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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

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30 1 Introduction

31 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.,
32 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
33 and benefits, alongside education, community development, recreation, climate change mitigation, urban biodiversity improvements, and organic waste
34 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
35 security, food justice, revenue generation, and access to fresh produce (Kirby et al., 2021; Pourias et al., 2016; Siegner et al., 2020). Agriculture's
36 contributions to many environmental issues are well-documented, such as climate change, water depletion, energy use, land degradation change and
37 degradation, eutrophication, and biodiversity loss (Campbell et al., 2017). As researchers and local leaders call for expanding UA in cities in support of
38 sustainable urban food systems, it is imperative that the practice provides environmental benefits (Armanda et al., 2019; Mohareb et al., 2017).

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

45 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
46 environmental performance because of *how* the LCAs were done, and *what systems* were studied (Dorr et al., 2021a). We identified challenges in three
47 areas:

- 48 1. System modeling decisions and reporting introduced variation into results and hampered interpretation. For example, important elements such
49 as post-farm transport and avoided emissions were inconsistently included, and reporting of results used varied terminology and breakdowns of
50 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.
- 53 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
54 or fewer), meaning that there were few replicates for each type of UA system and set of LCA modeling decisions.

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

60 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
61 doing so we address the various gaps in the existing literature. Namely we included a large sample size of functioning urban farms/gardens covering
62 two regions and climates and then assessed their environmental performance using robust primary data and a consistent, transparent modeling
63 approach. The overall objectives of this study were twofold. The first goal was to perform a comprehensive LCA of diverse UA, based on primary
64 data, to contribute to the knowledge around its environmental performance. In particular, we seek to explain the relative environmental performance of
65 diverse types of UA. The second goal was to simultaneously inform and demonstrate methodological guidelines to support more systematic and
66 consistent LCAs of UA. This was developed through an iterative process where the guidelines were informed by work with case studies (presented
67 here), and the case studies here adhered to the guidelines.

68 We found that infrastructure and irrigation had large contributions to several impact categories, followed by compost production and peat from
69 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
70 area basis. Conversely, farms with more social objectives or communal management had lower impacts on an area basis, and displayed examples of
71 both high and low impacts per kilogram of produce grown. Adhering to the UA LCA guidelines allowed us to perform a comprehensive and
72 transparent LCA, with consistent results. Our findings indicate which processes urban farmers should focus on to reduce their environmental impacts,
73 and highlight which types of UA may incur the least environmental tradeoffs for different objectives.

74 2 Methods

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

77 2.1 Geographic context

78 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
79 Area (cities of San Francisco, Berkeley, and El Sobrante). These locations were chosen because of their different population densities (affecting the
80 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),
81 which are detailed for each location in the Supplementary Material. UA is an established practice in both locations, going back hundreds of years in
82 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

85 The coded names and main characteristics of the farms/gardens are presented in Table 1, including their physical attributes and some primary data
86 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
88 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.

90 The degree of social engagement – interaction with local communities – was defined by the researchers through site visits. Low-engagement farms
91 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
92 were important. Medium-engagement farms welcomed specific outside groups—usually students—and farming was done mostly by employees and
93 with the help of volunteers. High-engagement farms encouraged participation from the public, were farmed roughly equally by both employees and
94 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
95 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
96 the Supplementary Material).

97

		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

99 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
100 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
101 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

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

113 2.4 Life cycle assessment

114 2.4.1 Goals

115 The goals of this LCA were to 1) quantify the environmental impacts of diverse types of UA
116 in different locations with different motivations; 2) to find what explains the relative
117 environmental performance of diverse types of UA, by looking at trends, hotspots, system
118 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
- 127 • 1 m² of area under food production for one year.

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

- 129 • 1 m² of total farm area for one year and
- 130 • 1 m² of green area for one year (i.e., area for food production plus ornamental or
131 native plants).

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

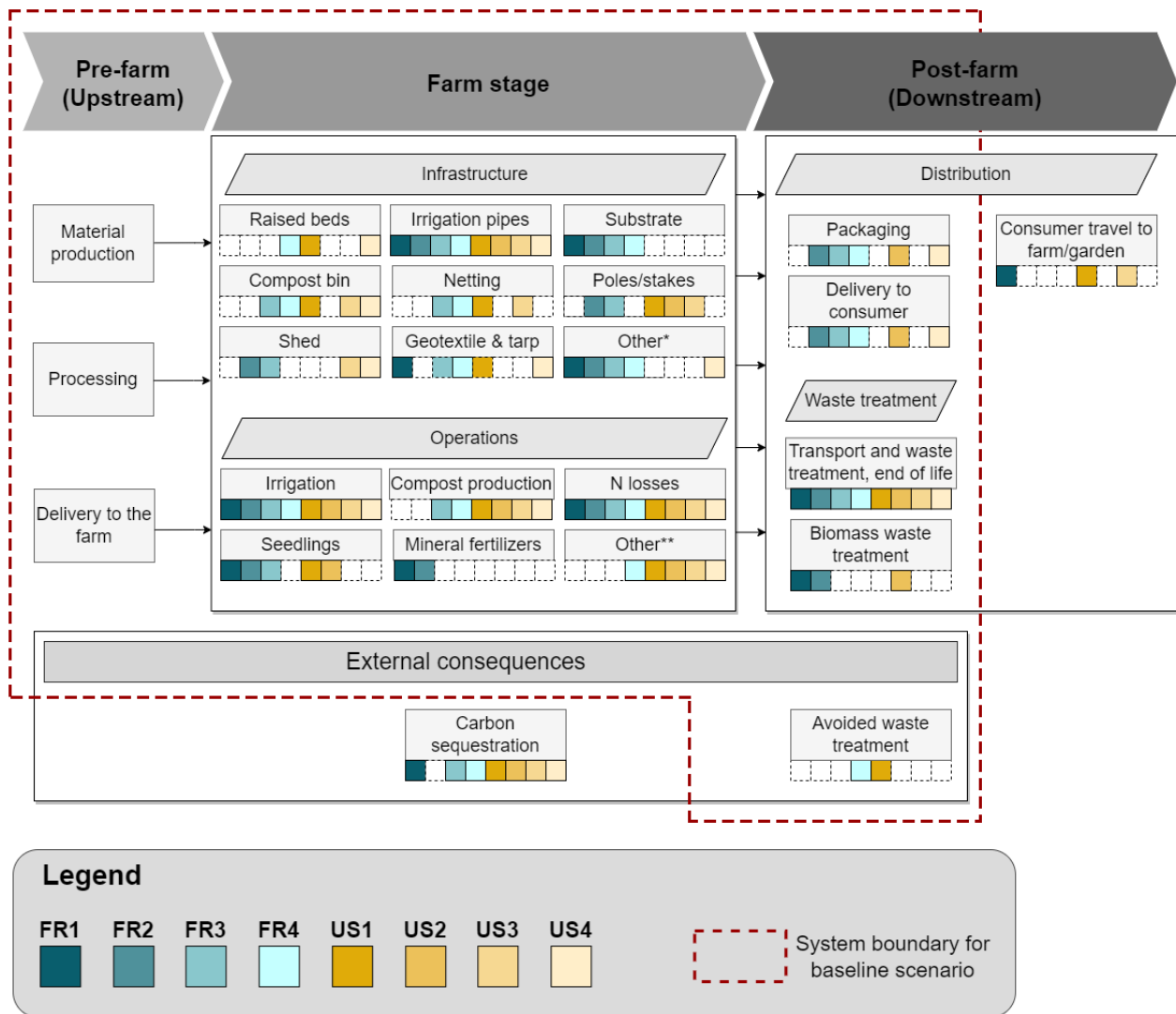


Figure 1 The process diagram shows what was included in the system boundaries of the LCA for each farm. Colored squares placed below a process indicate that the process was included for that farm, and a white square indicates that it was not relevant for that farm. Processes outside the red dashed line—carbon 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

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

145 Figure 1 shows which processes were considered for which farm. Other infrastructure for FR1
 146 was steel frames for vertical growing structures. FR2: hydroponics plastic structure,
 147 aeroponics plastic towers, large vat for fertigation mixing, steel tables, and weight distributing
 148 tiles. FR3: cables and sand bags. FR4: greenhouse. US4: greenhouse, wood tables. Other
 149 supplies for FR4 were beer brewing residues, mushroom compost, and straw. US1: mushroom

150 compost. US2: fuel for a tractor, crushed oyster shells, and feather meal. US3: wood chips,
151 crushed oyster shells, feather meal, alfalfa meal, and kelp meal. US4: manure, pesticide
152 (Sluggo©), fish emulsion, kelp meal, feather meal.

153 2.4.4 Life cycle impact assessment

154 We used the Product Environmental Footprint (PEF) impact assessment method, version 2.0
155 (European Commission, 2017). We included six impact categories that are particularly
156 relevant for agricultural production: climate change (kg CO₂ equivalent), water scarcity (m³ of
157 water deprived), land degradation (Pt, a dimensionless soil quality index, combining measures
158 of erosion resistance, mechanical filtration, physicochemical filtration, groundwater
159 regeneration, and biotic production (Bos et al., 2016)), energy demand (MJ), marine
160 eutrophication (kg N eq.), and terrestrial eutrophication (mol N eq.) Results for other impact
161 categories and other impact assessment methods (ReCiPe 2016, TRACI 2.1, CML-IA
162 baseline V3.05, and ILCD 2011 V1.10) are available in the Supplementary Material to
163 support comparisons with future studies.

164 2.4.5 Sensitivity and uncertainty analyses

165 We performed sensitivity analyses to test the impact on the results of modeling decisions that
166 we 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:

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

175 2.5 Creation and demonstration of methodological guidelines

176 Because the of the varied methods and decisions in available UA LCAs, we developed
177 methodological guidelines to support more consistent and complete UA LCAs (Dorr et al.,
178 2022a [under preparation]). Many similar methodological reflections and adaptations have
179 been done to improve LCAs of rural agriculture (Audsley et al., 1997; Caffrey and Veal,
180 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:

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

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

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

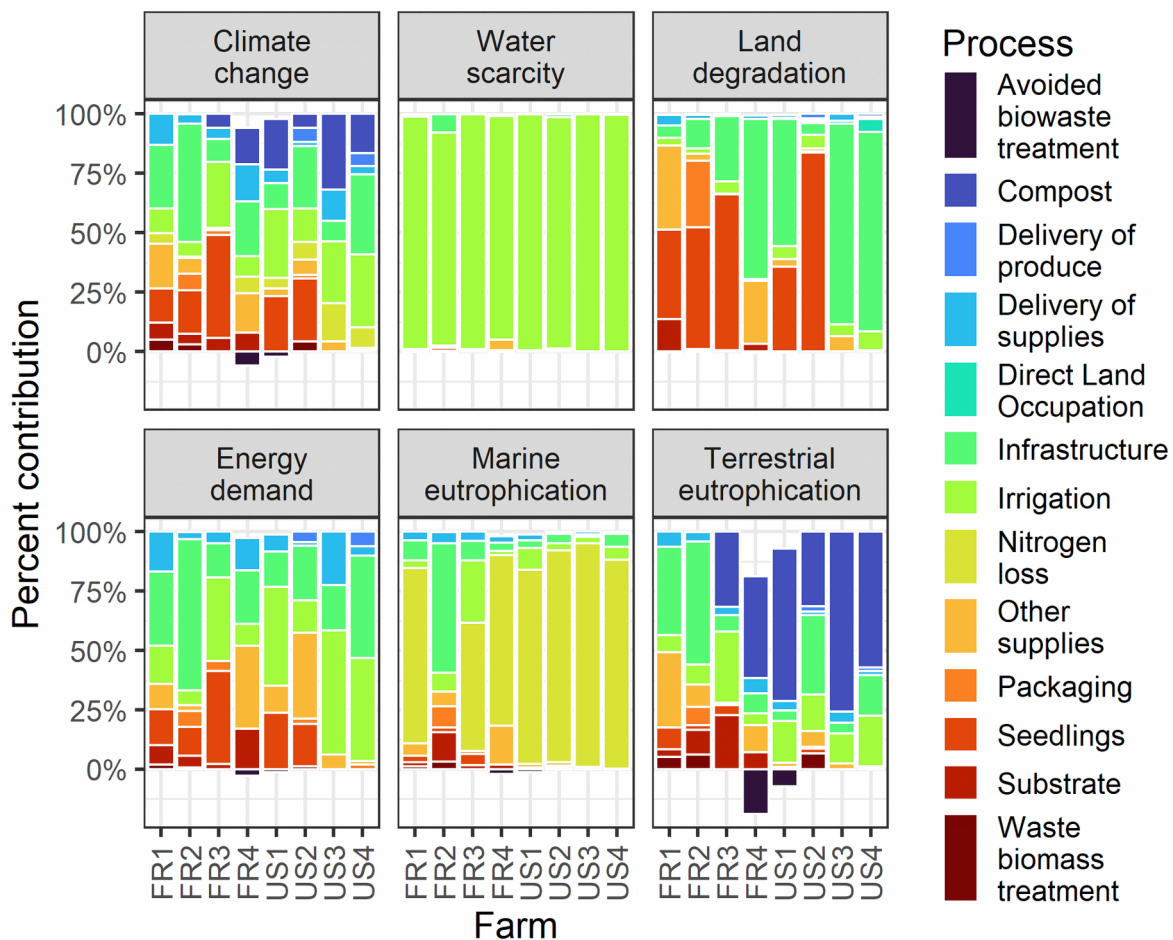


Figure 2 The relative contribution of each process category to each impact category is presented. More details on what is included in each category are provided in the Supplementary Material.

224 The next section presents a process contribution analysis, detailing which inputs and
 225 processes accounted for large impacts. The following section describes general trends in
 226 impacts among the farms. Raw results, including values for all assessed impact categories, are
 227 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

231 Infrastructure had the largest average contribution to land degradation with an average of 43%
 232 (mostly related to wood use), and for climate change it contributed an average of 24%. It was
 233 especially impactful for FR2, where it accounted for 50% of climate change impacts and 64%
 234 of energy resource use. Impacts in these categories for FR2 were driven by the significant
 235 amounts of plastic for the hydroponic structures and the aeroponic towers. US4 also had large
 236 infrastructure impacts, mostly due to the shipping container they used as a shed. Of note is the
 237 importance of this single piece of infrastructure, even though it was severely discounted for
 238 the farm, with a long lifespan of 50 years and half of the impacts since it was reused. At US4,
 239 infrastructure contributed to 34% of climate change, 84% of land degradation, and 43% of
 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
244 contributed on average 19% of climate change impacts, but this was as high as 26-31% for
245 US1, US3, US4, and FR3. It contributed 27% to energy resource use on average, and this was
246 52, 44, and 43% for US1, US3 and US4, respectively. Irrigation included both tap water
247 (delivered from a city water treatment plant) and on-farm electricity for pumping, but the
248 majority of impacts for most impact categories came from tap water. This points to the
249 potential benefits of substituting energy intensive municipal water sources for alternatives,
250 such as harvested rainwater.

251 3.1.3 Compost

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

259 3.1.4 Nitrogen losses

260 Nitrogen losses from nitrate leaching drove marine eutrophication, and contributed between
261 54 and 94% of impacts (on average 80%). This was excluding FR2, which we assumed had
262 no nitrate leaching due to recirculation of the fertigation water. There was large uncertainty
263 here regarding the actual fate of leached nitrate in urban wastewater systems and the emission
264 factor of leached nitrate. We used a standard emission factor based on the amount of nitrogen
265 applied, which is a rough approximation for rural agriculture, and is surely more uncertain for
266 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%
269 of climate change impacts, with an average of 6.4%. The largest contributions were from
270 US3, where emissions from compost and chicken feathers contributed almost equally.
271 Chicken feathers have high nitrogen content (about 16% of dry matter), compared to 0.9% for
272 compost assumed here. Indirect N₂O emissions from leaching of nitrogen and subsequent
273 volatilization were responsible for about 30% of these emissions, and direct emissions were
274 responsible for 70%.

275 3.1.5 Seedlings

276 For the five farms that purchased seedlings, seedling production was important for land
277 degradation (average 55% contribution), climate change impacts (25%), and energy use
278 (22%). Peat moss is typically the main substrate for the seedlings according to Ecoinvent and
279 our own observations at the farms, and its production was responsible for most of the impacts
280 from seedlings in all of these categories. For the three farms that started seedlings onsite, we
281 were not able to disaggregate the compost and water used for seedlings, but they were
282 accounted for in the farm-level totals.

283 3.1.6 Delivery of supplies and materials

284 Delivering supplies and materials to the farms contributed an average of 9% of energy
285 demand and 8% of climate change impacts. This process was most impactful at FR1, FR4,
286 and US3. For FR1, seedlings represented 75% of the delivery amounts (measured as
287 weighted-distance, or kilograms transported multiplied by distance). They purchased

288 seedlings from two suppliers 215 and 360 km away, 17 times per year. For US3, most of the
289 delivery amounts came from compost delivery (78%), and for FR4 this was delivery of
290 compost amendments (62%) and substrate for the initial application (28%). These
291 contributions were especially large because compost was delivered from rather far away for
292 these two farms: 56-58 km, compared to other farms with an average of 17 km.

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

297 3.1.7 Other supplies

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

309 3.1.8 Substrate

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

318 3.1.9 Remaining processes

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

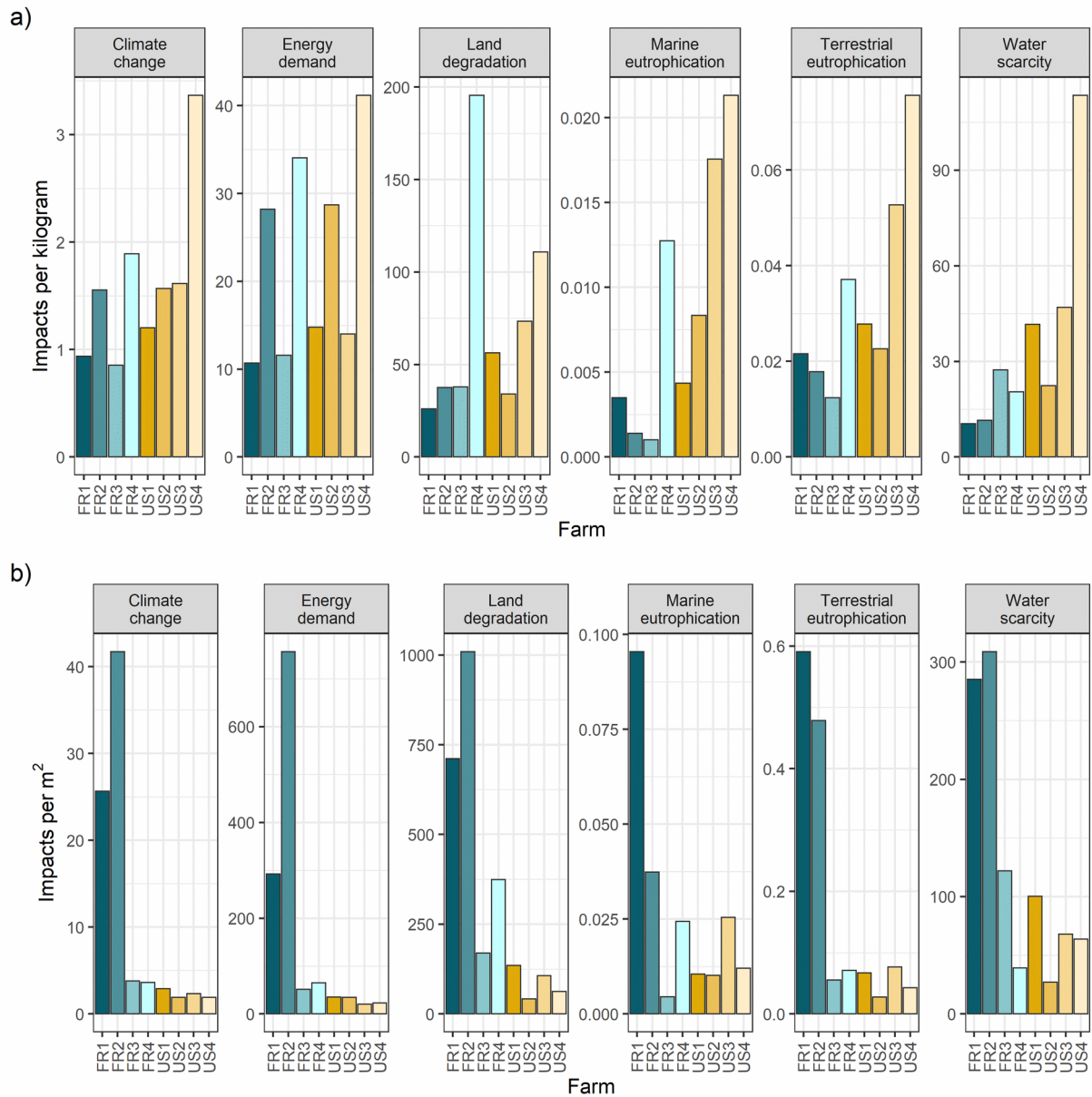


Figure 3 Results are shown for eight impact categories with a functional unit of a) kilograms of crop grown and b) m² of food growing area occupied per year. The six impact categories considered were: climate change (kg CO₂ eq), water scarcity (m³ deprived), land degradation (Pt), energy use (MJ), marine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

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

	FR1		FR2		FR3		FR4		US1		US2		US3		US4	
	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 m² 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
328 choice of functional unit. Results per kilogram of food were typically within one order of
329 magnitude across the farms. For instance, climate change impacts per kilogram of crop ranged
330 from 0.85 to 3.4 kg CO₂ eq., with a mean and standard deviation of 1.6±0.79 kg CO₂ eq.
331 (Figure 3a). Energy demand ranged from 11 to 41 MJ/kg, with a mean and standard deviation
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
334 performance of the farms shifted based on indicator, but US4 had the most environmentally
335 intensive food production across five of six indicators because of its low level of food
336 production (Table 2). FR4 was the most intensive for land degradation because of their large
337 use of land-based inputs such as wood for raised beds and straw for mulch.

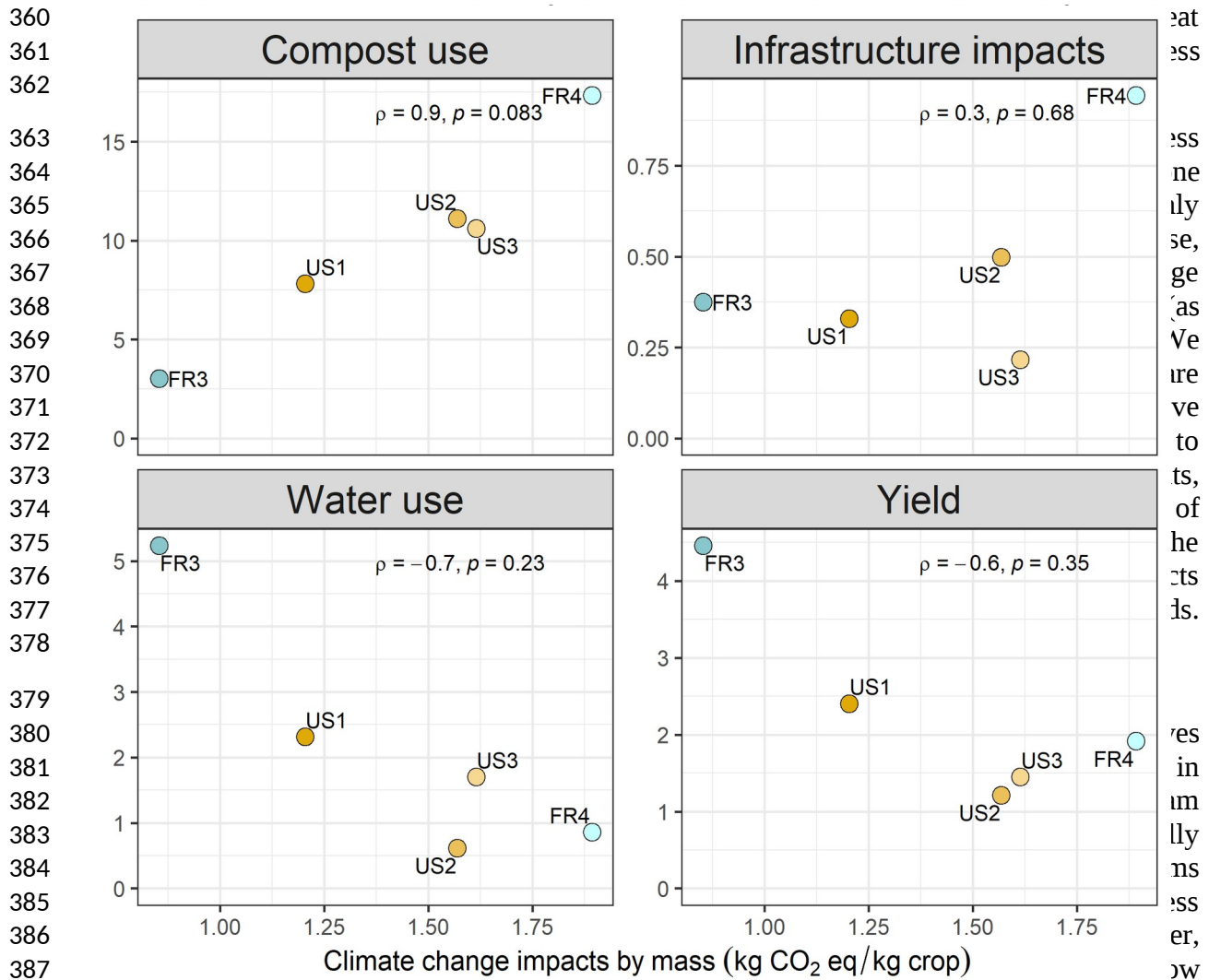
338 Conversely, there were orders of magnitude differences across most impact categories when
339 using an area-based assessment. FR1 and FR2 had significantly higher impacts than the other
340 farms because these two farms intensively used space with vertical growing structures to
341 increase yields (Figure 3b). For example, climate change impacts per m² of food cultivation
342 area were 26 and 42 kg CO₂ eq./m² for FR1 and FR2, and the other farms had a mean and
343 standard deviation of 2.7±0.84 kg CO₂ eq./m². As explained below, yield primarily explains
344 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

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

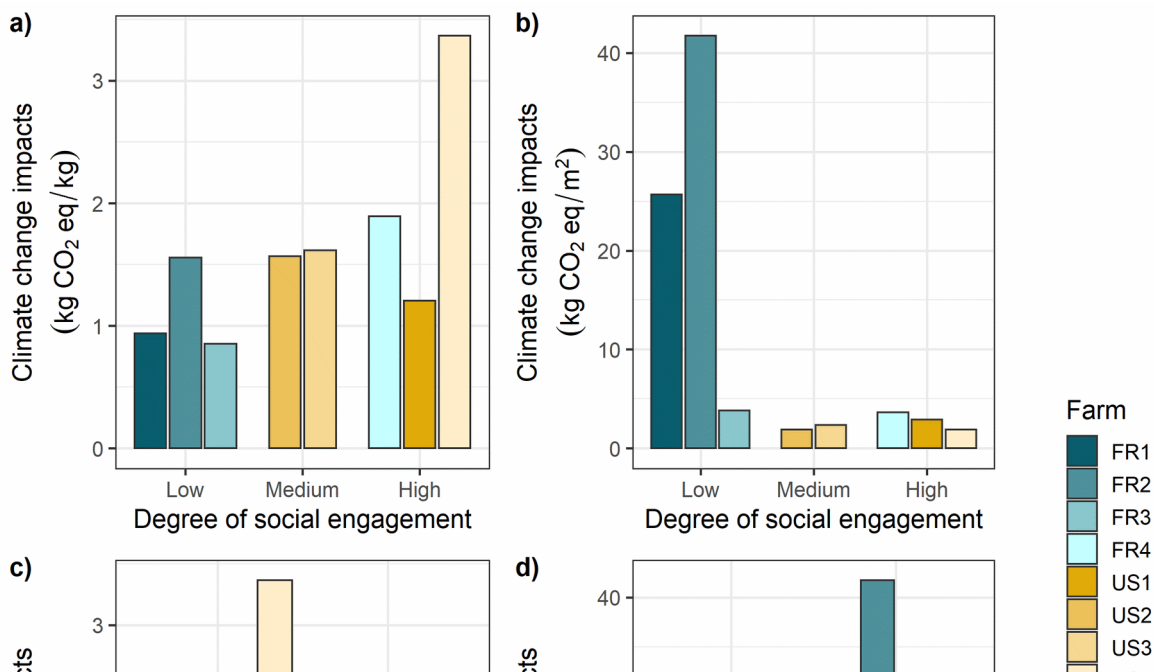
355

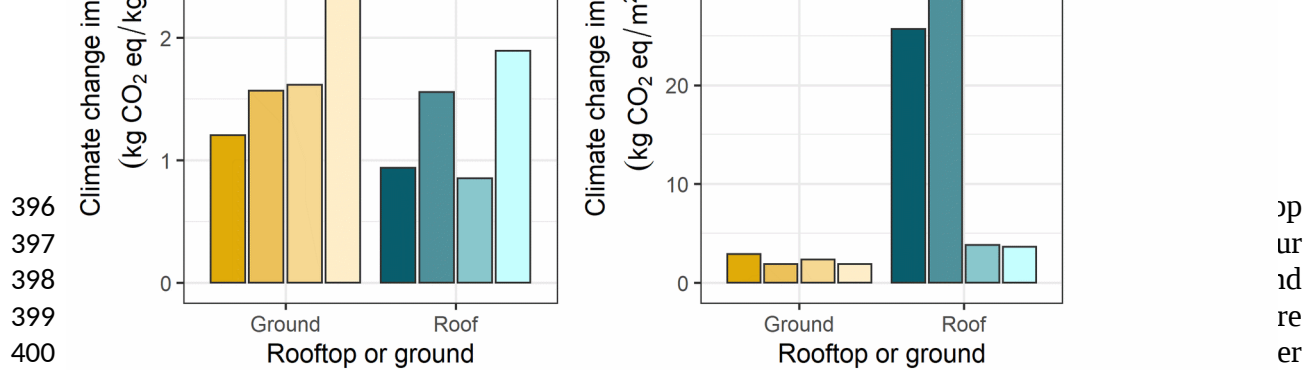
356 The other five farms had intermediate yields, similar to rural agriculture and other open-air
357 UA (1.2-4.5 kg/m²) (Dorr et al., 2021a), and had variable rankings in environmental impacts
358 related more to inputs and practices than yield. For example, FR4 had the highest land-use
359 impacts with a mass-based FU, mostly due to their use of wood for raised beds and straw for



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, it 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.

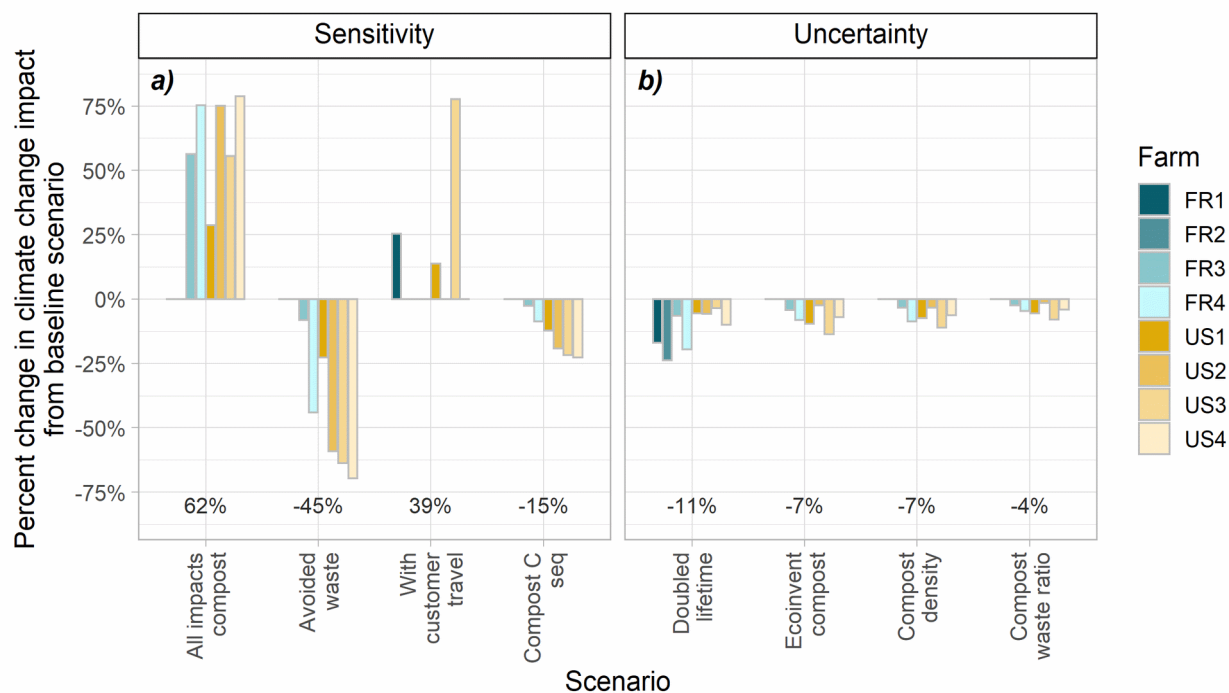


Figure 6 a) Sensitivity and b) uncertainty analyses were done to test the effect of different system modeling decisions and parameter values. Bars show the percent change from the baseline scenario's climate change impacts for each farm, and the value shown above the x-axis is the average percent change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

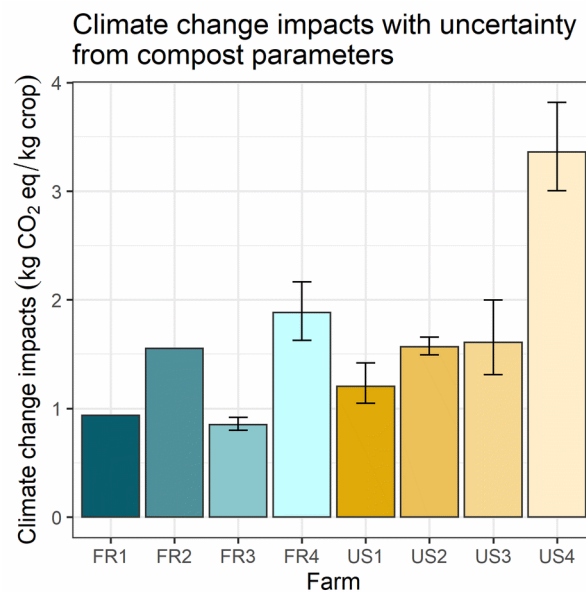
427 The largest changes in impact came from the scenario where purchased compost was given
 428 100% of the impacts of composting, as is frequently done in agricultural LCAs, rather than
 429 7% based on economic allocation in the baseline scenario (Adewale et al., 2016; Bartzas et
 430 al., 2015). Climate change impacts increased an average of 62%, and compost contributed to
 431 an average of 40% of climate change impacts. In the next scenario, we subtracted
 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
 434 these credits, but we wanted to explore the extent of its importance because this is a major
 435 proposed benefit of UA. Climate change impacts were reduced by an average of 45% for the
 436 six farms that used compost, and the hydroponics system FR2 emerged with largest impacts
 437 per kilogram. The next scenario included customer travel to the farm to purchase or harvest
 438 produce, and was not included in the baseline scenario due to high uncertainty in customer
 439 travel behaviors. Climate change impacts increased by 14%, 25%, and 78% for the three
 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
 442 thanks to carbon sequestration from annual compost amendments and resulted in reductions
 443 of 12-23% for the four US farms and 3-9% for the two French farms using compost. A more
 444 detailed presentation and interpretation of the sensitivity analyses are in the Supplementary
 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

453 change impacts by up to 24% for FR2, and FR1 became the farm with the lowest climate
 454 change impact per kilogram of produce. Land degradation impacts decreased 21% on average.
 455 The remaining uncertainty analyses were related to compost production, due to the high
 456 uncertainty in its parameters and inventory data. First, we modeled a scenario using emission
 457 factors for compost production from the Ecoinvent database (a common source of compost
 458 inventory data in LCA studies), which resulted in decreases in climate change impacts of 2-
 459 14%. Next, we performed a Monte Carlo simulation with 1,000 runs to test uncertainty in
 460 emission factors of methane and nitrous oxide from compost production, compost density,
 461 and the mass balance of organic waste input to compost output. With modest amounts of
 462 uncertainty in the distributions for these four parameters, the overlapping 95% confidence
 463 intervals suggest that several farms can be considered to have the same level of potential
 464 impacts (Figure 7). More details from the uncertainty analysis are in section 6 of the
 465 Supplementary Material.



466 Figure 7 We performed Monte Carlo simulations to test the uncertainty of four compost parameters:
 467 density, the waste-to-compost ratio, CH₄ emission factors, and N₂O emission factors. The figure shows
 468 the climate change impacts of the baseline scenario with error bars representing the 95% confidence
 469 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
 473 et al., 2021a). FR1 and FR2, with intensive vertical growing systems, were exceptionally
 474 productive. FR3 had high yields compared to similar types, likely because of its commercial
 475 nature and focus on food production. US4 had very low yields, which could be attributed to
 476 several factors: the farm manager was new and mostly experienced with ornamental
 477 production; the site was in San Francisco, which is notoriously cloudy, even compared to
 478 nearby cities; slow replanting after harvest cycles; and growing food was secondary to
 479 educational activities.

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

484 appropriate local characterization factors (see section 10.8 in the Supplementary Material for
485 details). Water use for all farms studied here was larger per kilogram and per m² than rural
486 agriculture in France and California growing similar vegetables (Table 3). UA in other studies
487 also shows lower water use than what we measured in the case studies, although there is large
488 variability.

489 Climate change impacts per kilogram for our farms were comparable to the averages from the
490 literature for UA, although on the high end (Dorr et al. 2021a). The average impact of the
491 seven open-air, soil-based farms was 1.6 kg CO₂ eq/kg of crop, compared to an average of 1.2
492 kg CO₂ eq/kg for similar farms in the literature (Table 3). The only outlier was US4, with a
493 climate change impact of 3.4 kg CO₂ eq/kg of crop. Regarding the open-air hydroponics farm
494 FR2, impacts per kilogram were lower than similar farms summarized in the literature, which
495 had an average of 2.1 kg CO₂ eq/kg. FR2 also used aeroponics, which may have lowered
496 impacts by efficiently using small amounts of sprayed fertigation. Climate change impacts per
497 kilogram for all farms were on average four times larger than the averages for similar baskets
498 of rural-grown vegetables summarized in the review by Clune et al. (2017). The coefficient of
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
501 results, where farms were still very diverse, than there was between values in the literature.
502 On an area basis, FR1 and FR2 had much higher impacts than other UA systems, but the other
503 six farms had impacts within the expected range. In contrast to other open-air, soil-based UA,
504 our farms had relatively large climate-change impact contributions from infrastructure (which
505 was typically more impactful for indoor farms), and small contributions from delivery of
506 crops (due to the prevalence of delivery by walking or bicycling) (Dorr et al., 2021a). We
507 found similarly high impacts from delivering supplies to farms, such as compost and soil
508 amendments, further highlighting this as a process to pay attention to.

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.

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

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
527 UA sites can provide lessons/insight for future LCAs (Dorr et al., 2022a [under review]). We
528 identified processes that were important and should be regularly included with high-quality
529 primary data (infrastructure, irrigation, compost, and peat-containing seedlings), and
530 processes containing considerable uncertainty. Compost emerged as a sensitive and
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
533 territorial LCA were identified, such as benefits from composting as an alternative waste
534 treatment, or customer travel to the farm. Our results reiterated the importance of using
535 multiple functional units to highlight strengths of different types of farms and farming
536 practices, as found in other agriculture LCAs (van der Werf et al., 2020). Overall, following
537 the guidelines strengthened this LCA, but further improvements could be made. More
538 rigorous data collection that tracked inputs per crop would allow for crop-level results, which
539 would be more comparable to produce from conventional, rural agriculture. Furthermore, our
540 comparisons to conventional food products were limited compared to the guideline
541 recommendations, because we excluded transport to the consumer (i.e. “last mile”) and

542 seasonality for conventional products which can influence results (Plawecki et al., 2014). As
543 mentioned in the guideline, accounting for these requires complex modeling and large
544 assumptions, which were outside the scope of this work.

545 Our study also highlights some of the practical difficulties of collaborating with urban farms.
546 A major difficulty in data collection was the dynamic nature of UA: farm layouts were
547 frequently changing, new cultivation areas were created, and new farming practices were
548 tested. This made it difficult to capture representative practices over one year. Indeed, where
549 we have data from multiple years, yield varied by up to 50% annually. There was a high
550 turnover rate among the farmers and managers, who were our main partners for the studies.
551 For half of the farms, the main farmer or point-person for data collection left during the 1-2
552 years of collaboration. This raised issues of inconsistency in farming practices, data collection
553 methods, and motivation/willingness to participate in the study. Another difficulty was
554 incomplete record keeping: it was not uncommon for data on harvest or supplies to go
555 unrecorded. Farmers were often not used to collecting such information, and this was manual
556 and intensive data collection which required substantial coaching and support by researchers.
557 Difficulties in data collection with UA have been widely reported in studies aiming to
558 characterize the agricultural practices of UA, let alone perform LCAs (McDougall et al.,
559 2019; Whittinghill and Sarr, 2021). We recommend outlining data collection expectations
560 with farmers/gardeners in the beginning of the project, and adapting to whatever type and
561 quality of data can be collected. More recommendations for primary data collection are
562 included in the guidelines. Using these adaptable measurement methods and regularly
563 checking in with farmers allowed us to obtain a satisfactory quality of data, despite the
564 challenges.

565 4.3 Lessons for improving environmental performance of urban agriculture

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

585 For policy makers, the environmental performance of different farms can profile which types
586 of UA to promote based on different objectives: if food production is the goal, for example, to
587 improve food security of a city, then medium-tech farms (such as FR1 and FR2) or
588 professional farms similar to the ones we included can optimize growing food with lower
589 impacts per kilogram. If food production is less important than education or social benefits,
590 then low-tech farms are better to minimize impacts per m² per year regardless of how much

591 food is grown. The importance of infrastructure in our results suggests that implementing UA
592 as a transitional land degradation can impart high environmental costs. Temporary urban
593 farms should use minimal infrastructure or use recycled or reused/repurposed material as
594 much as possible. Finally, our results suggest that UA uses substantial amounts of water,
595 although it must be evaluated how important this water use would be compared to what the
596 whole city consumes.

597 **5 Conclusion**

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

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

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

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