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Abstract

Urban agriculture (UA) is a widely proposed strategy to make cities and urban food systems more sustainable. However, its carbon footprint remains understudied. In fact, the small number of case studies suggest that UA may be worse for the climate than conventional agriculture. This is the first large-scale study to resolve this uncertainty across cities and types of UA, employing citizen science at 73 UA sites in Europe and the United States to compare UA products to food grown on conventional farms. The results reveal that one serving of food from UA is six times as carbon intensive as conventional agriculture (420 g vs 70 g CO_2 equivalent). Some UA crops (e.g., tomatoes) and sites (e.g., 25% of individually-managed gardens), however, outperform conventional agriculture. These exceptions suggest that cultivating crops that are conventionally high-carbon, increasing infrastructure lifespans, and enhancing circularity can contribute to climate-friendly UA.

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

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

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

This paper addresses these gaps through carbon footprinting of low-tech UA, covering 73 sites in France, Germany, Poland, the United Kingdom, and the United States using data collected through citizen-science.[14,15] We assess the carbon footprint across the lifecycle of producing food at three types of low-tech UA; urban farms (professionally managed, focused on food production), individual gardens (small plots managed by single gardeners), and collective gardens (communal spaces managed by groups of gardeners). We estimate climate change impacts and synthetic nutrient footprints of food from UA and compare these to conventional agricultural products sold in each of our five countries.

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

Results and discussion

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

Food produced at our UA study sites is more carbon-intensive than food produced on conventional farms (Figure 1). To reach this conclusion, we compare food produced on UA sites to conventional crops, produced both domestically and abroad, considering on-farm impacts, processing, and transportation to the city (see Methods for details). On average, UA emits 0.42 kilograms carbon dioxide equivalents (kg CO_2e, standard error [SE] = 0.07 kg CO_2e) per serving (equivalent to μ = 3.12 kg CO_2e/kg vegetables, SE = 0.53 kg CO_2e/kg), six times higher than the 0.07 kg CO_2e per serving (SE = 0.005 kg CO_2e per serving; μ = 0.47 kg CO_2e/kg vegetables, SE = 0.032 kg CO_2e/kg) of conventional produce (p-value << 0.001).

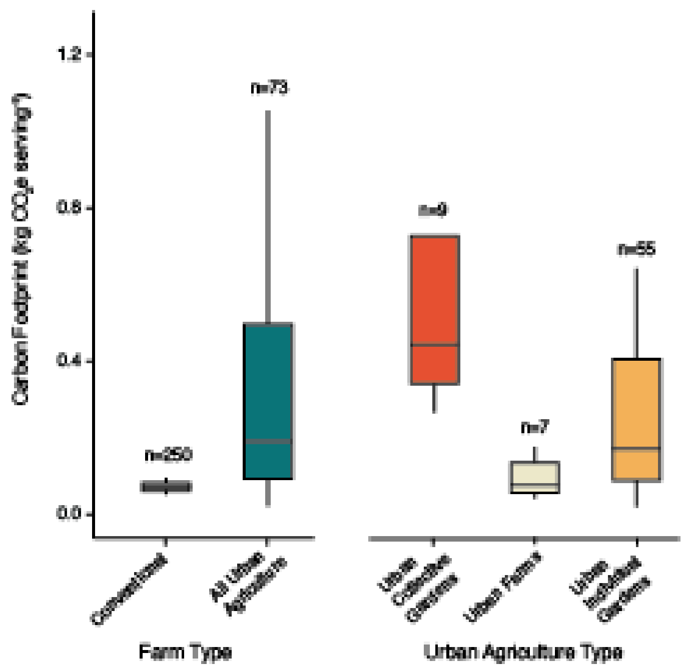

Figure 1. The carbon footprint of conventional vs urban agriculture. Results shown per serving of produce as defined by the United States Department of Agriculture. Boxplots reflect the median and interquartile range of GHG impact, and UA sites above 1.0 kg CO_2e/serving are removed to improve legibility (See Figure S1 for full results). Two UA sites could not be classified as Collective, Individual, or Farm, so only 71 sites are included in the right panel.

On average, all forms of UA studied here are more carbon intensive than conventional agriculture, though this difference is only statistically significant for collective gardens (p-val = 0.02) and individual gardens (p-val < 0.001). Collective gardens are the most carbon-intensive form of UA (μ = 0.81 kg CO_2e/serving, 7.50 kg CO_2e/kg). Individual gardens and urban farms are similar on average (both produce 0.34 kg CO_2e/serving), but variation among urban farms leaves them statistically indistinguishable from conventional farms (p-val = 0.33). In fact, most urban farms are carbon-competitive with conventional farms (median = 0.08 kg CO_2e/serving when one particularly carbon-intensive urban farm is excluded from the analysis). These findings mirror literature trends, which identify non-commercial UA as more carbon intensive than commercial UA except when the latter use energy intensive indoor farming.[16]

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

Select UA crops have similar carbon intensity to conventional agriculture

We allocated food impacts between crops using nutritional content, calorie content, economic value and mass (see Methods). Method of allocation did not affect directionality of results (see Table S1), and results presented in-text are averaged across allocation schemes. Carbon intensity per serving of fruit (N = 73) is higher in low-tech UA (μ = 0.47 kg CO_2e, 4.07 kg CO_2e/kg) than conventional agriculture (μ = 0.07 kg CO_2e, 0.49 kg CO_2e/kg). The same is true of vegetables (N = 73; μ = 0.46 vs. 0.08 kg CO_2e per serving, 3.48 vs. 0.52 kg CO_2e/kg). Similarly, the most popular crops consumed in our five countries are more carbon intensive when grown using low-tech UA (Figure 2).

However, selected crops are carbon competitive with conventional agriculture. Competitiveness depends on growing practices, both in urban and conventional settings. For example, the median urban tomato (0.17 kg CO_2e/serving) outperforms conventional tomatoes (μ = 0.27 kg CO_2e/serving). While on average urban tomatoes are more carbon-intensive than conventional tomatoes (p-val = 0.02), this low median demonstrates UA sites often outperform conventional tomato growing. This is largely due to the carbon-intensive greenhouses that supply most tomatoes to our case cities, as well as less than optimal distribution patterns of the crop from farm to city.[17–19] Similarly, when we test the sensitivity of our findings to air-freight importation (common with a small subset of highly perishable vegetables like asparagus[20]), we find that the statistical difference between individual gardens and conventional agriculture vanishes (Table S2).

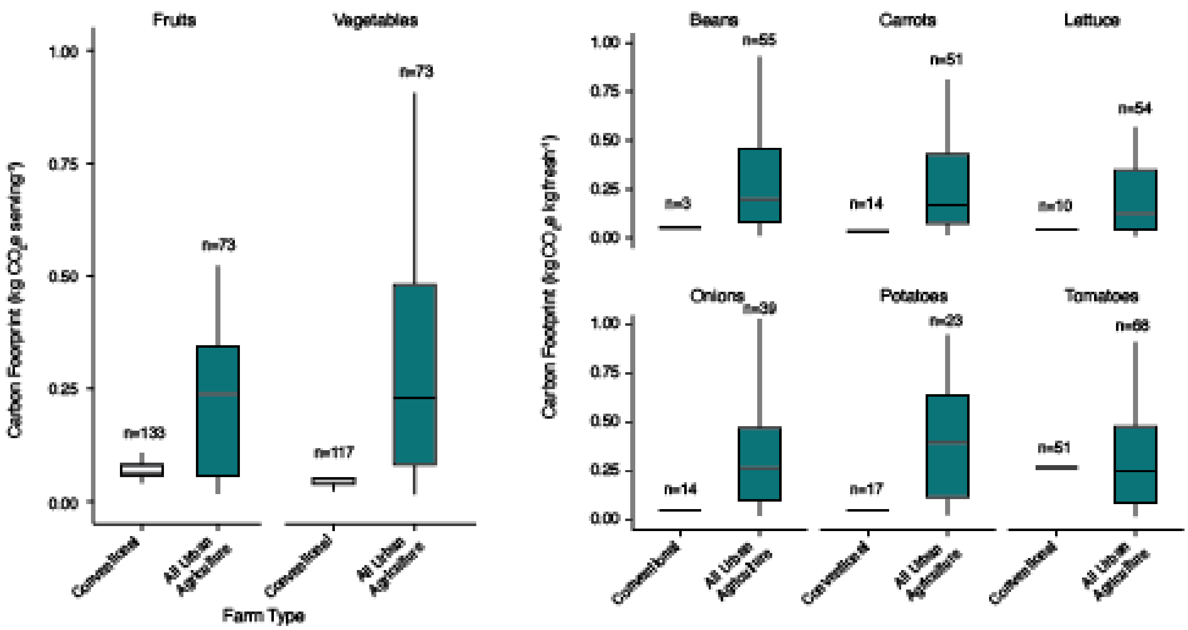

Figure 2. GHG emissions by farm type and product. Impacts in the left panel shown per serving of food. Impacts in the right panel shown per kilogram of crop. Boxplots reflect the median and interquartile range of GHG impact, and UA sites above 1.0 kg CO_2e/serving are removed to improve legibility.

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

Towards climate-friendly UA

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

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

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

UA sites should preserve infrastructure as long as possible

Infrastructure is the largest driver of carbon emissions at low-tech UA sites (63% of impacts), though this drops to ~⅓ for urban farms (Figure 3A). This includes raised beds, compost infrastructure, and structures (e.g., sheds; Table S4). UA must operate for sustained periods to amortize emissions invested in infrastructure (Figure 3B). For example, a raised bed built and used for five years will have approximately four times the environmental impact per serving as a raised bed used for 20 years. Yet, gardens and farms are precarious, especially in cities with development pressure, and some projects are designed as temporary uses, with infrastructure demolished in years, not decades.[22–25] Only urban farms overcome this challenge precisely because infrastructure plays a diminished role in their carbon footprint.

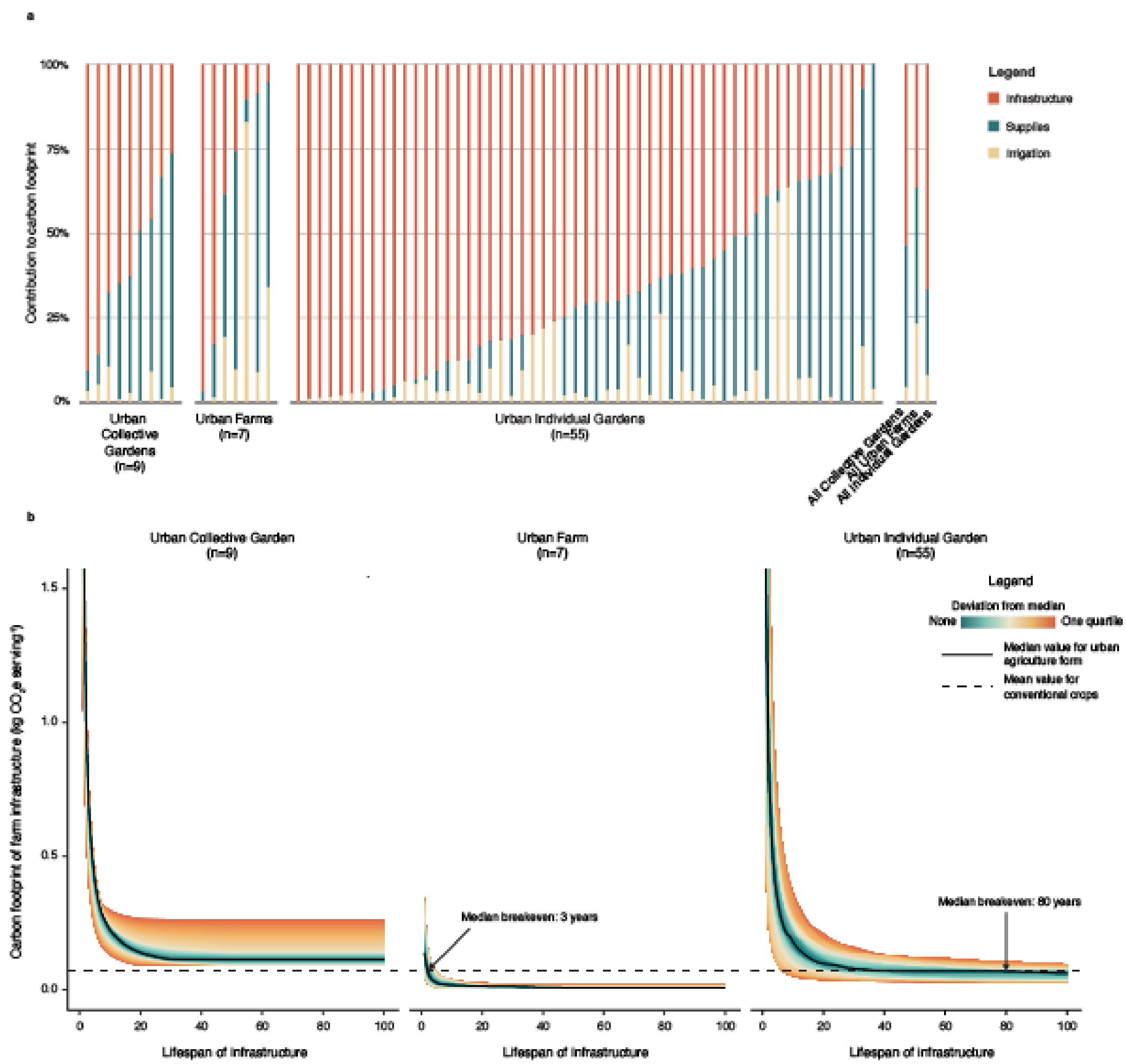

Figure 3. Infrastructure and carbon footprints at urban agriculture sites. a, Contributions of infrastructure, supplies, and irrigation to GHG impacts. Supplies include fertilizer, compost, gasoline, weed block textile, etc. Irrigation is blue water used on food crops. Each column is an individual urban farm or garden. **b**, Black line shows median infrastructure GHG impacts per serving of food produced at three types of UA spaces as a function of farm lifetime. Dashed line shows GHG impacts per serving using conventional agriculture. Urban farms amortize infrastructure investments after only 3 years. Individual gardens take decades, and collective gardens never break even.

This finding points to an important synergy between environmental and social sustainability in UA. Activists and scholars have long pointed to insecure land tenure as a pressing threat to UA.[26,27] This is most acute in cities experiencing economic growth. For example, New York City (NYC) in the 1990s saw land developers ally with city officials to displace community gardens.[26] Problematically, UA may fuel green gentrification in its vicinity, making farm sites vulnerable to development.[28–30] To avoid displacing farms and the associated demolition of infrastructure, policies are needed that promote stable land tenure for UA sites. For example, the establishment of community land trusts can help remove land from the real estate market[31] (e.g., NYC's Bronx Land Trust[26]).

UA sites can conserve carbon by engaging in urban symbiosis

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

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

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

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

Rainwater and greywater recycling for irrigation is a third area for symbiosis in UA.[35] In this study, more than 50 sites practiced rainwater recovery, but only four derived most of their irrigation this way. Instead, sites primarily used potable municipal water sources or groundwater wells, consistent with underutilization of rainwater seen across past research.[9] Irrigation from these sources emits GHGs from pumping, water treatment and distribution, which rose as high as 83% of total emissions on one UA site. Cities should support low-carbon (and drought-conscious) irrigation for UA through subsidies for rainwater catchment infrastructure[40] or establishing guidelines for greywater reuse.[41]

UA sites should invest in social benefits

Unlike conventional agriculture, where food is typically the sole output, low-tech UA sites often blend food and social production.[26,42–44] A survey conducted with our farmers and gardeners[21] identifies a variety of social benefits which align with past work.[43] UA practitioners overwhelmingly reported improved mental health, diets, and social networks.

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

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

While this threshold appears high, evidence suggests this is attainable. Cost-benefit analysis of a community garden in the UK estimated that social benefits, such as improved well-being and reduced hospital admissions, accounted for 99.4% of total economic value generated on-site.[47] Since emissions allocation often follows economic value generation,[46] growing spaces which maximize social benefits can outcompete conventional agriculture when UA benefits are considered holistically.

Future research

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

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

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

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

3. Better data are needed on carbon fluxes of composting at UA sites. We found composting contributes significantly to the carbon footprint of UA (Table S4). Despite this, little is known about differences in GHGs from various composting techniques.[50,51] Furthermore, the high application rates of compost in UA likely raises additional questions. For example, the effects of long-term composting on N_2O emissions are unclear, and strategic management of application scheduling and fertilizer combinations may be required to minimize emissions.[52,53] How the repeated use of compost affects soil carbon sequestration in raised beds is also unclear, though existing evidence suggests that compost-dependent systems may sequester substantial carbon.[54,55] Both topics warrant further study.
4. Study of different case cities is needed to understand how low-tech UA performs across climates and seasons. Our UA sites are in temperate, wet cities in the global north. Impacts likely vary substantially across UA sites in more diverse climates. Furthermore, we only analyzed the 2019 growing season. Future work should include multiple years to develop a more representative snapshot of UA.
5. UA produces social and food outputs. To allocate impacts between the two, we used interviews and surveys. LCA practitioners and social scientists can collaborate to develop methods to better assess UA co-products (e.g., cost-benefit analysis[47]). Another way to consider this web of co-products is through a land use lens, comparing UA to other urban land uses like housing, parks, and industry.[56] LCA results can be sensitive to these allocation methods, which are particularly important for UA work. While we found that the most socially-productive spaces studied (i.e., collective gardens) are also the most carbon intensive, variation in collective garden sites indicates that this is not a strict condition of social good provisioning. Careful allocation of impacts can help scholars and UA

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

Conclusions

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

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Methods

Urban Agriculture carbon footprint (via life cycle assessment)

Goal and Scope

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

We evaluated carbon intensity per kilogram fresh crop to compare between specific crops (available in SI). To account for heterogeneity across UA sites and to facilitate comparisons with the "basket" of conventional produce available in each country, we also calculated carbon intensity per serving of produce. A serving is the recommended mass of a given crop, as defined by nutritionists and doctors, that an individual should consume to align with national dietary guidelines (we use USDA values to unify servings across countries). Servings convert different crops to a single, comparable unit based on their nutritional content and is similar to converting foods to caloric content, [3] with the added benefit of considering macro- and micronutrients. We use the USDA Food Patterns Equivalents Database[4] (FPED) to convert yields to servings, including corrections for food preparation published in the USDA Food Intakes Converted to Retail Commodities Databases (FICRCD).[5] Servings are calculated by converting each food product to servings of fruits and vegetables using both an FPED servings count and an FICRCD conversion value, which converts fresh food to consumed food (i.e., accounts for peeling, etc.) For example, the total fruit servings of any given food are calculated by multiplying the yield in kilograms by the FICRCD conversion, then multiplying this new value by FPED servings (which has to be multiplied by 10 to convert from servings per 100g to servings per kg). All equivalencies between crops grown on-site and standardized commodities are based on the USDA Food and Nutrient Database for Dietary Studies.6 The relevant equivalencies can be found in the online supplemental materials as part of the SI Code and Inputs – "Crops_AllocationCodebook_Current.csv".

Case Studies and Typology

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

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

In this typology, urban farms are primarily commercial enterprises, managed by professional farmers to produce food (producing an average of 4161.98 kg on-site, enough vegetables to feed 40-50 people per year). On average, our urban individual gardens are relatively small, individually-managed plots producing food for their owners and their friends and families (averaging 164.45 kg produce per year). Urban collective gardens are socially-productive spaces supported largely by volunteer labor or non-profit support, producing food for community benefit (an average of 1384.70 kg per year) as a complement to broader community goals such as nature-based education, social justice, and job skills development. And finally, the Mixed model farms escape classification along these axes and are excluded from analyses which rely on this typology.

Life Cycle Inventory

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

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

Life Cycle Impact Assessment

We determined the environmental impact of those inputs and outputs using EcoInvent 3.8[8] and the PEF 3.0 midpoint indicators (specifically Global Warming Potential at 100 years). These impacts were exported from SimaPro to a csv file and then imported into R. In R, we used linear algebra to calculate the life cycle greenhouse gas footprint of each UA site, adding up the material and assembly impacts, use-phase impacts, and end-of-life impacts from all farm site components. For material end-of-life, we used the cut-off principle, meaning that landfill and incineration impacts were assigned to the current life cycle, while recycling impacts were assigned to the following life cycle. We accounted for recycling impacts in recycled inputs on our sites. An alternative would be to credit the systems for avoided impacts as a result of recycling. We tested this modeling choice and found that it had no influence on directionality of the results nor the statistical analysis. We calculated impact per serving by converting harvest values to servings of fruit and vegetables with USDA preparation and nutrition data (see above for details).[2,9] We then divided total impact by total harvest to calculate the per-serving values at farm level reported in this study. These impacts were also assigned to individual crops through co-product allocation, as discussed below.

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

Key dimensions of LCA and sensitivity analyses

Our life cycle assessment is dependent on three major assumptions:

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

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

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

Allocation between food products

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

Food production is measured in terms of mass, caloric, nutrient (NRF 9.3[7]), and economic output, and impacts are allocated to individual crops based on the value of the harvest of that crop (e.g., if 10 kg of tomatoes are harvested and 100 kg are produced in total, tomatoes would be allocated 10% of the food-related impacts under a mass allocation scheme). Mass allocation depended on the harvests recorded by farmers, while caloric and nutrient allocations used USDA food composition data[4,6,8] to convert these masses to calorie and nutrient outputs. Economic allocation was localized to each city, using prices at nearby grocery stores to estimate the economic value of food produced on each site.

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

Percent impacts to food

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

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

Allocation to co-products is a notoriously challenging component of LCA. To test the impacts of our allocation methods and to test the impact of great social productivity on sites, we conduct a sensitivity analysis of the percent of impacts allocated to food and to social services. We test the effects of altering the infrastructure impacts assigned to food by varying them between 0% and 100% (intervals of 5%). Breakeven analyses are discussed in the main text section and shown in the SI. Our results indicate that the majority of UA sites become environmentally friendly at higher levels of impacts allocated to non-food. However, collective gardens do not reach breakeven simply by allocating infrastructure impacts to non-food products; the supply and irrigation impacts exceed the total of conventional agriculture by themselves.

Age of farm at time of removal

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

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

Carbon-Friendly Urban Farms

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

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

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

Synthetic Fertilizer Inventories

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

Conventional Agriculture Comparison

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

Since crops are often imported from multiple locations, this system resulted in 107 unique crop-country combinations required to describe the environmental footprint of vegetables in each of our case study cities. To quantify the climate change impacts, we sought to identify either: 1.) at least 3 LCAs relevant to the crop and the country or 2.) a systematic summary of the impacts of a particular crop in each country. We used this system of focusing on large reviews or multiple case studies to iron out differences between cases and identify a relatively representative mean value for that product from the country of interest. In a few exceptional cases where data were scarce, we could not locate a summary and only identified 2 results. To quantify nutrient inputs, we sought at least one study of N, P, and K inputs into conventional agriculture for each unique crop-country combination. Most crop-country combinations were available from existing summaries. LCAs useful for this summarization come in three forms:

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

See SI for the database of conventional vegetable impacts developed to support this study and the R code used to compare these values to urban crops. In the case of farm-gate studies, we employed reasonable estimates of food waste, travel, and supermarket impacts. Specifically, we assumed food waste rates as reported by peer reviewed articles for the US, UK, and EU. We use EU wastes from Caldeira et al. (3.8% in distribution, 1.3% in retail),[9] UK waste rates from Jeswani et al. (1.6% in processing, 9.6% in retail),[10] and US waste rates from a Commission for Environmental Cooperation white paper[11] combined with USDA estimates[12] of overall waste (3.9% in distribution, 2.5% in retail). For travel, we assumed that vegetables were transported via semi-trailer and ocean freight, since most fruits and vegetables are not perishable enough to justify air freight.[13] We tested the sensitivity of our results to this assumption and found that urban agriculture is still statistically significantly more carbon-intensive than conventional solutions. The exception to this, individual gardens, is discussed in the manuscript. In all travel cases, we assume travel from the capital city of each country or from the largest city in a major agricultural export region. Details can be found in the SI. Using emissions estimates from SimaPro and distance estimates from online tools, we added travel impacts to farm gate studies based on each unique country combination (e.g., products traveling from South Africa to Dortmund were estimated to travel 530 km by road and 11,036 km by sea). Finally, we used a generic supermarket impact value from Burek and Nutter to supplement the farm-gate studies with supermarket emissions.[14]

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

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

Farmer survey

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

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

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

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

Data availability

All data used for this study are available in online supplementary materials. See the attached SI for more details, and see this link for access to the complete online supplementary data.

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