

1 Comparing the Carbon Footprint of 2 Urban and Conventional Agriculture

3 Authors:

4
5 Jason K. Hawes^{a†*}, Benjamin P. Goldstein^{a,b†}, Joshua P. Newell^a, Erica Dorr^c, Silvio Caputo^d, Runrid
6 Fox-Kämper^e, Baptiste Grard^{c,f}, Rositsa T. Ilieva^g, Agnès Fargue-Lelièvre^c, Lidia Ponizy^h, Victoria
7 Schoenⁱ, Kathrin Specht^e, Nevin Cohen^j

8 9 Affiliations:

10 ^a School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, USA 48108

11
12 ^b Department of Bioresource Engineering, McGill University, Ste-Anne-de-Bellevue, Quebec, Canada

13
14 ^c University Paris-Saclay, INRAE-AgroParisTech, UMR SAD-APT, Palaiseau, France

15
16 ^d School of Architecture and Planning, University of Kent, Canterbury, UK

17
18 ^e ILS Research, Dortmund, Germany

19
20 ^f ISARA, Agroecology and Environment research unit, Lyon, France

21
22 ^g CUNY Urban Food Policy Institute, CUNY Graduate School of Public Health & Health Policy, The City
23 University of New York, New York, NY, USA

24
25 ^h Faculty of Human Geography and Planning, Department of Integrated Geography, Adam Mickiewicz
26 University, Poznań, Poland

27
28 ⁱ Centre for Agroecology, Water, and Resilience (CAWR), Coventry University, Coventry, UK

29
30 ^j Graduate School of Public Health and Health Policy, The City University of New York, New York, NY,
31 USA

34 † Hawes and Goldstein contributed equally to this manuscript.

35 * Corresponding author

36 Corresponding author

37 Corresponding author: Jason K Hawes, jkhawes@umich.edu or jasonkhawes@gmail.com

38 Author contributions

39 Jason K. Hawes - Conceptualization; Methodology; Formal analysis; Data curation; Writing - original
40 draft; Writing - review and editing; Validation

41 Benjamin P. Goldstein - Conceptualization; Methodology; Formal analysis; Data curation; Writing -
42 original draft; Writing - review and editing; Validation

43 Joshua P. Newell - Conceptualization; Resources; Writing - original draft; Writing - review and editing;
44 Supervision; Funding Acquisition; Project administration

45 Erica Dorr - Conceptualization; Methodology; Investigation; Data curation; Writing - original draft;
46 Writing - review and editing

47 Silvio Caputo - Conceptualization; Investigation; Resources; Writing - review and editing

48 Runrid Fox-Kämper - Conceptualization; Investigation; Resources; Writing - review and editing

49 Baptiste Grard - Conceptualization; Investigation; Writing - Review & Editing

50 Rositsa T. Ilieva - Conceptualization; Investigation; Writing - Review & Editing

51 Agnès Fargue-Lelièvre - Conceptualization; Investigation; Resources; Writing - review and editing

52 Lidia Ponizy - Conceptualization; Investigation; Resources; Writing - review and editing; Project
53 administration

54 Victoria Schoen - Conceptualization; Investigation; Writing - review and editing

55 Kathrin Specht: Conceptualization; Investigation; Resources; Writing - review and editing

56 Nevin Cohen - Conceptualization; Investigation; Resources; Writing - review and editing

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67 **Abstract**

68 Urban agriculture (UA) is a widely proposed strategy to make cities and urban food systems more
69 sustainable. However, its carbon footprint remains understudied. In fact, the small number of case
70 studies suggest that UA may be worse for the climate than conventional agriculture. This is the first
71 large-scale study to resolve this uncertainty across cities and types of UA, employing citizen science at
72 73 UA sites in Europe and the United States to compare UA products to food grown on conventional
73 farms. The results reveal that one serving of food from UA is six times as carbon intensive as
74 conventional agriculture (420 g vs 70 g CO₂ equivalent). Some UA crops (e.g., tomatoes) and sites (e.g.,
75 25% of individually-managed gardens), however, outperform conventional agriculture. These exceptions
76 suggest that cultivating crops that are conventionally high-carbon, increasing infrastructure lifespans,
77 and enhancing circularity can contribute to climate-friendly UA.

78 Urban agriculture (UA) (i.e., growing food in and around cities) is intended to make cities more
79 sustainable, healthy, and just. Despite strong evidence of social and nutritional benefits from UA,
80 environmental claims are not well-supported, particularly how the environmental footprint of UA
81 compares to the conventional agriculture it could supplant.¹ As interest in UA increases,² policymakers,
82 citizens, and scientists must explore new avenues to make UA beneficial for people *and* planet.

83 How UA compares with conventional agriculture depends on crops, growing systems, and
84 climate.³ It is unclear what forms of UA are environmentally friendly since case studies of individual
85 cities typically only assess one form of UA.⁴⁻⁶ Environmental footprints of UA remain scarce, and most
86 published to-date have prioritized high-tech, energy-intensive forms of UA¹ (e.g., vertical farms, rooftop
87 greenhouses) in lieu of open-air, soil-based forms (referred to here as “low-tech UA”) which comprise
88 the bulk of food-growing spaces in cities.^{7,8} A recent systematic review found that only a third of
89 environmental assessments assessed low-tech UA.¹

90 And while existing research suggests that low-tech UA may produce total carbon emissions per
91 serving of vegetables similar to conventional agriculture,^{1,3} these findings are undermined by numerous
92 shortcomings. Sample sizes are often small.¹ Studies with large sample sizes only consider amounts and
93 types of resources used and not environmental impacts (e.g., carbon emissions).⁹⁻¹¹ When impacts are
94 considered, studies report them per kilogram of total harvest and not per crop or food-group.¹ Lastly,
95 low data representativeness is common. For instance, some studies incorrectly assume the only
96 difference between UA and conventional agriculture is transport distance.^{12,13} Taken as a whole, there
97 remain serious knowledge gaps with respect to the environmental performance of low-tech UA.

98 This paper addresses these gaps through carbon footprinting of low-tech UA, covering 73 sites in
99 France, Germany, Poland, the United Kingdom, and the United States using data collected through
100 citizen-science.^{14,15} We assess the carbon footprint across the lifecycle of producing food at three types
101 of low-tech UA; urban farms (professionally managed, focused on food production), individual gardens

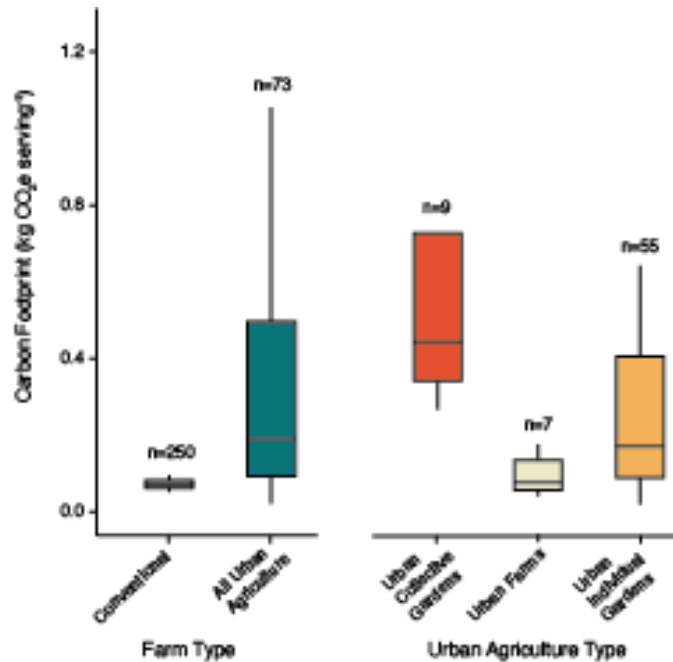
102 (small plots managed by single gardeners), and collective gardens (communal spaces managed by
103 groups of gardeners). We estimate climate change impacts and synthetic nutrient footprints of food
104 from UA and compare these to conventional agricultural products sold in each of our five countries.

105 By assessing actual inputs and outputs on UA sites, we are able to assign climate change impacts
106 to each serving of produce (i.e., recommended grams of a crop consumed to align with dietary
107 guidelines). This dataset reveals that UA has higher carbon emissions per serving of fruit or vegetable
108 than conventional agriculture irrespective of country. To promote UA that is more broadly sustainable -
109 climate-friendly, resource efficient, *and* socially beneficial – we analyze key trends across our sample of
110 UA sites and argue that policymakers and UA practitioners should maximize the lifespan of farm
111 infrastructure, promote urban waste streams as inputs, and use farms as sites for education, leisure, and
112 community building.

113 **Results and discussion**

114 **Low-tech UA has a carbon footprint six times higher than** 115 **conventional agriculture**

116 Food produced at our UA study sites is more carbon-intensive than food produced on
117 conventional farms (Figure 1). To reach this conclusion, we compare food produced on UA sites to
118 conventional crops, produced both domestically and abroad, considering on-farm impacts, processing,
119 and transportation to the city (see Methods for details). On average, UA emits 0.42 kilograms carbon
120 dioxide equivalents (kg CO₂e, standard error [SE] = 0.07 kg CO₂e) per serving (equivalent to $\mu = 3.12$ kg
121 CO₂e/kg vegetables, SE = 0.53 kg CO₂e/kg), six times higher than the 0.07 kg CO₂e per serving (SE = 0.005
122 kg CO₂e per serving; $\mu = 0.47$ kg CO₂e/kg vegetables, SE = 0.032 kg CO₂e/kg) of conventional produce (p-
123 value << 0.001).



124

125 **Figure 1. The carbon footprint of conventional vs urban agriculture.** Results shown per serving of
 126 produce as defined by the United States Department of Agriculture. Boxplots reflect the median and
 127 interquartile range of GHG impact, and UA sites above 1.0 kg CO₂e/serving are removed to improve
 128 legibility (See Figure S1 for full results). Two UA sites could not be classified as Collective, Individual, or
 129 Farm, so only 71 sites are included in the right panel.

130

131 On average, all forms of UA studied here are more carbon intensive than conventional
 132 agriculture, though this difference is only statistically significant for collective gardens (p-val = 0.02) and
 133 individual gardens (p-val < 0.001). Collective gardens are the most carbon-intensive form of UA ($\mu = 0.81$
 134 kg CO₂e/serving, 7.50 kg CO₂e/kg). Individual gardens and urban farms are similar on average (both
 135 produce 0.34 kg CO₂e/serving), but variation among urban farms leaves them statistically
 136 indistinguishable from conventional farms (p-val = 0.33). In fact, most urban farms are carbon-
 137 competitive with conventional farms (median = 0.08 kg CO₂e/serving when one particularly carbon-
 138 intensive urban farm is excluded from the analysis). These findings mirror literature trends, which

139 identify non-commercial UA as more carbon intensive than commercial UA except when the latter use
140 energy intensive indoor farming.¹⁶

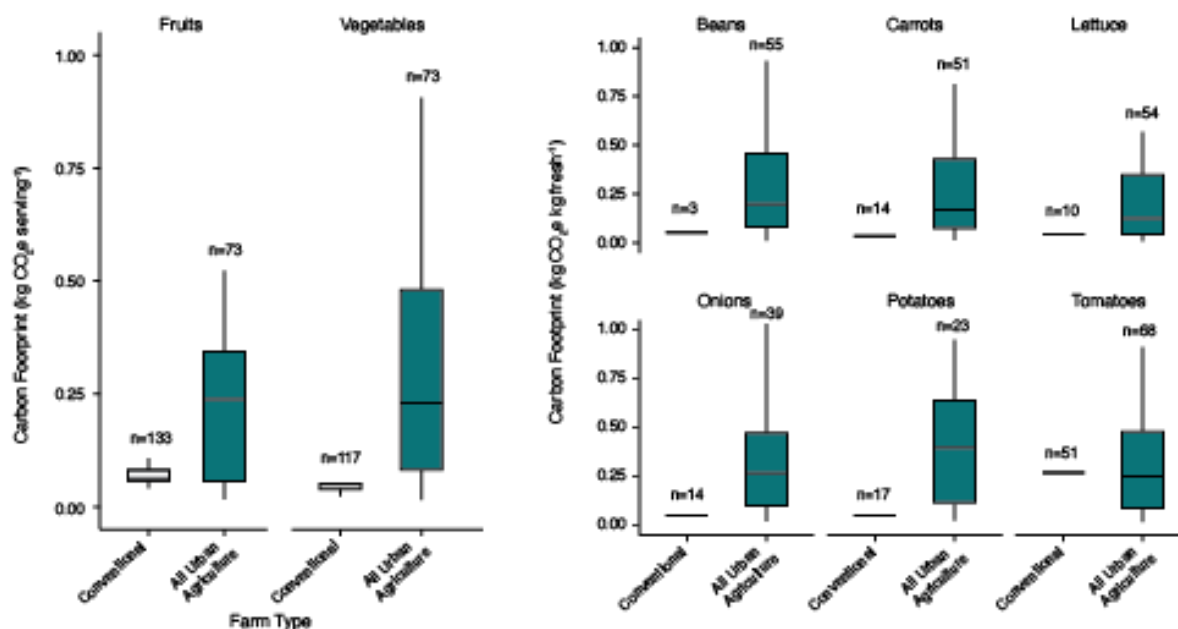
141 The carbon intensity of UA differs by country due to variations in forms of UA practiced. For
142 example, UA carbon impacts are lowest in Poland (N = 35), where our sample of gardens was dominated
143 by individual gardens, and highest in the UK (N = 6), where case studies are mostly collective gardens.
144 Nonetheless, the average vegetable at the local grocer outperforms the average vegetable on UA sites in
145 all five countries (Figure S2).

146 Select UA crops have similar carbon intensity to conventional 147 agriculture

148 We allocated food impacts between crops using nutritional content, calorie content, economic
149 value and mass (see Methods). Method of allocation did not affect directionality of results (see Table
150 S1), and results presented in-text are averaged across allocation schemes. Carbon intensity per serving
151 of fruit (N = 73) is higher in low-tech UA ($\mu = 0.47$ kg CO₂e, 4.07 kg CO₂e/kg) than conventional
152 agriculture ($\mu = 0.07$ kg CO₂e, 0.49 kg CO₂e/kg). The same is true of vegetables (N = 73; $\mu = 0.46$ vs. 0.08
153 kg CO₂e per serving, 3.48 vs. 0.52 kg CO₂e/kg). Similarly, the most popular crops consumed in our five
154 countries are more carbon intensive when grown using low-tech UA (Figure 2).

155 However, selected crops are carbon competitive with conventional agriculture. Competitiveness
156 depends on growing practices, both in urban and conventional settings. For example, the median urban
157 tomato (0.17 kg CO₂e/serving) outperforms conventional tomatoes ($\mu = 0.27$ kg CO₂e/serving). While on
158 average urban tomatoes are more carbon-intensive than conventional tomatoes (p-val = 0.02), this low
159 median demonstrates UA sites often outperform conventional tomato growing. This is largely due to the
160 carbon-intensive greenhouses that supply most tomatoes to our case cities, as well as less than optimal
161 distribution patterns of the crop from farm to city.¹⁷⁻¹⁹ Similarly, when we test the sensitivity of our
162 findings to air-freight importation (common with a small subset of highly perishable vegetables like

163 asparagus²⁰), we find that the statistical difference between individual gardens and conventional
164 agriculture vanishes (Table S2).



165
166 **Figure 2. GHG emissions by farm type and product.** Impacts in the left panel shown per serving of food.
167 Impacts in the right panel shown per kilogram of crop. Boxplots reflect the median and interquartile
168 range of GHG impact, and UA sites above 1.0 kg CO₂e/serving are removed to improve legibility.

169
170 With this in mind, urban food growers could maximize carbon benefits (or minimize carbon
171 losses) by selecting crops conventionally grown using carbon-intensive methods. Research shows that
172 growers' motivations for crop selection vary significantly, from balancing diets to cultural preferences.²¹
173 In our sample, environmental sustainability was the most common motivation for growing food.
174 Research elaborating on the types of vegetables which offer carbon benefits accompanied by education
175 on these climate-friendly crop choices could help urban food producers better achieve these goals.

178 Towards climate-friendly UA

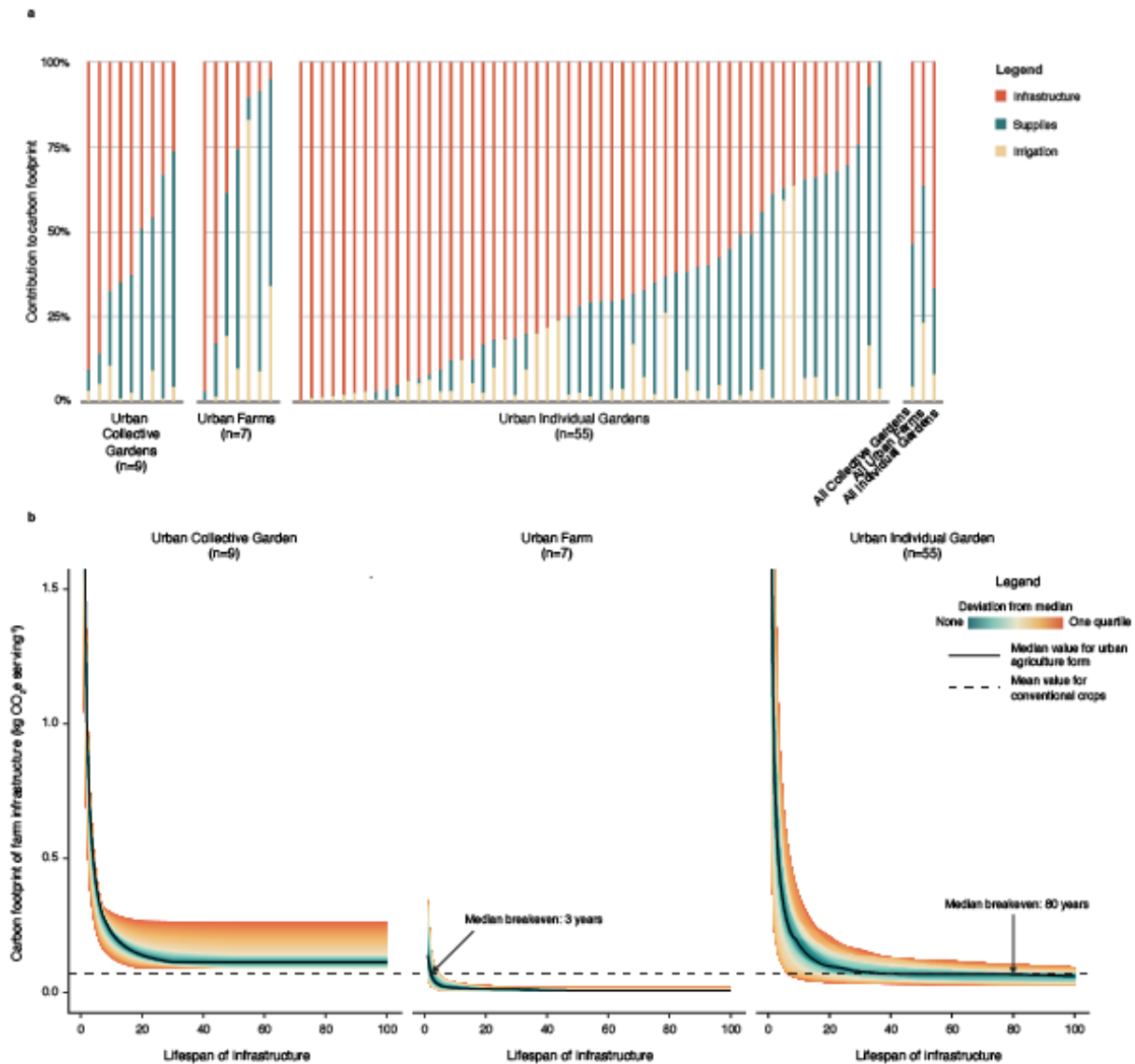
179 UA is expected to continue proliferating globally.^{2,15} Our findings suggest that steps must be
180 taken to ensure that urban food production supports, and does not undermine, decarbonization efforts.

181 We can glean insights into climate-friendly UA from the share of our sites which grow low-
182 carbon food. Although in the aggregate, UA is more carbon intensive than conventional agriculture, 17
183 of our 73 farms outperform conventional agriculture (referred to hereafter as “climate-friendly” - see
184 Methods for sensitivity analysis). Urban farms are most likely to be climate-friendly (43% of sites),
185 followed by individual gardens (25% of sites).

186 Interestingly, neither environmental actions (e.g., presence of solar panels) nor expressed values
187 are predictive of carbon emissions (Table S3). What, then, makes some sites more climate-friendly? We
188 identify three best practices crucial to making low-tech UA carbon-competitive with conventional
189 agriculture: 1. Extend infrastructure lifetimes, 2. Use urban waste as inputs, and 3. Generate high levels
190 of social benefits.

191 UA sites should preserve infrastructure as long as possible

192 Infrastructure is the largest driver of carbon emissions at low-tech UA sites (63% of impacts),
193 though this drops to ~1/3 for urban farms (Figure 3A). This includes raised beds, compost infrastructure,
194 and structures (e.g., sheds; Table S4). UA must operate for sustained periods to amortize emissions
195 invested in infrastructure (Figure 3B). For example, a raised bed built and used for five years will have
196 approximately four times the environmental impact per serving as a raised bed used for 20 years. Yet,
197 gardens and farms are precarious, especially in cities with development pressure, and some projects are
198 designed as temporary uses, with infrastructure demolished in years, not decades.^{22–25} Only urban farms
199 overcome this challenge precisely because infrastructure plays a diminished role in their carbon
200 footprint.



201

202 **Figure 3. Infrastructure and carbon footprints at urban agriculture sites. a,** Contributions of

203 infrastructure, supplies, and irrigation to GHG impacts. Supplies include fertilizer, compost, gasoline,

204 weed block textile, etc. Irrigation is blue water used on food crops. Each column is an individual urban

205 farm or garden. **b,** Black line shows median infrastructure GHG impacts per serving of food produced at

206 three types of UA spaces as a function of farm lifetime. Dashed line shows GHG impacts per serving

207 using conventional agriculture. Urban farms amortize infrastructure investments after only 3 years.

208 Individual gardens take decades, and collective gardens never break even.

209

210 This finding points to an important synergy between environmental and social sustainability in
211 UA. Activists and scholars have long pointed to insecure land tenure as a pressing threat to UA.^{26,27} This
212 is most acute in cities experiencing economic growth. For example, New York City (NYC) in the 1990s
213 saw land developers ally with city officials to displace community gardens.²⁶ Problematically, UA may
214 fuel green gentrification in its vicinity, making farm sites vulnerable to development.²⁸⁻³⁰ To avoid
215 displacing farms and the associated demolition of infrastructure, policies are needed that promote
216 stable land tenure for UA sites. For example, the establishment of community land trusts can help
217 remove land from the real estate market³¹ (e.g., NYC's Bronx Land Trust²⁶).

218 UA sites can conserve carbon by engaging in urban symbiosis

219 Urban symbiosis refers to processes by which urban systems reuse their own waste. According
220 to our findings, UA is most climate-friendly when it serves as a hub for symbiosis of building materials,
221 organic waste, and rainwater. This is consistent with recent work highlighting the potential for enhanced
222 circularity and innovative technology to reduce UA carbon footprints.^{32,33}

223 Climate-friendly sites in our sample cut their emissions by more than 52% by upcycling refuse
224 from the urban environment for raised beds, structures, and other infrastructure – twice as much
225 savings as high-carbon sites. If our UA sites sourced all their materials from urban waste, all three forms
226 of UA would be carbon competitive with conventional agriculture (i.e., there is no statistically significant
227 difference). However, much of the reuse of building materials at our sites is opportunistic, and overall
228 recycling rates of construction and demolition waste are abysmal (excepting crushed aggregates for
229 road fill).³⁴ Cities can work with the building sector to make these resources more widely available,
230 giving second life to materials that are unusable for construction but potentially useful in UA. This would
231 boost material reuse rates and contribute to climate-friendly UA.

232 Perhaps the most well-known symbiotic relationship between UA and cities is composting.³⁵ The
233 farms and gardens in our study applied 12 kg of compost per square meter annually, equivalent to
234 roughly 30 kg of biomass (e.g., food waste, yard trimmings) absorbed per square meter.³⁶⁻³⁹ This reduces
235 reliance on synthetic fertilizers. Sites in our sample used 95% less synthetic nutrients (0.06 g
236 nitrogen/serving, 0.04 g phosphorus/serving, 0.05 g potassium/serving) than conventional farms (0.88 g
237 nitrogen/serving, 1.4 g phosphorus/serving, 0.99 g potassium/serving) (Table S5). As noted by others,
238 different UA types apply fertilizer at different rates.^{9,35} None of the collective gardens in our sample
239 applied synthetic fertilizers. Conversely, urban farms used between three and five times as many
240 synthetic nutrients as the average UA site (0.18 g nitrogen/serving, 0.14 g phosphorus/serving, 0.23 g
241 potassium/serving), though this is still a statistically significant savings relative to conventional systems
242 (p -val = 0.014).

243 Compost at our farms is primarily derived from local food and yard waste; in some cases, this
244 relationship was symbiotic, with farms receiving compost from external sources, while in others
245 internally generated food waste was composted on-site. In either form, composting saves carbon
246 investment into potting soil (a heavy user of peat) and synthetic nutrients (energy-intensive and
247 dwindling). However, poorly-managed composting can exacerbate GHGs. The carbon footprint of
248 compost grows tenfold when methane-generating anaerobic conditions persist in compost piles.³⁹ This is
249 common during small-scale composting, and home compost is the highest-impact input on 22 of 73 UA
250 sites studied (Table S4). Cities can offset this risk by centralizing compost operations for professional
251 management or by training farmers on proper composting practices. In fact, we estimate that careful
252 compost management could cut greenhouse gasses (GHGs) by 39.4% on sites that use small-scale
253 composting.

254 Rainwater and greywater recycling for irrigation is a third area for symbiosis in UA.³⁵ In this
255 study, more than 50 sites practiced rainwater recovery, but only four derived most of their irrigation this

256 way. Instead, sites primarily used potable municipal water sources or groundwater wells, consistent
257 with underutilization of rainwater seen across past research.⁹ Irrigation from these sources emits GHGs
258 from pumping, water treatment and distribution, which rose as high as 83% of total emissions on one
259 UA site. Cities should support low-carbon (and drought-conscious) irrigation for UA through subsidies for
260 rainwater catchment infrastructure⁴⁰ or establishing guidelines for greywater reuse.⁴¹

261 UA sites should invest in social benefits

262 Unlike conventional agriculture, where food is typically the sole output, low-tech UA sites often
263 blend food and social production.^{26,42-44} A survey conducted with our farmers and gardeners²¹ identifies
264 a variety of social benefits which align with past work.⁴³ UA practitioners overwhelmingly reported
265 improved mental health, diets, and social networks.

266 Similar to other multifunctional systems, such as organic agriculture, allocating impacts between
267 UA's multiple benefits is challenging.⁴⁵ Since food and social benefits are co-products in UA, increasing
268 social benefits can reduce impacts allocated to food.⁴⁶ This study takes a conservative approach by
269 allocating all supplies and irrigation to food production, while infrastructure is allocated to food and
270 social co-benefits based on interviews with farmers and standardized calculations (e.g., 10% of a raised
271 bed allocated to non-food if 10% of the area grows ornamentals).

272 Assuming farms adopt climate-friendly practices for their supplies, what percentage of
273 infrastructure must be dedicated to non-food outputs to produce food with lower carbon intensity than
274 conventional agriculture? Sensitivity analysis shows that the majority of our urban farms and individual
275 gardens outperform conventional agriculture when more than 90% of infrastructure impacts are
276 allocated to non-food services (Figure S3).

277 While this threshold appears high, evidence suggests this is attainable. Cost-benefit analysis of a
278 community garden in the UK estimated that social benefits, such as improved well-being and reduced
279 hospital admissions, accounted for 99.4% of total economic value generated on-site.⁴⁷ Since emissions

280 allocation often follows economic value generation,⁴⁶ growing spaces which maximize social benefits
281 can outcompete conventional agriculture when UA benefits are considered holistically.

282 Future research

283 This study assesses the carbon impacts of low-tech UA to identify strategies for reducing these
284 impacts. Collaboration with citizen scientists was fundamental to achieving our large sample size and
285 will likely contribute to other large-scale carbon footprints, material flow analyses, and life cycle
286 assessments of UA. These tools, however, requires reliable data on farm inputs and outputs, the
287 collection of which was hampered by turnover in personnel and volunteers at UA sites. For instance,
288 incomplete recordkeeping undermined water consumption data. To avoid this, future projects should
289 provide continuous training, compensate citizen scientists for their efforts, and automate data collection
290 (e.g., water meters). To maintain confidence in our results, we excluded indicators compromised by
291 errors in data collection, instead focusing on indicators where results are consistent across sites and
292 where differences are large.

293 Other challenges faced in this study lead us to identify a number of key areas for future work in
294 this space:

- 295 1. Vegetables for wintertime consumption are unlikely to be replaced by low-tech UA in cities with
296 relatively cold winters (all of our case study cities). However, we did not model seasonal carbon
297 dynamics of conventionally-grown produce for lack of data, nor did we assess the environmental
298 impacts of local, alternative supply chains which might compete with UA in the summer (e.g.,
299 community-supported agriculture). This is particularly salient given our findings that excessive air
300 freight may negate carbon advantages seen in conventional production. Modeling seasonal
301 dynamics and assessing a wider array of rural food production systems can address these gaps.⁴⁸
- 302 2. Although UA may increase the carbon intensity of fruits and vegetables, these foods account for a
303 small share of total dietary carbon impacts, which are driven mainly by meat and dairy. Studies have

304 shown that UA practitioners often reduce their intake of animal products.⁴⁹ Future work should
305 quantify this tradeoff between elevated carbon footprint in urban produce and shifting diets.

306 3. Better data are needed on carbon fluxes of composting at UA sites. We found composting
307 contributes significantly to the carbon footprint of UA (Table S4). Despite this, little is known about
308 differences in GHGs from various composting techniques.^{50,51} Furthermore, the high application
309 rates of compost in UA likely raises additional questions. For example, the effects of long-term
310 composting on N₂O emissions are unclear, and strategic management of application scheduling and
311 fertilizer combinations may be required to minimize emissions.^{52,53} How the repeated use of
312 compost affects soil carbon sequestration in raised beds is also unclear, though existing evidence
313 suggests that compost-dependent systems may sequester substantial carbon.^{54,55} Both topics
314 warrant further study.

315 4. Study of different case cities is needed to understand how low-tech UA performs across climates
316 and seasons. Our UA sites are in temperate, wet cities in the global north. Impacts likely vary
317 substantially across UA sites in more diverse climates. Furthermore, we only analyzed the 2019
318 growing season. Future work should include multiple years to develop a more representative
319 snapshot of UA.

320 5. UA produces social and food outputs. To allocate impacts between the two, we used interviews and
321 surveys. LCA practitioners and social scientists can collaborate to develop methods to better assess
322 UA co-products (e.g., cost-benefit analysis⁴⁷). Another way to consider this web of co-products is
323 through a land use lens, comparing UA to other urban land uses like housing, parks, and industry.⁵⁶
324 LCA results can be sensitive to these allocation methods, which are particularly important for UA
325 work. While we found that the most socially-productive spaces studied (i.e., collective gardens) are
326 also the most carbon intensive, variation in collective garden sites indicates that this is not a strict
327 condition of social good provisioning. Careful allocation of impacts can help scholars and UA

328 designers to construct socially productive spaces which have a lower carbon footprint per unit of
329 food produced.

330 **Conclusions**

331 UA has numerous benefits, but this study suggests that even low-tech urban farms and gardens have
332 high carbon footprints. Our results show that today's UA generally produces more GHGs than
333 conventional agriculture, though this needs additional clarification in industrializing cities and in drier or
334 warmer climates. High-production urban farms focused on crops which are conventionally carbon-
335 intensive (e.g., greenhouse grown or air-freighted) may offer one path to a more climate-friendly UA.
336 Meanwhile, all UA sites must extend the useful life of infrastructure, reuse more materials, and
337 maximize social benefits to become carbon competitive with conventional agriculture. In other words,
338 UA must be judiciously designed and managed to achieve climate goals. Next steps should include
339 broader adoption of the best practices described as well as a suite of future research which will help to
340 expand and refine this list of best practices. Because of its critical social, nutritional, and place-based
341 environmental benefits, UA is likely to have a key role to play in future sustainable cities, but important
342 work remains to be done to ensure UA benefits the climate as well as the people and places it serves.

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476 **Methods**

477 **Urban Agriculture carbon footprint (via life cycle assessment)**

478 **Goal and Scope**

479 We conducted a case study of 73 urban farms and gardens, employing life cycle assessment to
480 quantify the environmental footprint of low-tech UA in industrialized cities in the global north. Life cycle
481 assessment is a widely-used method to estimate the environmental impacts of a good or service across
482 its entire value chain.^{1,2} By focusing on under-studied, low-tech forms of UA, we address a persistent gap
483 in literature and data, particularly in light of the continued predominance of these forms of UA. The goal
484 of this life cycle assessment was to quantify the climate impacts and nutrient demands per serving of
485 fruits and vegetables produced at an urban farm. The scope of analysis was farm to city for both urban
486 agriculture and conventional comparisons (see below). We considered emissions throughout the
487 lifecycle of the materials used to support food growth and accounted for food waste using USDA
488 consumer estimates.^{2,3} Consumer travel was excluded from analysis because we assumed consumer
489 travel to an urban farm site or travel to a grocery store would be equivalent.

490 We evaluated carbon intensity per kilogram fresh crop to compare between specific crops
491 (available in SI). To account for heterogeneity across UA sites and to facilitate comparisons with the
492 “basket” of conventional produce available in each country, we also calculated carbon intensity per
493 serving of produce. A serving is the recommended mass of a given crop, as defined by nutritionists and
494 doctors, that an individual should consume to align with national dietary guidelines (we use USDA values
495 to unify servings across countries). Servings convert different crops to a single, comparable unit based
496 on their nutritional content and is similar to converting foods to caloric content,³ with the added benefit
497 of considering macro- and micronutrients. We use the USDA Food Patterns Equivalents Database⁴
498 (FPED) to convert yields to servings, including corrections for food preparation published in the USDA
499 Food Intakes Converted to Retail Commodities Databases (FICRCD).⁵ Servings are calculated by
500 converting each food product to servings of fruits and vegetables using both an FPED servings count and
501 an FICRCD conversion value, which converts fresh food to consumed food (i.e., accounts for peeling,
502 etc.) For example, the total fruit servings of any given food are calculated by multiplying the yield in

503 kilograms by the FICRCD conversion, then multiplying this new value by FPED servings (which has to be
504 multiplied by 10 to convert from servings per 100g to servings per kg). All equivalencies between crops
505 grown on-site and standardized commodities are based on the USDA Food and Nutrient Database for
506 Dietary Studies.⁶ The relevant equivalencies can be found in the online supplemental materials as part
507 of the SI Code and Inputs – “Crops_AllocationCodebook_Current.csv”.

508 Case Studies and Typology

509 To execute this analysis, we focused on case studies from five countries: France, Germany,
510 Poland, the United Kingdom, and the United States. To manage partnerships with so many farm and
511 garden sites across countries, we formed an international team of collaborators from universities local
512 to the food-growing sites (the so-called “FEW-meter” team - for more details, see Caputo et al.)⁴. We
513 also sought to represent a breadth of forms of low-tech UA, ultimately creating our own typology to
514 effectively classify the variety of sites represented in the study.

515 UA projects vary widely in goals, format, and production systems. It is difficult to cleanly classify
516 UA projects into one group or another, and a staggering array of typologies has been presented in the
517 literature to date.⁵⁻⁷ Responding to this lack of consensus, members of the FEW-meter team developed
518 an internal typology based on input from farmers and gardeners at the 73 case study sites.⁴ These sites
519 are divided according to their goals, their management systems, and their funding structures, forming
520 four divisions: Urban farms, Individual gardens, Collective gardens, and Mixed model sites.

521 In this typology, urban farms are primarily commercial enterprises, managed by professional
522 farmers to produce food (producing an average of 4161.98 kg on-site, enough vegetables to feed 40-50
523 people per year). On average, our urban individual gardens are relatively small, individually-managed
524 plots producing food for their owners and their friends and families (averaging 164.45 kg produce per
525 year). Urban collective gardens are socially-productive spaces supported largely by volunteer labor or
526 non-profit support, producing food for community benefit (an average of 1384.70 kg per year) as a

527 complement to broader community goals such as nature-based education, social justice, and job skills
528 development. And finally, the Mixed model farms escape classification along these axes and are
529 excluded from analyses which rely on this typology.

530 Life Cycle Inventory

531 To capture this breadth of UA, we employed a citizen science approach, partnering with urban
532 farmers and gardeners in each of the case study regions to document inputs and outputs at their food-
533 growing sites. Inputs to urban agriculture sites come in a variety of forms, which we divided into three
534 primary categories: infrastructure, supplies, and irrigation water. Infrastructure combines those
535 relatively permanent aspects of each site, such as the raised beds in which food is grown or the
536 pathways between vegetable plots. Supplies consist of the regular inputs to the farm or garden,
537 including compost, fertilizer, and gasoline, while irrigation water includes any water applied to the
538 crops.

539 Infrastructure inputs were calculated by researchers in collaboration with gardeners during
540 walking tours of the gardens. Researchers used direct measurement to assess volumes of material or
541 made educated guesses with the help of gardeners (e.g., approximating the depth of a concrete path).
542 During these walking tours, researchers also cataloged the presence of climate-friendly infrastructure
543 like solar panels. Supply and irrigation inputs were recorded in written “diaries” or online logs developed
544 as part of preliminary collaborations with farmers and gardeners.⁴ In the diaries, farmers and gardeners
545 recorded the daily inputs and harvests from their site, keeping track of what they added and extracted
546 as the growing season went on. In preparation for the impact assessment, unusual units (e.g., 1 slab of
547 concrete cladding) were converted to mass or volume using online product data so that all units
548 matched Ecolnvent.

549 Life Cycle Impact Assessment

550 We determined the environmental impact of those inputs and outputs using EcoInvent 3.8⁸ and
551 the PEF 3.0 midpoint indicators (specifically Global Warming Potential at 100 years). These impacts were
552 exported from SimaPro to a csv file and then imported into R. In R, we used linear algebra to calculate
553 the life cycle greenhouse gas footprint of each UA site, adding up the material and assembly impacts,
554 use-phase impacts, and end-of-life impacts from all farm site components. For material end-of-life, we
555 used the cut-off principle, meaning that landfill and incineration impacts were assigned to the current
556 life cycle, while recycling impacts were assigned to the following life cycle. We accounted for recycling
557 impacts in recycled inputs on our sites. An alternative would be to credit the systems for avoided
558 impacts as a result of recycling. We tested this modeling choice and found that it had no influence on
559 directionality of the results nor the statistical analysis. We calculated impact per serving by converting
560 harvest values to servings of fruit and vegetables with USDA preparation and nutrition data (see above
561 for details).^{2,9} We then divided total impact by total harvest to calculate the per-serving values at farm
562 level reported in this study. These impacts were also assigned to individual crops through co-product
563 allocation, as discussed below.

564 All data were processed in R, and both data and code are available in the supplemental
565 materials.

566 Key dimensions of LCA and sensitivity analyses

567 Our life cycle assessment is dependent on three major assumptions:

- 568 1. Allocation between food products
- 569 2. Percent of site impacts allocated to food
- 570 3. Age of farm/garden at time of removal

571 Results presented in the main text assume an average across all four allocation schemes and an average
572 across time of removal scenarios from 1 to 100 years. Baseline percent of impacts allocated to food was
573 determined by interviews along with standardized calculations and is unique to each farm or garden.

574 Both percent impacts to food and age of farm are explored in the final section of the manuscript. The
575 development of these key variables proceeded as follows.

576 *Allocation between food products*

577 While the average conventional farm employs large, mono-cropped fields to produce vegetables
578 sold in a supermarket, low-tech urban farms and gardens typically host polycultures of a variety of
579 vegetables, fruits, and even chickens, goats or other small livestock. To identify the climate footprint of
580 urban crops, therefore, we must allocate the farm-level impacts between different farm products. We
581 treat the fruits, vegetables, and social goods produced by our case study gardens as co-products,
582 allocating the farm-level impacts to crops based on their contribution to the total production of the
583 farm.

584 Food production is measured in terms of mass, caloric, nutrient (NRF 9.3⁷), and economic
585 output, and impacts are allocated to individual crops based on the value of the harvest of that crop (e.g.,
586 if 10 kg of tomatoes are harvested and 100 kg are produced in total, tomatoes would be allocated 10%
587 of the food-related impacts under a mass allocation scheme). Mass allocation depended on the harvests
588 recorded by farmers, while caloric and nutrient allocations used USDA food composition data^{4,6,8} to
589 convert these masses to calorie and nutrient outputs. Economic allocation was localized to each city,
590 using prices at nearby grocery stores to estimate the economic value of food produced on each site.

591 Overall, our model is robust to allocation decisions. In most cases, all four allocation schemes
592 produce results within a factor of 2, though select crops like potatoes see variance up to a factor of 6.
593 This occurs when crops have significant variation between caloric density, nutrient density, and value
594 per kilogram. However, despite these isolated substantial variations, no allocation decision changes the
595 direction of the relationship between a conventional product and an urban one. When assessed across
596 scenarios and growing conditions, all urban crops are worse for the climate than their conventional
597 counterparts.

598 *Percent impacts to food*

599 In addition to allocating between different food co-products, we also allocate between material
600 and immaterial co-products. At urban collective gardens and other sites producing non-food services,
601 infrastructure is allocated between outputs (e.g., only 40% of the embodied impacts of a picnic table
602 might be allocated to food, since it is more often used for outdoor education classes than vegetable
603 sorting). Our model is sensitive to the percent of infrastructure impacts allocated to food. As explored in
604 the discussion section, urban farming and gardening often has a variety of co-products, both material
605 and immaterial. Allocating between these products is both challenging and extremely important for the
606 overall findings of an urban agriculture LCA.

607 Our baseline scenario for impacts to food is unique to each site. Through interviews with
608 farmers and walking tours of the site, researchers used simple rules to estimate the percent of impacts
609 from each piece of infrastructure should be allocated to food. For example, if half of a raised bed is used
610 to grow decorative flowers, only half of the impact of that raised bed should be allocated to food. If
611 most of the work done in an on-site pavilion is educational or community-building, then only a small
612 percentage of the impacts of that pavilion should be allocated to food to account for the time spent
613 sorting or boxing food there. It is worth noting that sorting infrastructure and packaging are sometimes
614 excluded from conventional vegetable LCAs. Since we worked directly with farmers to identify the scope
615 of infrastructure which was relevant to food production, we felt this potential inconsistency was
616 reflective of food production realities in urban systems. Furthermore, sorting and packaging
617 infrastructures on farms are unlikely to make up a significant portion of impact at the scale of
618 production seen on a typical industrial monoculture site.

619 Allocation to co-products is a notoriously challenging component of LCA. To test the impacts of
620 our allocation methods and to test the impact of great social productivity on sites, we conduct a
621 sensitivity analysis of the percent of impacts allocated to food and to social services. We test the effects

622 of altering the infrastructure impacts assigned to food by varying them between 0% and 100% (intervals
623 of 5%). Breakeven analyses are discussed in the main text section and shown in the SI. Our results
624 indicate that the majority of UA sites become environmentally friendly at higher levels of impacts
625 allocated to non-food. However, collective gardens do not reach breakeven simply by allocating
626 infrastructure impacts to non-food products; the supply and irrigation impacts exceed the total of
627 conventional agriculture by themselves.

628

629 *Age of farm at time of removal*

630 Finally, we also test the sensitivity of UA impacts to length of tenure in a single site. We do this
631 in two parts. For most main-text graphs, we calculate the average impact of food produced at each site
632 if it was moved anywhere between 1 and 100 years after establishment (intervals of 1 year). In the
633 discussion section, we display the breakeven points for infrastructure on each type of UA site.

634 We use 100 years as the maximum land tenure considered because that is the longest lifespan
635 of any material used on one of our farms. At 101 years, no part of any original farm would remain (ala
636 the ship of Theseus). Some of the oldest allotment gardens in Europe can trace their roots to the 19th
637 century, and several gardens in the eastern US began as Victory Gardens during WWII, but little of the
638 original structures remain even on these sites, and 100 years is likely a highly conservative estimate for
639 any part of an urban farm or garden to continue being used.

640 Carbon-Friendly Urban Farms

641 Carbon-friendly urban farms were defined as farms that had lower greenhouse gas emissions
642 per serving than conventional agriculture when averaged across all sensitivity scenarios. The total
643 number of scenarios per farm is:

644 4 allocation schemes * 21 values of percent impact * 100 ages = 8,400 scenarios

645 As defined, carbon-friendly farms have lower GHG impact than conventional agriculture when averaged
646 across all 8,400 scenarios.

647 Synthetic Fertilizer Inventories

648 In tandem with the Life Cycle Assessment, we also collected data on synthetic fertilizer
649 application, tracking the flows of synthetic nutrients into food products. We tracked the mass of
650 synthetic nutrients consumed on all sites and allocated them evenly across all servings of food produced
651 on the sites. Again, data and code are available in SI.

652 Conventional Agriculture Comparison

653 To compare UA impacts to the greenhouse gas footprint of conventionally-grown fruits and
654 vegetables, we quantified the greenhouse gas footprint of the five most consumed fruits and vegetables
655 (by mass) in each case study country. We chose the top 5 fruits and vegetables because they collectively
656 make up more than three-quarters of fruit and vegetable intake in each country of interest. Using FAO
657 data, we identified the countries which collectively serve as sources of 90% of each of these fruits and
658 vegetables. For example, 96% of onions available in German supermarkets are grown in Germany (71%),
659 Spain (13%), and The Netherlands (12%). Taking a weighted average (weighted by percent of sales) of
660 the carbon footprint of onions grown and shipped from each of these sources, we approximated the
661 carbon footprint of a typical onion in a German supermarket. We can then compare these supermarket
662 onions to onions grown on our sites.

663 Since crops are often imported from multiple locations, this system resulted in 107 unique crop-
664 country combinations required to describe the environmental footprint of vegetables in each of our case
665 study cities. To quantify the climate change impacts, we sought to identify either: 1.) at least 3 LCAs
666 relevant to the crop and the country or 2.) a systematic summary of the impacts of a particular crop in
667 each country. We used this system of focusing on large reviews or multiple case studies to iron out

668 differences between cases and identify a relatively representative mean value for that product from the
669 country of interest. In a few exceptional cases where data were scarce, we could not locate a summary
670 and only identified 2 results. To quantify nutrient inputs, we sought at least one study of N, P, and K
671 inputs into conventional agriculture for each unique crop-country combination. Most crop-country
672 combinations were available from existing summaries. LCAs useful for this summarization come in three
673 forms:

- 674 1. Farm-to-supermarket LCA of a particular product sold in one of our countries of interest (e.g.,
675 Agribalyse analysis of strawberries sold in France, which already accounts for inputs across
676 countries)
- 677 2. Farm-to-Supermarket LCA of a particular product that matches one of our crop-country
678 combinations (e.g., an analysis of Spanish strawberries imported to England)
- 679 3. Farm-to-Farm Gate LCA of a particular product grown in one of our crop-country combinations
680 (e.g., an analysis of Spanish strawberries that ends at the farm gate, to which we can manually
681 add estimates of food waste, travel, and supermarket impacts)

682 See SI for the database of conventional vegetable impacts developed to support this study and the R
683 code used to compare these values to urban crops. In the case of farm-gate studies, we employed
684 reasonable estimates of food waste, travel, and supermarket impacts. Specifically, we assumed food
685 waste rates as reported by peer reviewed articles for the US, UK, and EU. We use EU wastes from
686 Caldeira et al. (3.8% in distribution, 1.3% in retail),⁹ UK waste rates from Jeswani et al. (1.6% in
687 processing, 9.6% in retail),¹⁰ and US waste rates from a Commission for Environmental Cooperation
688 white paper¹¹ combined with USDA estimates¹² of overall waste (3.9% in distribution, 2.5% in retail). For
689 travel, we assumed that vegetables were transported via semi-trailer and ocean freight, since most
690 fruits and vegetables are not perishable enough to justify air freight.¹³ We tested the sensitivity of our
691 results to this assumption and found that urban agriculture is still statistically significantly more carbon-

692 intensive than conventional solutions. The exception to this, individual gardens, is discussed in the
693 manuscript. In all travel cases, we assume travel from the capital city of each country or from the largest
694 city in a major agricultural export region. Details can be found in the SI. Using emissions estimates from
695 SimaPro and distance estimates from online tools, we added travel impacts to farm gate studies based
696 on each unique country combination (e.g., products traveling from South Africa to Dortmund were
697 estimated to travel 530 km by road and 11,036 km by sea). Finally, we used a generic supermarket
698 impact value from Burek and Nutter to supplement the farm-gate studies with supermarket emissions.¹⁴

699 Since our urban food-growing sites produce a huge variety of crops, we also created a “basket”
700 of crops for each country, comprising the top five fruits and the top five vegetables (as well as
701 independent fruit and vegetable baskets). Using a weighted average (weighted by the % of consumption
702 in that country), we calculated the impacts per serving for each of these country-level baskets. Finally,
703 we calculated the average conventional produce impact by averaging across these baskets.

704 We conducted two-sided t-tests at 0.05 significance level to test for statistically significant
705 differences between urban and conventional crops and country-level baskets. We used a false-discovery
706 rate correction to adjust for multiple tests. All assessment was done in R, and all code is available in SI.

707 Farmer survey

708 To understand the relationship between climate impacts, urban agriculture form, and
709 participant attitudes, we draw on the results of a survey of farmers and gardeners conducted at each of
710 our case study sites (SI). The survey was designed to assess farmer participation, motivations, and
711 perceived benefits; our analysis focuses only on their motivations and the relationship between these
712 and their climate outcomes (Table S2).

713 Motivations questions were designed to assess the importance of a variety of possible reasons
714 for gardening and were accompanied by questions assessing the goals of the farm or garden.

715 Participants responded to “People have many different motivations for gardening and farming. How
716 important is each of the following reasons for gardening/farming to you?” on a Likert-type scale ranging
717 from *Not important at all* to *Very important*.

718 The list of motivations assessed (SI) was based on previous literature,^{15,16} and the survey was
719 translated into the local language of each garden or farm. Survey administration varied by country;
720 therefore, ethical approval was handled by the lead institution in each country. In those countries where
721 board review was required, it was sought and granted. All participants consented to participation in the
722 study, and all data were anonymized and stored in secure data repositories. For more details on survey
723 administration in each country, see existing analysis of the survey by Kirby et al.¹⁶

724 Data availability

725 All data used for this study are available in online supplementary materials. See the attached SI
726 for more details, and see this [link](#) for access to the complete online supplementary data.

727

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