Urban Agriculture’s Bounty: Contributions to Phoenix’s Sustainability

Goals

Nazli Uludere Aragon, Michelle Stuhlmacher, Jordan P. Smith, Nicholas Clinton and Matei Georgescu

Supplemental Information

SI-1 Methods

SI-1-1 Available area estimation for UA. Our approach for determining suitable vacant lots has two stages. First, we identify privately-owned vacant properties based on cadastral data. We then refine this initial inventory using high-resolution imagery (NAIP) and a digital elevation model using GIS and spatial statistics (Smith et al 2017). We exclude built vacant properties or paved vacant lots to avoid the additional cost of converting them into UA sites and count only undeveloped vacant lots. The 2017 inventory informs our baseline estimate and the 2010 assessment is used as a sensitivity.

Prior to computing available rooftop and vertical area using building footprint data from LiDAR, redundant features associated with building footprints (like awnings, overhangs, chimneys, etc.) are eliminated to prevent an overestimation of available area.

For rooftop surfaces, we consider only flat rooftop buildings with base roof area greater than 464.5 m² (5,000 ft²). Existing commercial rooftop UA operations in Europe and the U.S. point towards the use of larger rooftops to facilitate food production at scale (Buehler and Junge, 2016 and Berger, 2013). Larger rooftops are also more likely to have the structural stability for supporting incremental loads from UA substrate, although we do not treat this as a binding constraint in our analysis. Our sample therefore consists of medium- and large-size commercial / industrial buildings, and excludes most single-family homes, producing a conservative estimate for the available rooftop UA area.

To estimate potential area from building façades, we multiply the average of length and width for each building with an assumed vertical cultivable surface of 1.83 meters (6 feet). Cultivation is limited to one building side, based on the location of services (e.g. utility hookup) and appropriate sun exposure. This is an agnostic approach, as we do not restrict UA deployment to...
a specific side, assuming that would be the most advantageous for a façade application. However, we also considered an alternative estimation that is exposure-specific. We estimated the same area using building sides with either south or east exposure, although in Phoenix the south exposure may be undesirable even in the cooler months. Available area is higher by 10% using a south-facing exposure, and by 4% using an east-facing exposure. However, due to excessive radiation loading for south-facing exposure in our study area, the added area will likely not increase crop yield or provide higher benefits. We therefore view our base case assumption as more realistic. Building height does not factor into our estimation of available vertical and rooftop areas. This means we have not eliminated few very short or very tall structures (that meet other criteria) where height might adversely affect crop viability (e.g. on rooftops due to high winds).

**SI-1-2 Crop selection and area allocation.** There are three steps to crop selection and area allocation. The first step is an initial screening of the crops. We start with a list of crops that are grown in Maricopa County commercially (for which data is available). This excludes crops grown on hobby or educational farms which may be experimenting with different crops/varietals. We then eliminate from contention some types of crops due to their physical attributes and potential space and time (crop growth) limitations in a UA setting. Specifically, we exclude perennial tree crops (citrus, other fruit trees), because they would be difficult to grow in an UA setting either due to the medium chosen which may limit rooting depth (e.g. rooftop, vertical) or due to land tenure concerns. We also exclude grains like corn, process-intensive oil crops like sunflowers, feed crops like alfalfa, and non-edible fiber crops like cotton, as well as ornamental crops, since the purpose of UA is to supply food, and mainly fruits and vegetables. We end up with 34 crops that are mostly annual vegetable crops, and a few fruits.

The second step is to rank these 34 crops to determine area allocation. The decision to change land use and/or utilize underutilized spaces associated with buildings (façades, rooftops) will be based on economics. The ranking approach is used to approximate this decision. In absence of detailed estimates for cost, we use water consumption of crops as a proxy for operating (input) costs. Combined with (higher) yields and (higher) prices, the preference lower water use is meant to be a proxy for profitability. We are not suggesting these are the only preferred qualities, but considered the combination of the three to be a practical benchmark. In the case of Phoenix, a preference for crops with lower water use is a sustainability indicator as well.
We then group the 34 crops into terciles based on their rankings. The highest ranked crops are in the top (3rd) tercile, and lowest ranked crops are in the bottom (1st) tercile. Finally, we allocate area proportionally: i.e., larger proportion of area is allocated to crops in the top tercile, and smaller proportion is allocated to crops in the bottom tercile. For example, for a 0.6 ha-sized UA lot, 0.3 ha would be allocated to top tercile crops, 0.2 ha to the second or middle tercile, and 0.1 ha to the bottom tercile.

Below is the list of crops assumed suitable for UA in Phoenix (N=34). The underlined crops (N=22) were assumed suitable for cultivation along building façades. The suitability categories of good, average and poor correspond to the terciles 3, 2, and 1 described above.

| Good        | Average       | Poor          |
|-------------|---------------|---------------|
| Brussels Sprouts | Artichokes    | Broccoli     |
| Herbs       | Beans, Snap   | Cabbage       |
| Lettuce, Head| Beets         | Cauliflower  |
| Lettuce, Romaine| Carrots      | Cucumbers    |
| Onions, Dry | Celery        | Eggplant     |
| Onions, Spring| Greens, Collard| Melons, Cantaloup|
| Parsley     | Greens, Kale  | Melons, Watermelon|
| Spinach     | Greens, Mustard| Peppers, Chile|
| Squash      | Lettuce, Leaf| Potatoes     |
| Strawberries| Melons, Honeydew| Pumpkins   |
| Tomatoes    | Peppers, Bell | Radishes     |
|             |               | Turnips      |

Figure SI-1-2-1: UA crops used in analysis by suitability category. Underlined crops represent the subset assigned for UA applications along building façades.

Figure SI-1-2 shows the dispersion in crop yields (tons/ha), water use (mm/m²) and retail prices ($/ton) for the crops selected for UA in Phoenix by suitability category (described above). Across the three suitability categories, we observe less dispersion in yields, and more variation with respect to prices and water use. Overall, crops in the good category have higher median yields; lower median water use, and retail for higher median prices. The converse is true for the crops in the poor category.
Figure SI-1-2-2. Box plots of unit yields (A), water use (B), and prices (C) for UA crops by crop suitability category. A box plot, or a box-whisker plot is used to show dispersion in data. The box portion bounds the values that lie between the 25th and 75th percentiles for each group (also known as the interquartile range, or IQR). The dividing line in each box shows the median for that group. The whiskers show the upper and lower adjacent values which are calculated as (1.5*IQR)+75th percentile and 25th percentile-(1.5*IQR), respectively. Any values outside these ranges are indicated by a marker, indicating the presence of outlier(s).

We use the following data sources for crop-specific yields, water use, and retail prices. Historical county-level yields are from the USDA annual surveys (2000-2016) for most crops, or the last two observations reported in the Census of Agriculture (2007 and 2012), if annual data is not available. We substitute with comparable county-level data from Southern California, and in absence of that, national yields when yields for Maricopa county are not reported. If a crop (e.g. cucumber) is grown both for fresh market sale or processing, we use fresh market yields.
Crop-specific water needs are obtained from the UN FAO (1986) and two university cooperative extensions (Masabni 2011 at Texas A&M and the UC Davis Vegetable Research Information Center). Urban farmers can have a wide range of farming skill and experience (Waldman et al 2010). Here, we conservatively assume the average urban farmer to be less experienced in farming than their commercial counterparts. Therefore, when calculating output, we use the minimum of historically reported yields. For the same reason, we use the higher estimates for crop-specific water use (if more than one estimate is available).

Crop retail prices are the 2016 averages from regional (in our case, the Southwest) supermarket surveys conducted weekly (USDA AMS 2016).

**SI-1-3 Open green space provision.** First, we determine existing open green spaces, which include all public parks within or adjacent to the study area. Golf courses and school yards are excluded for limited access reasons. We then compute total park area by block group. Where large regional parks overlap or are adjacent to multiple block groups, park area is allocated proportional to block group area.

The size threshold we use for the prioritized deployment case (5,000 m²) is based on the distribution of existing park sizes in Phoenix. More than 95% of all parks in our study area are larger than 5,000 m². However, this cutoff would exclude many proximate (adjacent) small vacant parcels if evaluated individually. Therefore, if such parcels are located within 10m of each other (which is narrower than representative street canyons in Phoenix; see Hedquist and Brazel, 2014) and their aggregation is greater than 5,000 m², they are counted towards the sub-sample of vacant lots used for prioritized deployment. We refer to these larger vacant lots (either on an individual or aggregated basis) as “vacant sites”.

We utilize these vacant sites (which are sub-sample of all available vacant lots for UA) in a walkability analysis. First, we define walkability zones as green open spaces plus a 402-meter (0.25 mile) surrounding buffer. This buffer corresponds to 5-minute walking distance at approximately 4.83 kilometer/hour (3 mile/hour) average walking speed for a typical adult (Browning et al 2006). We then compute these buffers for existing parks and then again for the vacant sites. Finally, we measure the change in total area at the study area-scale before and after UA deployment.
Energy savings and avoided emissions from buildings. We assume electricity is used for both heating and cooling to maintain indoor temperatures between 21°C (70F) and 25°C (77F). Across the U.S. and in Arizona, electricity is the dominant fuel for cooling. For space heating, 3 out of 5 Arizona households rely on electricity, and so do nearly half of commercial buildings in the Western U.S. (U.S. EIA 2016b and 2019).

We then derive temperature gradients between these target indoor temperatures and air temperature data for 2017 using NASA’s GLDAS-2.1 dataset that has a 3-hour temporal and 0.25 arc degrees spatial resolution (Rodell 2004). Summing the 3-hourly gradients over a year produces cumulative $\Delta T$ (heating and cooling needs) in Kelvins (K).

Thermal resistance for rooftops is represented by R-values in m² K/W. Three different R-values are used to characterize existing insulation on rooftops ($R_0$), before any UA substrate is added. These are 1.84 (average, for average roof insulation; representing the baseline), 0.25 (low, for poorly insulated roofs) and 3.66 (high, for well insulated roofs). These values are based on observed values reported in the literature (e.g., Castleton et al 2010; Clark et al 2008; Niachou et al 2001; Vacek et al 2017; Van Hooff et al 2014 and Wong et al 2003). For UA, a 10cm thick, high moisture substrate with an R-value ($R_a$) of 0.25 is added onto roofs (Sailor et al 2008).

Since thermal resistivity of layers are additive, roofs with UA have higher R-values ($R_0 + R_a$).

Avoided energy use due to UA (kWh/block group/year) =

\[
\text{A}_{2j} * \left( \sum_{t=1}^{2920} \frac{\Delta T}{R_0} \right) * \frac{3}{1000} - \text{A}_{2j} * \left( \sum_{t=1}^{2920} \frac{\Delta T}{(R_0 + R_a)} \right) * \frac{3}{1000} = \text{A}_{2j} * \left( \sum_{t=1}^{2920} \frac{\Delta T}{R_0(R_0 + R_a)} \right) * \frac{3}{1000}
\]  

(4)

Where:

- $\text{A}_{2j} =$ Available rooftop area per block group $j$ (m²)
- Unit flux (W, watts) = $A * \Delta T / R$
- $\Delta T =$ Difference between 3-hourly (t) outdoor and indoor target temperature (K)
- $t =$ period in GLADS-2.1 = [1,2920]
- $3/1000 =$ factor to convert to kWh per year
- Indoor temperature targets for Phoenix = 21°C (70F) for heating, 25°C (77F) for cooling
- $R$ is thermal resistance of roof (m²K/W):
  - $R_0 =$ $R_{\text{existing roof}} =$ 1.84 (average); 0.25 (low); or 3.66 (high)
  - $R_a =$ $R_{\text{UA substrate}} =$ 0.25 (10cm thick, high moisture substrate)

Lastly, we convert resulting quantities to kWh/m² and multiply by block group area (m²) to obtain electricity used for heating and cooling in kWh per block group.

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Wong NH, Cheong DKW, Yan H, Soh J, Ong CL, and Sia A (2003). “The effects of rooftop garden on energy consumption of a commercial building in Singapore” Energy and Buildings 35(4):353–64. https://doi.org/10.1016/S0378-7788(02)00108-1.
SI-2  Local fresh produce supply from UA: sensitivity analysis

In our baseline analysis, we use a set of crops that are already grown in Maricopa county (where Phoenix is situated), excluding from that list crops we deem not suitable for UA applications (such as tree crops, fiber crops, etc.). In the sensitivity analysis, we do not deviate from this crop list and maintain the same approach -i.e. ranking according to one or more criteria and then grouping in terciles- so that the sensitivities are comparable to the base case.

We consider two scenarios that alter the ranking and therefore the area allocation for these crops in a UA setting:

(1) The “high productivity” scenario: Rank and then group into terciles our selected crops according to yield alone (productivity).

(2) The “national consumption pattern” scenario: Rank and group into terciles our selected crops based on each crop’s consumption (in primary weight per capita terms) using the 2016 national per capita food availability data from the USDA. If a crop that we selected as suitable for UA in the City of Phoenix does not appear in this summary, which focuses on the most sold individual crops, we assign them the lowest ranking.

Table S-2-1 shows how the suitability category for the crops we selected for UA application vary by scenario. For example, in the base case, potato is ranked 1 (poor) because it is among the low-value / high-water use crops in our list. In the high productivity sensitivity, this crop moves up a rank (2) to the average category, because it is in the middle tercile purely on a kg/ha basis. In the national consumption pattern sensitivity, it moves up to the good category (rank 3) because it is the most consumed vegetable in the country on a (primary) weight per capita basis. *(Recall that rank 3 = good, rank 2 = average, rank 1 = poor; and crops ranked 3 get 3 times the area allocated to them than those ranked 1.)*
Table SI-2-1. UA crops used in analysis by suitability category: base case and two sensitivities.

| Selected crops | Base case | High yield sensitivity | National consumption pattern sensitivity |
|----------------|-----------|------------------------|------------------------------------------|
| 1 Artichokes   | Average   | Poor                   | Average                                  |
| 2 Beans, Snap  | Average   | Poor                   | Average                                  |
| 3 Beets        | Average   | Good                   | Poor                                     |
| 4 Broccoli     | Poor      | Poor                   | Good                                     |
| 5 Brussels Sprouts | Good       | Average               | Poor                                     |
| 6 Cabbage      | Poor      | Good                   | Average                                  |
| 7 Carrots      | Average   | Good                   | Good                                     |
| 8 Cauliflower  | Poor      | Average               | Average                                  |
| 9 Celery       | Average   | Good                   | Average                                  |
| 10 Cucumbers   | Poor      | Average               | Good                                     |
| 11 Eggplant    | Poor      | Average               | Poor                                     |
| 12 Greens, Collard | Average | Poor                   | Average                                  |
| 13 Greens, Kale | Average | Average               | Poor                                     |
| 14 Greens, Mustard | Average | Poor                   | Poor                                     |
| 15 Herbs       | Good      | Poor                   | Poor                                     |
| 16 Lettuce, Head | Good      | Good                   | Good                                     |
| 17 Lettuce, Leaf | Average | Average               | Good                                     |
| 18 Lettuce, Romaine | Good | Good                   | Good                                     |
| 19 Melons, Cantaloup | Poor       | Average               | Average                                  |
| 20 Melons, Honeydew | Average | Average               | Average                                  |
| 21 Melons, Watermelon | Poor | Average               | Good                                     |
| 22 Onions, Dry, Summer, Non-Storage | Good | Good                   | Good                                     |
| 23 Onions, Spring | Good     | Good                   | Poor                                     |
| 24 Parsley     | Good      | Poor                   | Poor                                     |
| 25 Peppers, Bell | Average | Good                   | Good                                     |
| 26 Peppers, Chile | Poor   | Poor                   | Poor                                     |
| 27 Potatoes    | Poor      | Average               | Good                                     |
| 28 Pumpkins    | Poor      | Average               | Average                                  |
| 29 Radishes    | Poor      | Poor                   | Poor                                     |
| 30 Spinach     | Good      | Poor                   | Average                                  |
| 31 Squash      | Good      | Average               | Average                                  |
| 32 Strawberries | Good    | Good                   | Good                                     |
| 33 Tomatoes    | Good      | Good                   | Good                                     |
| 34 Turnips     | Poor      | Poor                   | Poor                                     |

The food supply from UA is higher under both sensitivities (Table SI-2-2). This is not surprising because we relax the constraint on water use and crop value (price), and sort and group crops along a single dimension (yield in one case, and national per capita consumption in the other). Moreover, both sensitivities result in higher water use, but the high yield sensitivity exhibits a smaller increase in unit water use—i.e., response—per each incremental ton of output. On the other hand, the national consumption pattern results in water use response of over 100%. This means for each ton of incremental output in that scenario requires a higher unit use of water.
| Total annual food supply from UA by scenario | **Food supply** | **Water use** |
|--------------------------------------------|----------------|--------------|
|                                            | Tons | Tons per ha | Kg per person | Increase over base case (%) | Water use ('000 m³) | Increase over base case (%) | Water use response (%) |
| Baseline                                  | 182,983 | 25.3 | 124.9 |  | 35,631 |  |  |
| High productivity                         | 211,625 | 29.3 | 144.5 | 16% | 39,741 | 12% | 74% |
| National consumption pattern               | 194,633 | 26.9 | 132.9 | 6% | 38,628 | 8% | 132% |

**Table SI-2-2. Summary results for the food supply sensitivity analyses.** Food supply by scenario in terms primary weight. Water use response is the percentage change (increase) in water use divided by percentage change (increase) in food supply over the baseline.
SI-3  Local fresh produce supply from UA: calorie analysis

We also add a measure of calories to the original measure of weight to describe food supply from UA. We start with the existing primary weight measure (tons/year), which is the harvested amount for the selected set of fruits and vegetables under UA. We then account for food losses along the supply chain and determine the edible weight per crop. These losses occur when going from producer to retailer and from retailer to consumer. The consumers then separate food items into edible and non-edible parts (discarded). The last stage is cooking loss and uneaten food (waste).

Crop-specific loss factors (for year 2016) and edible shares are obtained from the USDA’s Food Availability (Per Capita) Data System (USDA 2018a). After accounting for losses and determining the edible weight by crop, we combine this with the calorie and cup-equivalency data from the USDA’s Nutrient Database for Standard Reference Release (USDA 2018b) for each crop (in terms of kilocalories per 100 grams of edible portion). For six crops in our list (out of 34), there were no corresponding loss factor or edible share estimates in the USDA data. For those, we used the average of existing factors. Also, calories can vary by how each food item is prepared. We make no assumptions concerning that, and use calorie data for the fresh/raw fruit and vegetable. We then derive per capita/day calories based on study area population.

We estimate daily calories for the base case and the two food supply sensitivities. We also consider that retail losses might be lower in the case of UA due to shortened supply chain, and conduct a sensitivity where we assume no retail losses (i.e., from retailer to consumer). In the U.S., total losses accumulated along the conventional supply chain average 51% for vegetables and 57% for fruits (share of primary weight, 2016 figures from USDA 2018a). For our crop mix, the comparable mean loss rate is 60%; ranging from a low of 38% (tomatoes) to a high of 83% (pumpkins). If we assume away the retail losses, the average loss factor decreases to 46%.

Table SI-3-1 provides summary results from this analysis. Based on primary weight, the base case per capita output from UA represents 90% of the national average consumption of fresh fruits and vegetables. Under the two food supply sensitivities, food supply from UA is higher and closer to existing national per capita consumption of fruits and vegetables. On a loss-adjusted basis, the ratio of per capita UA food supply relative to the national average is slightly lower (86%, base case) because of the higher UA supply of some crops with higher loss rates (e.g. artichokes, melons).

Estimated food supply from UA yields fewer calories compared to the national averages from fruits and vegetables (driven mainly by our overall less use of calorie-dense crops like...
potatoes). Daily calories from UA food supply range from 42 kcal/person/day under the base case, to 60.5 kcal/person/day under the high productivity sensitivity and assuming no retail losses. Nationally, the average daily calories from the consumption of fresh fruits and vegetables are estimated at 92 kcal/person/day.

However, we also calculate the cup equivalent measures (using conversion factors from USDA 2018b) which form the basis of recommended fruit (2 cups) and vegetable (2.5 cups) daily intake in the Dietary Guidelines for Americans (U.S. Department of Health and Human Services and U.S. Department of Agriculture 2015). On a cup-equivalent basis, the food supply from UA is higher than the national average under the base case (1.38 vs 1.40), as well as under all the other scenarios we consider (Table 3, final column). Yet, even under the high productivity scenario, and assuming no retail losses, the UA food supply would meet only the half of the recommended daily intake amounts on a cup-equivalent basis.

| Study area averages under UA | Food supply scenario | Losses | Weight (kg/person/year) | Daily calories (kcal/person/day) | Cups per day (cup equivalent per person/day) |
|-----------------------------|----------------------|--------|-------------------------|----------------------------------|--------------------------------------------|
|                            | Base case            | Conventional | Primary | Loss-adjusted | Loss-adjusted | Loss-adjusted | Loss-adjusted |
|                            |                      |         | 124.9 | 55.6 | 42.0 | 1.40 |
|                            |                      |         | 144.5 | 64.1 | 48.8 | 1.55 |
|                            |                      |         | 132.9 | 58.8 | 45.4 | 1.42 |
|                            | High productivity    | No retail loss | 124.9 | 71.0 | 53.0 | 1.86 |
|                            |                      |         | 144.5 | 80.6 | 60.5 | 2.00 |
|                            |                      |         | 132.9 | 75.7 | 57.6 | 1.89 |
|                            | National consumption pattern | Conventional | 138.7 | 65.0 | 92.0 | 1.38 |

Table SI-3-1. Per capita availability of fresh produce. Summary results from UA and comparison with U.S. averages by primary and loss-adjusted weight (kg/person/day), daily calories and cups equivalent per day. National consumption figures based on per capita food availability data from the USDA (2018a) for fresh vegetables and non-citrus fresh fruit. In the Losses column, “conventional” means all losses along the traditional food supply chain are included; “no retail loss” means we assumed away losses when going from retail to consumer.

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SI-4  Other data used in the analysis

**SI-4-1 Income, housing characteristics and demographics.** We use data from the American Community Survey (ACS) 2012-2016 5-year estimates (U.S. Census Bureau 2018c) for block group level data on population, income, home values, receipt of supplemental nutrition assistance (SNAP) benefits and age of residential structures.

**SI-4-2 Food deserts.** We use the USDA’s latest national assessment of food deserts based on income and access to retail food outlets (ERS 2015 and Rhone et al 2017). All the retail food outlets included in the USDA’s assessment of food access sell fruits and vegetables (Ver Ploeg et al 2012). We use the half-mile measure that qualifies a food desert as a low-income census tract with a significant number (at least 500 people) or share of the population (at least 33%) that is more than 0.5 mile (0.8 kilometer) from the nearest supermarket, supercenter, or large grocery store for an urban area. A low-income census tract has either (i) poverty rate >20%; or (ii) median family income ≤ 80% of the state-wide median family income; or (iii) median family income ≤ 80% of the metropolitan area median family income.

The USDA’s definition of food deserts is a widely used measure of food access in the U.S. This is relevant to our analysis, because the City of Phoenix’s sustainability goal under local food systems is the “elimination of food deserts”, and the city also utilizes the same USDA definition of food deserts.

**SI-4-3 Buildings and energy.** As benchmarks for the results from the buildings and energy analysis, we use Arizona-level data on electricity consumption by end-use sector and CO₂ emission rates from electricity generation (U.S. EIA 2018b). We also rely on the City of Phoenix’s 2012 inventory of city-wide GHG emissions (City of Phoenix 2017b). To estimate total electricity consumption in our study area, we calculate per capita electricity consumption for the entire state and then scale this up by the study area population. These are summarized in Table SI-4-2-1:
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Table SI-4-2-1. Reference figures for contextualizing avoided energy and emissions estimates from rooftop deployment of UA. All energy and emissions figures are for year 2016 and from the EIA (2018b), except (*) from the City of Phoenix (2017b) and (**) from the U.S. Census Bureau (2018c).

Table SI-4-4-1. Average residential land price estimates for various areas of interest. Table summarizes average residential land price estimates from Davis et al (2019) using 2012-2017 pooled cross-section data. The averages are calculated over census tract-level estimates.
We do not know which vacant lots we identify would be candidates for residential or commercial (including industrial) development (in absence of UA). Commercial land values can diverge from residential land values for economic reasons. Residential property values reflect locational amenities valued by households (good schools, availability of employment opportunities, recreation and transportation options; low crime, etc.). Commercial property values also depend on location, but are more sensitive to the proximity to roads, airports, and railroads; nearby complementary businesses; and the income and demographics of the local population (Nichols et al 2010).

Albouy et al (2018) estimates a combined average for residential and commercial land prices for the Phoenix metro area at $1.1 million/hectare. This is higher than the residential-only average land price based on Davis et al (2019). Hence, the cost of land for UA we calculate can be treated as a lower bound.

Table SI-4-4-2 shows the urban land value estimates for a select number of US metro areas for 2005-2010, adapted from Table 2 of Albouy et al (2018). Values for Phoenix are highlighted in yellow. Average urban land values for Phoenix metro area is estimated to be $452,000 per acre, or $1.1 million per hectare. For the quarter mile zone around the downtown areas, the land values jump to $3.5 million per acre, or $8.7 million per hectare. This study finds New York City to have the most expensive land, and San Francisco ranks fourth. The study reports land values over $300 million per hectare in the heart of New York City, and $13 million per hectare for the metro area. For San Francisco, values in the city center average over $40 million per hectare, and average over $8 million for the entire metro area.

Average residential land value from Davis et al (2019) for the comparable area (Phoenix metro) is $720,748/ha. Note that this average is based on census tract level estimates; covers a later period than Albouy et al (2018); and is estimated using a different method, a different data source, and with a larger sample size. With those caveats in mind, we note that the average estimate for bundled land values from Albouy et al (2018) is higher than the estimate for residential lands alone. If we assume the two studies are comparable, then we can conclude commercial land values are higher than residential land values. In that case, the weighted average cost of land for UA that we calculate in the main text can be considered a lower bound.
Table SI-4-4-2 Metro-area level land values adapted from Table 2 in Albouy et al. (2018). Shows 1250 metro areas are ranked by average (estimated) urban land values. Here, the top ten based on Albouy et al. (2018)'s analysis and a selection of other large metro areas for comparison are included. Land value data from CoStar COMPS database for years 2005 to 2010. Simple average is based on raw, observed prices per acre. The two estimated value columns are Albouy et al. (2018) model results. The first is the estimated average land value for the entire urban area. The second reports estimated land values within ½ mile radius from downtown (or multiple downtowns). The data is pooled for all types of land sales. Dollars per hectare ($/ha) conversion involves multiplying $ per acre values with 2.47105, and are done by us. Values for Phoenix metro area are highlighted.

| Rank | Metro area name | Total urban area (sq miles) | Number of land sales | Simple average | Estimated average value for the entire urban area | Estimated value for the city center | Simple average | Estimated average value for the entire urban area | Estimated value for the city center |
|------|----------------|-----------------------------|----------------------|---------------|-----------------------------------------------|----------------------------------|---------------|-----------------------------------------------|----------------------------------|
| 1    | New York, NY   | 749                         | 1,603                | 26,139        | 5,264                                         | 123,335                          | 64,591        | 13,008                                        | 304,767                          |
| 2    | Jersey City, NJ| 47                          | 43                   | 7,067         | 3,305                                         | 9,554                            | 18,946        | 8,167                                         | 23,608                            |
| 3    | Honolulu, HI   | 198                         | 56                   | 4,357         | 3,290                                         | 16,256                           | 10,766        | 8,130                                         | 40,169                           |
| 4    | San Francisco, CA | 300             | 152                  | 8,722         | 3,239                                         | 25,446                           | 21,553        | 8,004                                         | 62,878                           |
| 5    | Los Angeles--Long Beach, CA | 1,359     | 1,760               | 3,709         | 2,675                                         | 16,801                           | 9,165         | 6,610                                         | 41,516                           |
| 6    | Orange County, CA | 494              | 233                  | 3,163         | 2,595                                         | 3,208                            | 7,816         | 6,412                                         | 7,927                            |
| 7    | San Jose, CA   | 305                         | 217                  | 2,580         | 2,347                                         | 3,552                            | 6,375         | 5,800                                         | 8,777                            |
| 8    | Miami, FL      | 372                         | 1,233                | 3,052         | 1,794                                         | 4,478                            | 7,542         | 4,433                                         | 11,065                           |
| 9    | Stamford-Norwalk, CT | 179           | 19                   | 2,753         | 1,505                                         | 2,740                            | 6,803         | 3,719                                         | 6,771                            |
| 10   | Bergen-Passaic, NJ | 316           | 79                   | 1,957         | 1,423                                         | 4,145                            | 4,836         | 3,516                                         | 10,243                           |
| 11   | Washington, DC-MD-VA-WV | 1,458  | 1,840               | 3,548         | 1,214                                         | 36,913                           | 8,767         | 6,000                                         | 91,214                           |
| 12   | Las Vegas, NV-AZ | 317            | 2,553                | 1,193         | 219                                          | 849                              | 1,841         | 2,098                                         | 4,549                            |
| 13   | Chicago, IL    | 2,035                       | 3,511                | 1,455         | 663                                           | 37,632                           | 3,595         | 1,638                                         | 92,991                           |
| 14   | Boston, MA-NH  | 1,295                       | 122                  | 1,243         | 600                                           | 8,457                            | 3,072         | 1,483                                         | 20,898                           |
| 15   | Denver, CO     | 536                         | 2,015                | 828           | 539                                           | 7,586                            | 2,046         | 1,332                                         | 18,745                           |
| 16   | Phoenix-Mesa, AZ | 897            | 5,946                | 370           | 452                                           | 3,529                            | 914           | 1,117                                         | 8,720                            |
| 17   | Dallas, TX     | 1,057                       | 811                  | 454           | 305                                           | 2,774                            | 1,122         | 754                                           | 6,855                            |
| 18   | Houston, TX    | 1,341                       | 1,143                | 423           | 272                                           | 2,813                            | 1,045         | 672                                           | 6,951                            |
| 19   | Detroit, MI    | 1,426                       | 679                  | 456           | 270                                           | 2,321                            | 1,127         | 667                                           | 5,735                            |
| 20   | Atlanta, GA    | 2,105                       | 5,229                | 402           | 251                                           | 1,750                            | 993           | 620                                           | 4,324                            |
| 21   | Pittsburgh, PA | 1,003                       | 240                  | 433           | 156                                           | 1,772                            | 1,070         | 385                                           | 4,379                            |

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SI-5 Change in available vacant lot area between 2010 and 2017

Change in undeveloped vacant lot area between 2010 and 2017 was calculated for 562 block groups in the study area. We record more block groups with a decline in vacant lot area (N=345, red) than those with an increase (N=161, blue). For 56 block groups (yellow), the absolute change in vacant lot area was less than 50m² -- an amount small enough to constitute measurement error. Block groups that had no undeveloped vacant lots inventoried in either year (N=280; grey) were excluded from this analysis, as well as a subset of block groups (N=68; striped) that had data comparability issues.

**Figure SI-3-1.** Change in available (unpaved) vacant lot area for UA between 2010 and 2017.

There is some evidence of clustering in the changes by block group (using Moran’s I spatial autocorrelation measure, p<0.05). Targeting areas where vacant lots persist--determination of which requires more than one change period and thus beyond the scope of this paper--might be a strategy to achieve sustainable contributions from UA, even if this means the area deployed for UA would be lower than the maximum possible.
SI-6 Water use and cost

SI-6-1 Water use by UA. We assume UA applications use municipal (potable) water to take advantage of existing urban infrastructure. We are not converting land or building surfaces with existing irrigation water use into UA, therefore, estimated UA water use is incremental to current municipal water use in the City of Phoenix.

Total estimated annual crop water use by UA across all three types of surfaces is 35,630,953 m³ (or 9,412,706 thousand gallons). This is calculated as follows:

Total water use (gallons) = Total acres by crop (acres) * Water use by crop (inches / acre) * 27,160 (gallons / inch)

Here, the total area planted to each crop is estimated as part of our analysis. We use independent estimates of water use by each crop during growing season (see SI-1-2). The last term is a constant representing the volume of water that would cover an area of 1-acre at 1-inch deep.

We then convert gallons of water use by crop into cubic meters by crop (where 1,000 U.S. gallons are equivalent to 3.78541 cubic meters). Lastly, we sum water use across all 34 crops. The amount of water used is specific to the baseline crop selection and area allocation, and would change under alternative configurations (e.g., the sensitivities reported in Table SI-2-2).

Figure SI-6-1 shows the annual water use (sorted) by crop and indicates crops that are above versus below average water users.

According to the City of Phoenix, municipal water use was about 400,000 acre-feet in 2014. An acre-foot is a unit of volume equal to a sheet of water to cover one acre (=0.405 hectare) to the depth of one foot (=30.48 cm). It is equal to 1,233.5 m³ (or 325,851 gallons). Thus, on an aggregate basis, the annual water use by UA crops is 7.2% of municipal water use in Phoenix.

The state’s annual water consumption is about 7 million acre-feet, 74% of which is used for irrigated agriculture (2017 figures from ADWR, undated-1). Our assessment of UA for Phoenix would add 0.6% to state water usage.
Figure SI-6-1. Annual water use by selected UA crops (cubic meters), sorted from lowest to highest by water use.

**SI-6-2 Indicative cost of water for UA applications in study area.** We calculate indicative water cost to UA operators based on current monthly municipal water rates for City of Phoenix (2019). The rate structure has a fixed and a variable (volumetric) component. The fixed component varies by meter size; location (inside vs. outside the city); and season (low-medium-high season; where high season is June-September). During the low/medium seasons, 6 units of water (1 water unit = 748 gallons), is included in the fixed charge. For locations inside the city, the lowest fixed charge is $5.50 and the highest is $24.60 per month. The volumetric component also varies seasonally and by location. For locations inside the city, the volumetric rates are $3.05 (low season); $3.56 (medium season) and $3.90 (high season) per month. Effective March 2019, there is also an environmental charge levied on all users. For users inside the city, this environmental charge is $0.56 per water unit.

For UA applications, we assume an indicative $10 per month fixed charge per site, and a volumetric charge of $3.31 per water unit per month over an 8-month growing season from October to May (outside of the June-September high water rate season). The $3.31 volumetric
We add the environmental charge of $0.56 per water unit to the volumetric charge. We treat each vacant lot, rooftop or façade UA application identified in our analysis as a unique metered site for water consumption. We then estimate total water use equal to 16.3 gallons/m² per month, based on crop water use; the area of each UA site; and area allocated to each crop per site. In our study area, the typical (average) vacant lot UA operation is estimated to consume 120.6 m³ (31,859 gallons) per month; typical rooftop UA application 117.1 m³ (30,922 gallons) per month and building façade applications about 1.87 m³ (494 gallons) per month (based on unit areas in Table 2).

We then apply the assumed water rate structure for the UA sites. Note that even though most of the actual water use would take place over an 8-month growing season, users would pay the monthly fixed charge for the entire year (12 months). The estimated annual average water cost is comparable for vacant lot and rooftop UA sites at about $0.64/m² and nearly $4/m² for building façades. Applications along building façades have a higher cost of water, because they are smaller in size (area) and need to pay the entire fixed charge even though monthly water use could be much smaller than the 6 water units included as part of the fixed charge.

Finally, we compare this $/m² water cost to that of fertilizer, which is generally considered to be an expensive (and necessary) input for agriculture. We assume the application of a complete fertilizer mix suitable for vegetable gardens (containing twice as much phosphorus (P) than nitrogen (N) or potassium (K), e.g. 10-20-10 N-P-K) at a rate of 1,221 kg/ha per year (or 2.5 lbs per 100 ft² – an average rate for vegetable gardens). Using national fertilizer prices from the ERS (2015) over 2007-2014, we estimate the average cost of a complete fertilizer is about $705 per ton. Multiplying this with the application rate (e.g. 705 $/ton * (1,221 kg/ha / 10⁷), we calculate fertilizer cost at 0.086 $/m².

We focus on local impacts in this paper. However, both water (irrigation) and synthetic fertilizers could have potentially large off-site CO₂ footprints associated with their use. Use of reclaimed water instead of potable water where feasible, and minimal application of commercial fertilizers supplemented with compost are sustainable practices that can mitigate some of these lifecycle impacts.
Estimated water use by mesic landscapes and backyard pools in Phoenix. To provide context for the estimated water use by UA, we compare it to water use for maintaining existing mesic landscapes (e.g. turfgrass) and backyard pools in Phoenix.

We assume about 30% of residential structures in our study area have a pool (N=547,000*30%; based on LiDAR data) and the typical backyard pool to contain 45.4 m³ (12,000 gallons) of water with a surface area of 20 m² (0.005 acres). Based on a water evaporation rate of 1.83 m (6 feet) per year (ADWR, undated-2), we estimate total annual water consumption of pools at 4,865 acre-feet in our study area. This is equivalent to 6,002,102 m³ (1,585,588 thousand gallons).

We also assume a similar proportion (30%) of all properties—but this time including commercial structures as well (N=800,000*30%)—maintain year-round turf grass of about 80 m² (0.02 acres). Acceptable quality turf grass is assumed to use water at a rate of 4.2 feet per year in the Phoenix area (University of Arizona Cooperative Extension). Total water consumption of turfgrass in our study area is therefore estimated at 19,927 acre-feet, equivalent to 24,578,990 m³ (6,493,085 thousand gallons). The combined water use by residential backyard pools and turfgrass is 30,581,092 m³ (8,078,674 thousand gallons). This amount corresponds to 86% of estimated UA water use of 35,630,953 m³ (9,412,706 thousand gallons).

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Reduced building electricity use and CO₂ emissions savings from rooftop UA deployment

**Calculation of avoided emissions.** The avoided CO₂ emissions associated with building energy savings are calculated using the actual CO₂ emissions rate for power generation in Arizona (U.S. EIA 2018b). This rate is 901 lbs/MWh for 2016, equivalent to 0.409 tons/MWh. The city of Phoenix is part of the grid in Arizona, which is in turn part of the larger Western Interconnection. Because of this interconnectedness, it is not physically possible to determine the underlying supply mix for electricity consumed in Phoenix. Therefore, we assume it is the same as the supply mix for Arizona. We also assume all buildings for which we estimate energy and emissions savings are grid-connected.

**Alternative analysis based on building age.** The underlying spatial distribution of median year built data (U.S. Census Bureau, 2018b) by block group is shown in Fig. SI-7-1. In our study area, the block groups nearer the city’s historic core tend to have the oldest buildings and the outlying block groups have the newer buildings.

Figure SI-7-1. The spatial distribution of median year structure built by quartiles of block groups.
Table SI-7-1 shows the breakdown of total avoided electricity use and associated CO₂ emissions savings shown in Fig. 6B by building age category. The avoided CO₂ emissions are calculated as above. We assign the average (1.84), low (0.25), and high (3.66) R-values to quartiles of block groups based on the median year structure built.

The U.S. Department of Energy’s commercial reference buildings data provides support for our assumption associating roof insulation with building age (U.S. DOE 2010). According to this data, which represents approximately 70% of the commercial building stock in the U.S. (Deru et al. 2011), roof R-values are lower for buildings constructed prior to 1980, and higher for those constructed from 1980 to 2004. The data indicates R-values for the latest vintage of buildings (constructed post-2004) are lower, possibly due to less strict building codes. Because the median year built for 98% of the block groups in our sample precedes 2004, we maintain our assumption that amount of roof insulation is inversely related with building age.

Block groups in the top quartile have the newest buildings (median year built varying from 1988 to 2006) and are assigned the highest Rₒ-value. Block groups in the bottom quartile have the oldest buildings (median year built varying from 1939-1968) and are assigned the lowest Rₒ-value. The block groups in the interquartile range (IQR, combination of the 2nd and 3rd quartiles, with median year built varying from 1967-1987) are assigned the average Rₒ-value. Twenty block groups had no reported data on median year structure built, and which were assigned the average Rₒ-value. We then compute total avoided electricity use and emissions across block groups.

| Quartiles of block groups by median year structure built | Assigned thermal resistivity (Rₒ) | Avoided electricity use (MWh) | Avoided CO₂ emissions (metric tons) |
|-------------------------------------------------------|----------------------------------|--------------------------------|-------------------------------------|
| Top (1988-2006)                                        | High                             | 11,015                         | 4,502                               |
| IQR (1969-1987)                                        | Average                          | 50,568                         | 20,666                              |
| Bottom (1939-1968)                                     | Low                              | 1,042,747                      | 426,156                             |
| **Total**                                             |                                  | **1,104,329**                  | **451,324**                         |

Table SI-7-1. Total avoided electricity use (kWh) and CO₂ emissions (tons) with Rₒ-values varying with building age. Each row represents the subtotal of avoided electricity use and corresponding CO₂ emissions over block groups that belong to the indicated quartiles (top, bottom, or the interquartile range – labeled IQR) of median building age. Quantities in the final row is the sum of these three rows.

The estimated total reduction in building electricity use of 1,104,329 MWh savings represent 3.7% of total commercial electricity use in Arizona, and 6.7% of the estimated electricity use in
our study area. Total avoided emissions of 451,324 tons. account for 14.7% of commercial
building GHG emissions in Phoenix (City of Phoenix 2017b). Block groups with the oldest
buildings and largest UA rooftop area achieve the largest benefits.

The criteria used for determining suitable rooftops for UA (flat and >464.5 m² area) might
preferentially select commercial buildings for UA provision. We do not have the same granularity
of data on commercial building age in our study area. We know, however that commercial
building stock in the region (specifically, the Mountain West census division of the U.S.) is of
similar vintage newer (median year built = 1984; U.S. EIA 2016c) to the residential building
stock (median year built = 1980-1989; U.S. EIA 2018b). Therefore, the savings shown in Fig. 6B
are not likely to be sensitive to the underlying building type (residential or commercial).

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