year.
- 128 We provide impacts in the Supplementary Material for additional functional units:
- 129 1 m^2 of total farm area for one year and
- 1 m² 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.

134 2.4.3 Life cycle inventory

The processes and inputs at all farms varied, but we categorized them into consistent 135 categories to help interpret the results. The categories included substrate, infrastructure, 136 delivery of inputs, compost, other supplies, nitrogen losses, irrigation, seedlings, delivery of 137 product, packaging, avoided municipal biowaste treatment, and waste treatment of inedible 138 biomass. Lifetimes for infrastructure were determined based on the expected lifetime of either 139 the material or the object, depending on which is shorter. For example, the lifetime of drip 140 141 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 142 description of the categories and what they included, and of how they were measured or 143 calculated, are in section 10 of the Supplementary Material. 144

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.

153 2.4.4 Life cycle impact assessment

We used the Product Environmental Footprint (PEF) impact assessment method, version 2.0 154 (European Commission, 2017). We included six impact categories that are particularly 155 relevant for agricultural production: climate change (kg CO₂ equivalent), water scarcity (m³ of 156 water deprived), land degradation (Pt, a dimensionless soil quality index, combining measures 157 of erosion resistance, mechanical filtration, physicochemical filtration, groundwater 158 regeneration, and biotic production (Bos et al., 2016)), energy demand (MJ), marine 159 160 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 161 baseline V3.05, and ILCD 2011 V1.10) are available in the Supplementary Material to 162 support comparisons with future studies. 163

164 2.4.5 Sensitivity and uncertainty analyses

- We performed sensitivity analyses to test the impact on the results of modeling decisions thatwe identified as important in our recent literature review of UA LCAs (Dorr et al., 2021a) as
- 167 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.

175 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.

181 We created these guidelines iteratively and in parallel to the present work, where this LCA 182 both informed and demonstrates the guidelines. We present the challenges, review the many 183 ways they have been overcome, and recommend how to deal with them in the future. Our 184 literature review of UA LCAs (Dorr et al., 2021a) and firsthand experience with these farms 185 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 wastegenerator 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.

223 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.

228 3.1 Process contribution analysis

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

230 3.1.1 Infrastructure

Infrastructure had the largest average contribution to land degradation with an average of 43% 231 (mostly related to wood use), and for climate change it contributed an average of 24%. It was 232 especially impactful for FR2, where it accounted for 50% of climate change impacts and 64% 233 of energy resource use. Impacts in these categories for FR2 were driven by the significant 234 235 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 236 importance of this single piece of infrastructure, even though it was severely discounted for 237 238 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 239 240 energy use.

241 3.1.2 Irrigation

242 Water scarcity impacts were dominated by irrigation, with a contribution ranging from 90 to 243 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 244 US1, US3, US4, and FR3. It contributed 27% to energy resource use on average, and this was 245 246 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 247 majority of impacts for most impact categories came from tap water. This points to the 248 potential benefits of substituting energy intensive municipal water sources for alternatives, 249 such as harvested rainwater. 250

251 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).

259 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).

267 Nitrous oxide, N₂O, is a potent greenhouse gas with approximately 300 times the radiative 268 forcing over carbon dioxide over a century. N₂O emissions were responsible for 0.5% to 16% of climate change impacts, with an average of 6.4%. The largest contributions were from 269 US3, where emissions from compost and chicken feathers contributed almost equally. 270 Chicken feathers have high nitrogen content (about 16% of dry matter), compared to 0.9% for 271 compost assumed here. Indirect N₂O emissions from leaching of nitrogen and subsequent 272 273 volatilization were responsible for about 30% of these emissions, and direct emissions were 274 responsible for 70%.

275 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.

283 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.

297 3.1.7 Other supplies

The 'Other supplies' category was particularly impactful for FR4 and FR1. For FR4, this was 298 299 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 300 impacts between mushrooms and their leftover substrate. This substrate accounted for 35% of 301 FR4's total energy use and 14% of climate change impacts. Straw for mulching was the other 302 303 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 304 fertilizers accounted for 19% of total climate change impacts, and 37% of land degradation 305 impacts. FR2 also used liquid mineral fertilizers, but smaller amounts: 0.002 kg N/kg crop, 306 307 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. 308

309 3.1.8 Substrate

310 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, 311 with 9% of climate change and 12% of terrestrial eutrophication impacts. These impact 312 categories were strongly affected by compost, which composed the bulk of the substrate. 313 Substrate impacts from FR1 and FR2 were relatively small, with 5-7% contribution to climate 314 change and 3-10% to terrestrial eutrophication. This was because their substrate was mostly 315 composed of coconut fiber which had no allocated production impacts since it is a waste 316 317 material.

318 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).

325 3.2 Explaining the relative performance across diverse forms of urban 326 agriculture

	FF	R 1	FI	R2	FR	3	FR	4	U	S1	US	2	US	53	US	4
	kg	m^2	kg	m^2	kg	m^2	kg	m^2	kg	m^2	kg	m^2	kg	m^2	kg	m^2
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.

327 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 328 magnitude across the farms. For instance, climate change impacts per kilogram of crop ranged 329 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. 330 (Figure 3a). Energy demand ranged from 11 to 41 MJ/kg, with a mean and standard deviation 331 332 of 23±12 MJ/kg. Notable exceptions were water scarcity which ranged from 10 to 113 m³, 333 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 334 intensive food production across five of six indicators because of its low level of food 335 336 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. 337

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 m² of food cultivation area were 26 and 42 kg CO₂ eq./m² for FR1 and FR2, and the other farms had a mean and standard deviation of 2.7 ± 0.84 kg CO₂ eq./m². As explained below, yield primarily explains the jump in environmental impacts for these farms when switching between functional units.

345 3.2.1 Yield, water use, compost use, and infrastructure intensity

Yield was highly influential in determining the relative performance of some farms. For 346 instance, high-yield farms FR1 and FR2 (both commercial rooftop farms had yields of 27 347 kg/m²), had low environmental impacts per kilogram but extremely large impacts per m² due 348 to the use of vertical space (with tall structures filled with substrate or aeroponic towers) and 349 subsequent intensive material inputs per unit of floor space. The high productivity at these 350 farms counterbalanced their resource intensity. This effect was also visible for the school 351 garden US4. Here, the farm had a very low yield of 0.56 kg/m² compared to an average of 2.0 352 kg/m² for the other non-vertical farms in our sample. So even though the material inputs per 353 m^2 were moderate, the low outputs from this area led to very high impacts per kilogram. 354

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The other five farms had intermediate yields, similar to rural agriculture and other open-air UA (1.2-4.5 kg/m²) (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

359 impacts with a mass-based FU, mostly due to their use of wood for raised beds and straw for





401 or compost, and have lower impacts per kilogram.

Figure 5 Climate change impacts were compared between farms' social engagement level (a and b), 402 and their rooftop or ground placement (c and d). High engagement farms had performed well using 403 an area-based functional unit (b), but had large impacts per kilogram (a). Rooftop farms had large 404 impacts than ground-based farms considering an area-based functional unit, but this was driven by 405 two of the four farms (FR1 and FR2). Ground-based farms tended to have larger impacts per 406 kilogram.

407 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 408 on top of an impermeable surface) needed to apply large amounts of compost to create fertile 409 410 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 411 to impact categories sensitive to compost for FR4 and FR3. No rooftop farms studied here 412 made structural modifications to the buildings, therefore avoiding large infrastructure burdens 413 seen in other studies (Goldstein et al., 2016). Their rooftop position led to weight load 414 constraints, resulting in the lightweight substrate at FR1 and weight-distributing tiles for 415 heavy fertigation tanks at FR2, but these did not contribute significantly to impacts. 416 Ultimately, the placement on a building did not explain environmental performance. 417

418 3.3 Sensitivity analysis

Sensitivity analysis was performed to test the effects of our system modeling choices. The 419 scenarios were chosen mainly on recommendations from the guidelines we developed for 420 doing UA LCAs, and are presented in the Methods section 2.4.5. These scenarios test the 421 422 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 423 or calculations, or because they are atypical modeling methods. The relative changes from the 424 425 baseline scenario for each farm are shown in Figure 6a for climate change impact, plus the 426 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.

427 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 428 429 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 430 an average of 40% of climate change impacts. In the next scenario, we subtracted 431 432 environmental impacts of municipal waste treatment of the organic waste that was used to 433 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 434 proposed benefit of UA. Climate change impacts were reduced by an average of 45% for the 435 six farms that used compost, and the hydroponics system FR2 emerged with largest impacts 436 437 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 438 travel behaviors. Climate change impacts increased by 14%, 25%, and 78% for the three 439 440 farms considered, and varied based on the assumed mode of transportation and distances 441 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 442 443 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 444 445 Material, section 5.

446 3.4 Uncertainty analysis

447 Uncertainty analysis was done to test the effect of uncertainty in inventory data and 448 parameters. Similar to sensitivity analysis, these tests were done by rerunning the models with 449 changes in the inventory data. Relative changes to the baseline scenario for each farm are 450 shown in Figure 6b, plus the average relative change.

451 Because impacts of infrastructure and substrate are directly related to their estimated 452 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 453 change impact per kilogram of produce. Land degradation impacts decreased 21% on average. 454 The remaining uncertainty analyses were related to compost production, due to the high 455 uncertainty in its parameters and inventory data. First, we modeled a scenario using emission 456 factors for compost production from the Ecoinvent database (a common source of compost 457 inventory data in LCA studies), which resulted in decreases in climate change impacts of 2-458 14%. Next, we performed a Monte Carlo simulation with 1,000 runs to test uncertainty in 459 emission factors of methane and nitrous oxide from compost production, compost density, 460 and the mass balance of organic waste input to compost output. With modest amounts of 461 uncertainty in the distributions for these four parameters, the overlapping 95% confidence 462 463 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 464 465 Supplementary Material.



Figure 7 We performed Monte Carlo simulations to test the uncertainty of four compost parameters:
density, the waste-to-compost ratio, CH₄ emission factors, and N₂O 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.

470 4 Discussion

471 4.1 Comparison to other studies

472 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 473 productive. FR3 had high yields compared to similar types, likely because of its commercial 474 475 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 476 production; the site was in San Francisco, which is notoriously cloudy, even compared to 477 478 nearby cities; slow replanting after harvest cycles; and growing food was secondary to educational activities. 479

480 Our comparison presents direct irrigation water use (i.e., blue water) rather than the LCA 481 impact category of water scarcity. This is because there are few studies that use the same 482 impact assessment method that we did (AWARE, included in the PEF guidelines), and 483 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 m² 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 489 literature for UA, although on the high end (Dorr et al. 2021a). The average impact of the 490 491 seven open-air, soil-based farms was 1.6 kg CO₂ eq/kg of crop, compared to an average of 1.2 kg CO₂ eg/kg for similar farms in the literature (Table 3). The only outlier was US4, with a 492 climate change impact of 3.4 kg CO₂ eq/kg of crop. Regarding the open-air hydroponics farm 493 FR2, impacts per kilogram were lower than similar farms summarized in the literature, which 494 had an average of 2.1 kg CO₂ eg/kg. FR2 also used aeroponics, which may have lowered 495 impacts by efficiently using small amounts of sprayed fertigation. Climate change impacts per 496 kilogram for all farms were on average four times larger than the averages for similar baskets 497 of rural-grown vegetables summarized in the review by Clune et al. (2017). The coefficient of 498 499 variation was 1.45 for the meta-analysis sample of intra-urban, soil-based, open-air systems, 500 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. 501 On an area basis, FR1 and FR2 had much higher impacts than other UA systems, but the other 502 503 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 504 was typically more impactful for indoor farms), and small contributions from delivery of 505 crops (due to the prevalence of delivery by walking or bicycling) (Dorr et al., 2021a). We 506 found similarly high impacts from delivering supplies to farms, such as compost and soil 507 amendments, further highlighting this as a process to pay attention to. 508

509 There were few comparable results available for energy demand, but our case studies had 510 larger values than the average found in the literature.

We should note that these comparisons, along with the comparisons between the farms we 511 studied, are cursory since each farm grew a different mix of crops. Considering both the mass 512 and area-based functional units, different functions were technically fulfilled, since different 513 vegetables were produced. We found no suitable method to allocate inputs/impacts among 514 crops at any farm due to the large number of crops grown, and the fact that many crops were 515 516 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 517 allocation methods (Boneta et al., 2019; Pérez-Neira and Grollmus-Venegas, 2018; Sanyé-518 Mengual et al., 2018). 519

Measure	System type	Average	St Dev	Range	Sample size
	Case study- low tech ¹	2.0	1.4	0.6-4.5	6
Viold $(l(\alpha/m^2))$	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
	Case study- California ¹	1.3	0.58	0.61-2.0	4
(m^3/m^2)	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	Case study- California ¹	1.3	0.92	0.51-2.6	4
(m³/kg)	California rural ag ⁴	0.27	0.10	0.08-0.51	13
	Case study- soil-based ¹	6.1	3.4	3.0-11.4	7
Energy	Case study- hydroponics +				
demand	aeroponics ¹	7.8	0	7.8	1
(kWh/kg)	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
	Case study- soil based ¹	1.6	0.85	0.85-3.4	7
Climate	Case study- hydroponics +				

520 Table 3 Our results (in bold text) are compared to averages from the literature for urban and rural 521 agriculture. ¹Case studies presented in this paper, ²(Dorr et al., 2021a), only intraurban agriculture, 522 ³(Dorr et al., 2022b [in press]), ⁴(Stone et al., 2021), ⁵(Clune et al., 2017), considering only lettuce, 523 tomato, cucumber, zucchini, squash, pumpkin, strawberry, onion, carrot, and apple. In our case 524 studies, medium-tech farms include FR1 and FR2, and all other farms are low-tech.

525 4.2 Lessons for doing UA LCAs

526 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 527 identified processes that were important and should be regularly included with high-quality 528 primary data (infrastructure, irrigation, compost, and peat-containing seedlings), and 529 processes containing considerable uncertainty. Compost emerged as a sensitive and 530 531 potentially important input, which has been inadequately studied in existing UA LCAs (or 532 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 533 treatment, or customer travel to the farm. Our results reiterated the importance of using 534 multiple functional units to highlight strengths of different types of farms and farming 535 practices, as found in other agriculture LCAs (van der Werf et al., 2020). Overall, following 536 the guidelines strengthened this LCA, but further improvements could be made. More 537 rigorous data collection that tracked inputs per crop would allow for crop-level results, which 538 would be more comparable to produce from conventional, rural agriculture. Furthermore, our 539 comparisons to conventional food products were limited compared to the guideline 540 recommendations, because we excluded transport to the consumer (i.e. "last mile") and 541

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. 545 A major difficulty in data collection was the dynamic nature of UA: farm layouts were 546 frequently changing, new cultivation areas were created, and new farming practices were 547 tested. This made it difficult to capture representative practices over one year. Indeed, where 548 549 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. 550 For half of the farms, the main farmer or point-person for data collection left during the 1-2 551 years of collaboration. This raised issues of inconsistency in farming practices, data collection 552 methods, and motivation/willingness to participate in the study. Another difficulty was 553 incomplete record keeping: it was not uncommon for data on harvest or supplies to go 554 unrecorded. Farmers were often not used to collecting such information, and this was manual 555 and intensive data collection which required substantial coaching and support by researchers. 556 Difficulties in data collection with UA have been widely reported in studies aiming to 557 558 characterize the agricultural practices of UA, let alone perform LCAs (McDougall et al., 2019; Whittinghill and Sarr, 2021). We recommend outlining data collection expectations 559 with farmers/gardeners in the beginning of the project, and adapting to whatever type and 560 561 quality of data can be collected. More recommendations for primary data collection are included in the guidelines. Using these adaptable measurement methods and regularly 562 checking in with farmers allowed us to obtain a satisfactory quality of data, despite the 563 challenges. 564

565 4.3 Lessons for improving environmental performance of urban agriculture

For urban farmers, our results suggest how to manage and design farms to reduce 566 environmental impacts (although we acknowledge that efficiency may not be a main priority 567 or objective for farmers). Overall, our study showed which processes to prioritize, as they are 568 consistently impactful, and which processes may not be worth as much effort. For a simple 569 interpretation, farmers/gardeners should focus on infrastructure and irrigation because they 570 were found to be consistently impactful across farms and impact categories. For 571 infrastructure, farmers should prioritize using recycled or reused materials (either through 572 direct reuse or purchasing items made from recycled materials) and using infrastructure for as 573 long as possible. For irrigation, the type of water can be changed to collected rainwater or 574 treated wastewater, which comes with less impacts than municipally-treated tap water (Qin 575 and Horvath, 2020). The amount of water may also be reduced by avoiding wasted water 576 through leaks (Stokes et al., 2013), using timed drip-irrigation settings (and adapting these 577 578 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 579 compost and seedling procurement. For compost, farmers can adjust the amount used to 580 ensure they do not use more than is necessary, purchase compost from facilities that prioritize 581 reducing or capturing fugitive greenhouse gas emissions, and source compost locally to 582 583 reduce transport of such a large input. Finally, seedlings should be started with a minimum 584 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 m² 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.

597 **5** Conclusion

Existing LCAs have provided mixed conclusions about the environmental performance of 598 UA, due to inconsistent application of the method; use of secondary data; lack of functioning, 599 representative case studies; and a small number of studies. We worked with a diverse set of 600 eight urban farms and gardens across two regions, collected essential primary data, performed 601 LCA, and identified which processes and decisions were essential and must be improved for 602 more robust studies in the future. By adhering to strict guidelines for doing LCAs of UA we 603 604 showed that it is possible to comprehensively, transparently, and consistently model UA using LCA. 605

Infrastructure and irrigation emerged as impactful for many impact categories. Compost, 606 607 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 608 severely discounted through economic allocation. This highlights the importance of managing 609 composting operations to minimize greenhouse gas emissions. Following this finding, we 610 explored sources of sensitivity and uncertainty for compost, and found that small changes in 611 parameters changed climate change impacts by up to 14%, and a different system modeling 612 decision increased climate change impacts by 62%. Using two functional units, based on mass 613 of food produced and area cultivated, resulted in very different rankings of the farms. 614 Extremely high or low yield was a determining factor of relative impacts for three farms, but 615 616 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 617 professional farms performed best using the amount of food grown as a functional unit, 618 suggesting that this type of UA may be better for efficiently growing food and alleviating 619 food insecurity. Inversely, they had the largest impacts on an area basis, where the low-tech 620 farms and gardens with more social objectives tended to perform better with an area-based 621 622 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. 623

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.

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