Vibrant Land: The Benefits of Food Forests and Urban Farms in San Antonio

MAY 2023

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The Benefits of Food Forests and Urban Farms in San Antonio

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The Natural Capital Project

San Antonio Urban Agriculture Analysis

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SUGGESTED CITATION:

Guerry, AD, M. Hagney, B. Janke, L. Liu, E. Lonsdorf, C. Nootenboom, and J. Silver. 2023. Vibrant Land: The benefits of food forests and urban farms in San Antonio. The Natural Capital Project at Stanford University, Stanford CA, USA. May 18, 2023.

ACKNOWLEDGEMENTS

Contributing experts from:

- San Antonio Office of Innovation
- San Antonio Office of Sustainability
- San Antonio Metropolitan Health District

Layout:

- Talia Trepte, Communications Assistant, Natural Capital Project

Financial Support:

- Charles & Roberta Katz Family Foundation
- Peter and Helen Bing
- Marianne and Marcus Wallenberg Foundation
- NASA grant NO. 80NSSC22K1701
- University of Minnesota Institute on the Environment

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Executive Summary

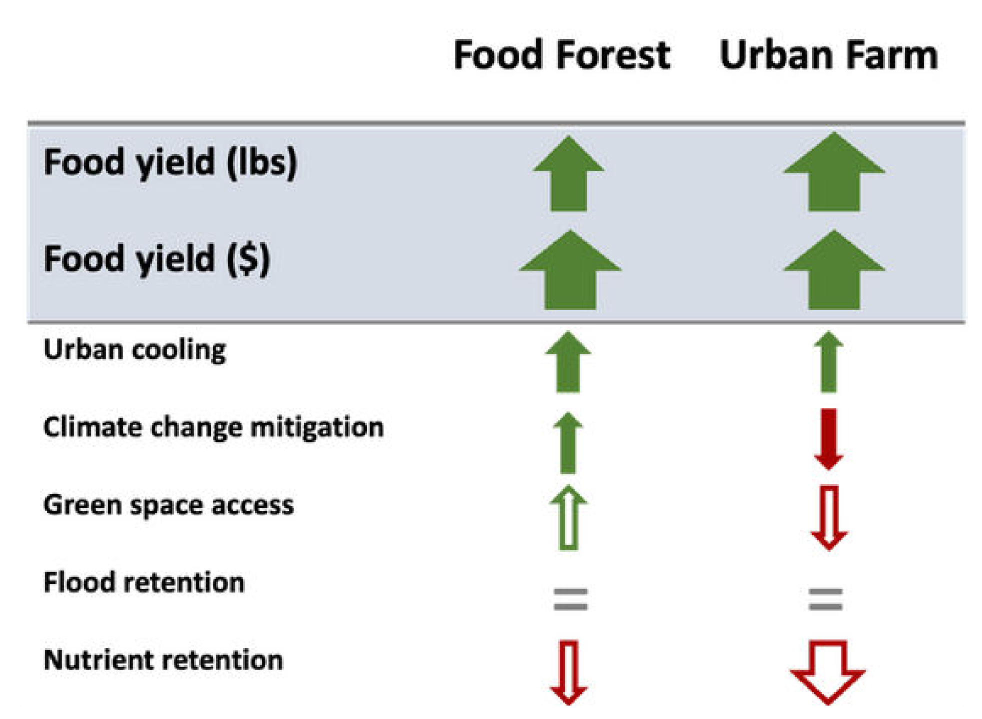
Background and Project Overview:
Urban agriculture can provide cross-cutting benefits: supporting local food production and increasing access to healthy food across San Antonio, while simultaneously offering urban cooling, carbon sequestration, flood retention, and access to green space. A coalition of leaders from the Food Policy Council of San Antonio and from three San Antonio city departments (Innovation, Metro Health, and Sustainability) worked with Stanford University's Natural Capital Project to quantify key benefits of urban agriculture across the city of San Antonio, with the goal of informing decisions about investments in urban agriculture throughout the city.

We used current San Antonio urban agriculture sites, including Tamōx Talōm Food Forest and Garcia Street Urban Farm, to inform assumptions about farming practices and crop selection and to estimate yield. We also used state-of-the-art modeling to quantify and map the environmental co-benefits of urban agriculture. To more fully understand the possibilities for urban agriculture in the city, we estimated the food yields and co-benefits of food forests (urban orchards) and urban farms at three scales: individual case studies, city districts, and citywide. Throughout our analyses, we explored the potential benefits of investing in urban agriculture on underutilized properties (such as city-owned vacant lots) and looked for ways to improve equity in the flow of those benefits to people.

Key assumptions and caveats: This is a modeling study focused on urban food forests and farms. To understand its implications, it is important to understand what we did and did not include. While San Antonio has a number of community-based organizations working at the neighborhood scale to advance local food production through community gardens, they are not the focus of this study. Because we based our models on information and practices from existing farms and food forests in San Antonio, they primarily represent regenerative practices (no till, pollinator forage, efficient water use, no industrial fertilizer), though we assume moderate levels of annual compost application on farms. Changes in agricultural practices could lead to changes in expected outcomes. All comparisons we make are between existing land use (publicly-owned, underutilized, vacant, undeveloped lands) and transitioning those lands to urban farms or forests. We assume that urban food forests are accessible to the public and that urban farms are not.

Results:

Urban food forests and urban farms can increase access to high-quality foods by providing abundant, healthy, fresh food from very localized production. We show that linking demand (from households facing food insecurity) with supply (of underutilized publicly owned land for urban agriculture) can help guide decision-makers in implementing urban agriculture where it will be most beneficial to vulnerable communities. District 3 and 5 have the highest rates of food insecurity, according to SNAP usage, in the city and are thus good locations to invest in urban agriculture. However, these districts differ significantly in their supply of available underutilized lands, with District 3 having the most publicly owned green space in the city and District 5 having the least.



Summary figure. Relative food yield (in pounds and market value) and co-benefits provided by food forests and urban agriculture in San Antonio. Green arrows indicate increased benefits relative to today's baseline. Equal signs indicate little to no change. Red arrows indicate decreases in benefits. The empty arrows for green space access reflect that we made broad assumptions about current access to underutilized lands, farms, and forests; empty arrows for nutrient export reflect that agricultural practices could significantly mitigate this effect.

Food forests provide less food (by weight) than urban farms but potentially similar value, and forests can offer significant additional ecosystem service co-benefits such as urban cooling, carbon storage, flood retention, and green space access. Food forests may increase nutrient pollution (e.g., from litterfall) relative to underutilized lands, but these increases are negligible and can be easily mitigated with management practices. This analysis shows food forests provide small benefits in terms of flood retention compared to baseline underutilized lands, but this service is likely significant compared to alternative development options that would add impervious surfaces (e.g., asphalt).

Overall, urban farms provide more food than food forests but fewer co-benefits, and could add nutrient pollution to the water system (e.g., from compost or erosion), though on-farm practices can significantly mitigate this cost. Urban farms provide some cooling services, but they store less carbon than existing underutilized lands, decrease green space access, and decrease flood retention services as well.

To understand the maximum benefits that could flow from large-scale urban agriculture, we examined hypothetical scenarios in which we converted all available, publicly owned, underutilized natural lands to food forests or urban farms (see summary figure). Compared to today's baseline, we found that:

- Food forests on underutilized lands could provide:
  - 192+ million pounds of food/year (worth $995M; enough to feed nearly 314,000 households)
  - $3.5M worth of urban cooling services that mitigate the urban heat island
  - Additional co-benefits of carbon sequestration, flood retention, and green space access.
- Urban farms on underutilized lands could provide:
  - 926+ million pounds of food (worth $1.17B; enough to feed 1.27 million households)
  - Some cooling services
  - However they may increase nutrient runoff into the city and decrease carbon sequestration and green space access.

Recommendations:

A mixture of urban farms and urban food forests will likely provide the best portfolio of benefits to the people of San Antonio. Based on our modeling assumptions about crops and farm management for each type of urban agriculture, this study suggests that urban farms provide more food but fewer co-benefits, while urban food forests provide less food and more co-benefits. We recommend that the city of San Antonio:

- Consider neighborhood effects when siting farms and food forests – who will benefit and who may bear the costs (such as reduced access to public green space). Such considerations could help target farms in places where many households experience food insecurity.
- Invest in additional actions such as:
  - Opening additional public access to green space if it has been reduced by the addition of a farm.
  - Using additional best management practices, such as reducing compost application, to limit costs like nutrient pollution.
- Implement policies directed at increasing urban agriculture to take advantage of environmental co-benefits. Such policies could include:
  - Expanding the existing Community Toolshed[1] to include agricultural equipment like trenchers, tillers, tree augers, broadforks, and walk-behind tractors,
  - Making certain public lots available under a long-term lease for urban farmers, and
  - Integrating the installation and maintenance of food forests into land management plans for public space by the Parks and Public Works departments.

Next steps and future work:
In future work, we plan to drill down further to assess the benefits of converting individual parcels to food forests or urban farms. This will offer useful information for prioritizing investments in urban agriculture that seek to provide multiple benefits in equitable ways.

In addition, San Antonio is a pilot city in the Natural Capital Project's development of a user-friendly toolkit for urban planners to apply this assessment approach and explore how different development scenarios would affect the equitable distribution of nature's benefits. This new work is funded by NASA's Environmental Equity and Justice program. The team is building a web-application so that users without particular technical expertise can change individual parcels or groups of parcels on a map to see how those changes might impact the delivery of selected benefits. An initial version of this tool is now ready for demonstration. Feedback at this point will help create a tool with maximum utility for informing urban planning decisions–regarding urban agriculture or other changes in land use–in San Antonio and elsewhere.

[1] City of San Antonio Development Services Department – Code Enforcement Services. (2023). Community Tool Shed. City of San Antonio. https://www.sanantonio.gov/ces/resources/toolshed

Introduction

San Antonio struggles with food insecurity, urban heat islands, and flood risk, with serious consequences that are not equitably distributed across the city. According to Feeding America, more than one in five children[2] in San Antonio lack access to healthy foods—leading to increased risk for obesity, diabetes, and heart disease. Food insecurity is most prevalent in under-resourced communities, many of which are concentrated in Districts 1-5. Compared to citywide averages, these five districts have greater SNAP usage (14% - 34%; compared to 13%), poverty rates (15% - 30%; compared to 15%), and minority populations (78% - 97% non-white; compared to 71%; Figure 3). The urban heat island effect causes dense urban areas of San Antonio–predominantly low-income neighborhoods–to be up to twenty degrees hotter[3] than peri-urban areas. San Antonio and Bexar County hold the highest number of fatalities resulting from flash flooding in Texas, according to 2019's Climate Ready Vulnerability and Risk Assessment[4]; low-income neighborhoods in city council Districts 1-5 face the highest risk.

Urban agriculture offers an opportunity to provide cross-cutting benefits to alleviate effects of food insecurity, urban heat, and flooding all at once. In July 2020, a City Council Consideration Request[5] issued recommendations for enhanced urban agriculture after San Antonio's Food Insecurity Task Force, during the height of the COVID-19 Pandemic, declared, "Urban Farms serve important community purposes, including environmental services, community food security, economic generation, and community and neighborhood building." Among their benefits, councilmembers state that urban farms and forests "reduce urban heat island effects, reduce standing water in areas of inadequate drainage and resulting vector-borne diseases, reduce stress, anxiety, and depression, i.e. increase mental health, result in improved flooding infrastructure, [and] responses to flooding." This report is a first step towards mapping and quantifying the full set of these benefits, exploring the equity of their distribution, understanding potential trade-offs, and considering where best to prioritize investments in urban agriculture.

[2] Feeding America. (2023). *Map the Meal Gap: Food Insecurity among Child (<18 years) Population in the San Antonio Food Bank Service Area*. Feeding America. https://map.feedingamerica.org/county/2017/child/texas/organization/san-antonio-food-bank

[3] Sandoval, E. (2022, July 26). In San Antonio, the poor live on their own islands of heat. The New York Times. https://www.nytimes.com/2022/07/26/us/texas-heat-poverty-islands-san-antonio.html

[4] City of San Antonio. (2019). SA Climate Ready Vulnerability & Risk Assessment. https://www.sanantonio.gov/Portals/0/Files/Sustainability/SAClimateReady/Vulnerability-Risk-Assessment.pdf

[5] City Council, & Havrda, M. C., Council Consideration Request (2020). San Antonio, Texas; City of San Antonio. https://webapp9.sanantonio.gov/ArchiveSearch/Viewer2.aspx?Id=%7b582DE0B3-54C5-4682-863E-6A475A486B3A%7d&DocTitle=City%20Council%20Consideration%20Request:%20Councilmember%20Melissa%20Cabello%20Havrda&PageNo=&TotalPages=&MimeType=.pdf&RelatedDocs=

It is important to note that while urban agriculture provides many services to people, there is the potential for disservice too. For example, urban farms can increase nutrient loading to local water bodies through the addition of nutrient-rich compost or fertilizer, with negative impacts to water quality and stormwater treatment costs. Urban agriculture is, by its very nature, located near more impermeable surfaces than more rural agriculture, decreasing the ability of the landscape to mitigate nutrient pollution. San Antonio's focus on implementing best management practices supporting regenerative urban agriculture, exemplified by the no-till, diversified Garcia Street Urban farm, will help to ensure that as urban agriculture is scaled up it is done so in a sustainable way.

This report shares the results of a year-long collaboration between Stanford's Natural Capital Project and the Food Policy Council of San Antonio, with guidance and feedback throughout from three key city departments: the Office of Innovation, Office of Sustainability, and Metro Health. The goal of the collaboration was to quantify urban agriculture's benefits in San Antonio and to help identify strategic intervention sites through advanced mapping and modeling techniques using local data.

The Food Policy Council of San Antonio is an all-volunteer 501c3 nonprofit dedicated to a more equitable and sustainable food system. It sponsored code revisions in 2015 and 2022 that reduced restrictions on urban farming, created and helped pilot Metro Health's Healthy Corner Store Initiative, and created and operates the Tamōx Talōm Food Forest.

With a global hub at Stanford University, the Natural Capital Project (NatCap) advances science and creates actionable tools to bring the values of nature into decisions. Their work is inspired by, created with, and implemented through a network of hundreds of public and private sector institutions around the world.

The history and growth of urban agriculture

Pre-colonization South Texas was a food forest full of pecans, mulberries, mustang grapes, persimmons, plums, prickly pear, agarita, amaranth, sunflowers, and other plants that were used and maintained by native peoples. Following the arrival of the Spanish, San Antonio's water resources were leveraged for farming operations surrounding the missions leading to consistent regional growth, connected with a booming livestock industry. In the mid-1900s, mechanization and chemical input innovations transitioned agriculture away from population centers and towards rural areas (Miller, 2005).

In the early 2000s, interest in urban agriculture grew, causing a surge of community gardens. By the late 2010s, new urban farms emerged at Garcia Street Urban Farm, Talking Tree, the San Antonio Food Bank, the Greenies, LocalSprout, and others. Schools and community organizations like Gardopia have grown large volumes of crops through community engagement. Urban agriculture is already boosting local food production for residents and STEM education at more than fifteen San Antonio schools. With these factors and growing recognition of the cross-cutting benefits it provides, conditions are now ripe for an expansion of urban agriculture at scale.

Definitions and existing urban agriculture policy in San Antonio

Urban Farms are defined in San Antonio's Unified Development Code as "A tract of land within city limits, not at one’s own residence, on which produce is raised and sold on-site or elsewhere. This can include farming on vacant lots or acreage."

Food Forests are defined as "A self-sustaining, no-till system of perennial crops inter-planted in layers to mimic a mature ecosystem to provide food, a haven for beneficial, pollinating insects and other wildlife and to conserve water through topography alterations that serve to capture water in the landscape."

In this study, we define underutilized lands as potential areas that could be transitioned from their current land use to urban agriculture. See the section “Identifying underutilized lands in San Antonio” below and Appendix 2 for more detail.

Currently, there are approximately 51 acres dedicated to urban farms and large community gardens (e.g., San Antonio Food Bank, Mission San Juan, Garcia Street Urban Farm, the Greenies, Gardopia Gardens) across three districts (1, 2, and 6) and approximately 72 acres of urban food forests (e.g., Red Berry Estate Pecan Orchard and Tamox Talom Food Forest) in Districts 2 and 3.

The expansion of urban farms and food forests has been codified as a goal in multiple city council comprehensive plans.

- The SA Tomorrow Sustainability Plan[6] declared the public's top choice for food system goals as FS8: To pilot a program that includes incentives and resources to facilitate urban agricultural uses on vacant or underutilized land.
- The SA Climate Ready, Climate Action and Adaptation Plan[7] has multiple relevant goals. Goal 30 encourages local food production through various incentive programs. Goal 34 aims to diversify local crops through agriculture experts to create more drought and pest resistant crops that support wildlife and ecosystem services. Goal 36 strives to assess pilot urban agriculture projects for potential scaling and to incentivize and provide resources to facilitate urban agricultural uses on vacant or underutilized land, including city-owned and other public land.
- Metro Health's SA Forward[8] has declared addressing food insecurity and nutrition as one of its six priority areas, which urban agriculture can help address.

[6] City of San Antonio. (2016). *SA Tomorrow: Sustainability Plan*. https://www.sanantonio.gov/Portals/0/Files/Sustainability/SATomorrowSustainabilityPlan.pdf

[7] City of San Antonio. (2019). *SA Climate Ready: A Pathway for Climate Action & Adaptation.* https://www.sanantonio.gov/Portals/0/Files/Sustainability/SAClimateReady/SACRReportOctober2019.pdf.

[8] City of San Antonio Metropolitan Health District. (2023). SA Forward. https://www.sanantonio.gov/Portals/0/Files/health/About/SAForwardPlan.pdf?ver=2022-04-07-131856-947.

Three key questions we explored in our analysis of urban agriculture in San Antonio

The driving questions behind our collaboration are:

- **1) How much food could be produced by urban agriculture (both urban farms and food forests) on underutilized lands in the city?** To simplify estimates for this analysis, we narrowed food production by urban food forests to 4 crops (pecans, figs, mulberry, and nopal) and urban farms to 8 crops (eggplant, cabbage, potato, onion, tomatoes, squash, radish, and lettuce); in practice urban agriculture includes more crop diversity.
- **2) What additional co-benefits could be produced by investing in urban agriculture on those lands?** We explored the delivery of several key benefits provided by food forests and urban farms: urban cooling, carbon storage, access to green space, floodwater retention, and nutrient retention.
- **3) Where might investments in urban agriculture provide benefits to vulnerable people, decreasing inequities?** We considered equity from several different angles, including those that are more directly related to food access as well as broader metrics. We used census data on the fraction of households within a given census tract or city district accessing the Supplemental Nutrition Assistance Program (SNAP) benefits as a proxy of insecurity or low access to healthy foods. We also used data on 'low income and low [food] access' census tracts (formerly 'food deserts') from the USDA's Food Research Atlas, as well as local data mapping and measuring food security and nutrition by San Antonio as part of the city's SA Forward planning work. We also explored inequities in the distribution of co-benefits with regards to race (% people of color) and income (% below federal poverty line).

Teams from the Natural Capital Project, Food Policy Council of San Antonio, Metro Health, Innovation, and Sustainability met approximately bi-weekly since January of 2022. This allowed for co-development of our decisions about shared goals and about details of the analysis (such as data sources and assumptions).

Three scales over which we assessed the potential benefits of urban agriculture.

We assessed the benefits that could be provided by urban agriculture at three different scales: an individual food forest or urban farm, district-wide, and city-wide. The scale of an individual food forest or urban farm is the scale at which projects are often conceived, funded, and implemented. We chose 3 different case studies: Villa Coronado Urban Food Forest (District 3), Tamōx Talōm Food Forest (District 3), and Garza and Linear Park Food Forest (District 7). However, thinking more expansively, we explored how scaling up such efforts could have the potential to address food insecurity and deliver additional benefits to residents citywide. Thus, we examined the benefits of urban agriculture at the district scale. Finally, we summarized urban agriculture's benefits citywide.

Identifying "Underutilized lands" in the city of San Antonio

To quantify the benefits to people of implementing urban agriculture across San Antonio, we first identified areas across the city where existing land could potentially be transitioned from its current use to urban agriculture (Figure 1). We considered several factors including existing land use type, property ownership, and parcel size to create our map of "underutilized lands." In terms of land use, we assumed that any natural land class–with the exception of wetlands and existing crops–was open for transition to urban agriculture. The majority of natural land in San Antonio is classified in the National Land Cover database from satellite imagery as "developed open space," but we also included forested and scrub/shrub land because they tend to be invasive species that many hope to clear (Figure 2). Building on this, only parcels that were publicly owned were considered open for conversion. We used property ownership data from the Bexar County Appraisal District (bcad.org) to identify parcels that were owned by the city, county or state. We also included utility-owned land—specifically land stewarded by the San Antonio River Authority and San Antonio Water System. Lastly, we applied a size filter to remove parcels <1 acre in size to focus on large urban farm and food forest sites for this analysis. While urban agriculture can produce significant yields from smaller parcels (in fact San Antonio has examined the cost-benefit of urban at smaller <1 acre scales), the ecosystem service models used to quantify co-benefits in this study are most effective for quantifying co-benefits at slightly larger spatial scales, so 1 acre was considered the smallest analytical unit. The result, shown in Figures 1 and 2, is a comprehensive (but not exhaustive) map of potential areas across the city where urban agriculture could potentially be implemented based on very simple screening criteria. We acknowledge that there is significant privately owned natural land in the city (e.g., golf courses, country clubs, academic institutions, etc.) that may be open to hosting agricultural projects, but wanted to constrain our analysis to public land at this stage. More information about the creation of this map is provided in Appendix 2.

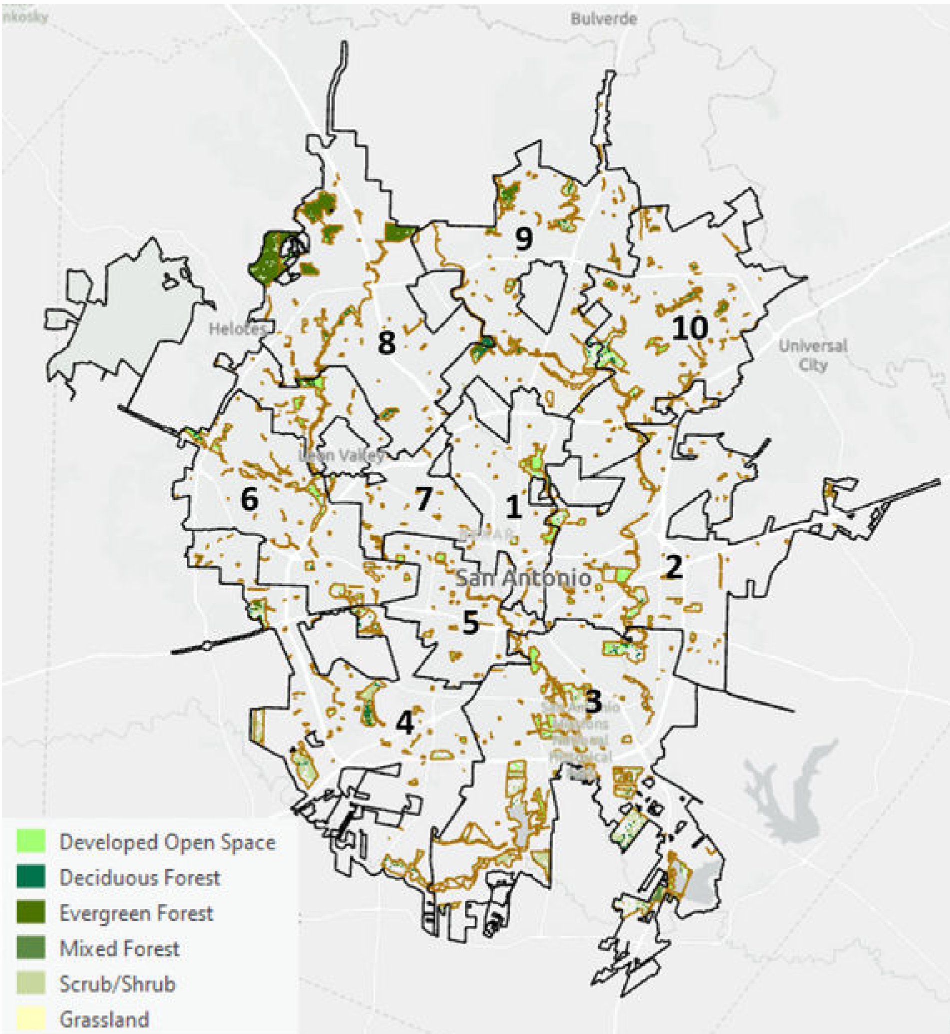


Figure 1. Publicly owned (>1 acre) natural lands (and their current land cover type) within the 10 districts of the city of San Antonio. This is the suite of possible areas (outlined in brown) where underutilized lands could be transitioned to urban agriculture evaluated in this analysis.

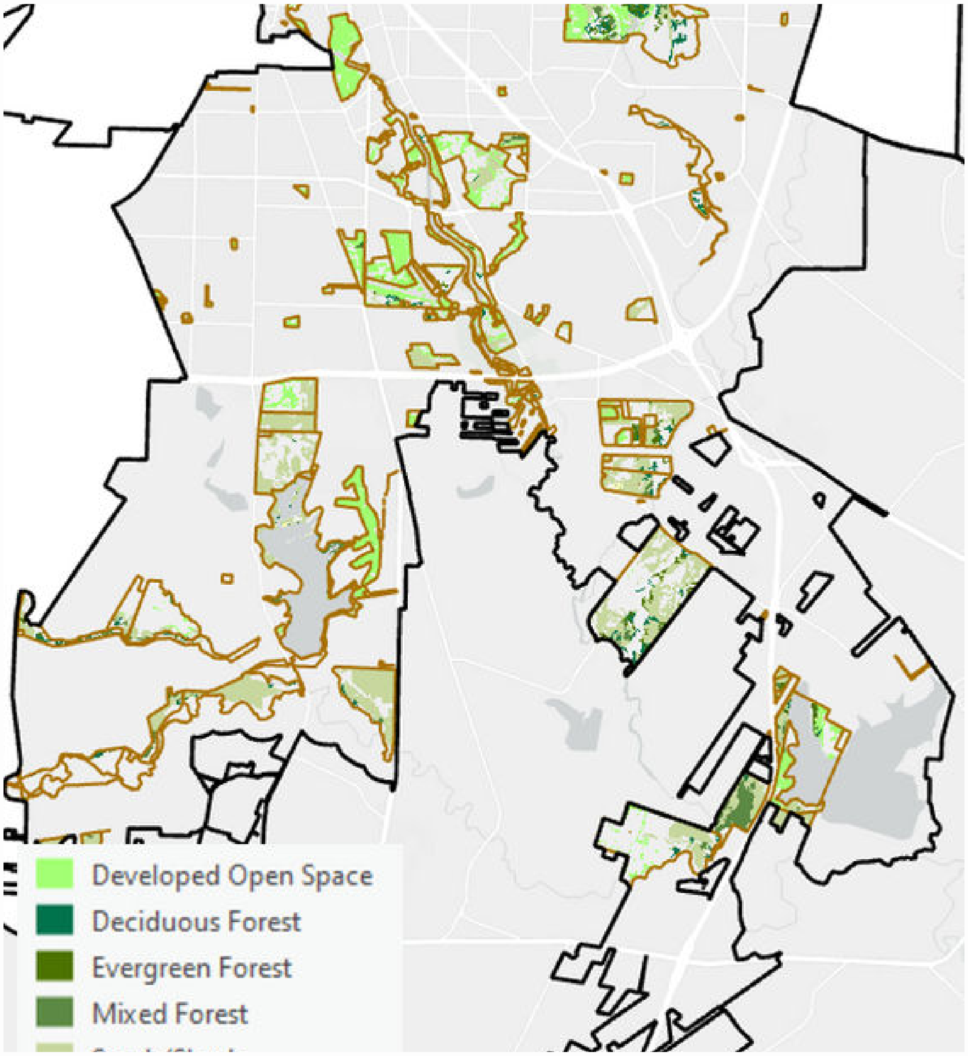


Figure 2. Publicly owned (>1 acre) natural lands (and their current land cover type) in District 3. This is the suite of possible areas (outlined in brown) where underutilized lands could be transitioned to urban agriculture evaluated in this analysis.

Scenarios of change

We considered two different types of urban agriculture in San Antonio: an "urban farm" with annual crops of diversified vegetables and a "food forest" with perennial trees providing nuts and fruits. We describe each in detail below but generally we assume urban farms are more intensely managed lands in which supplemental nutrients (in the case of San Antonio this is in the form of compost) are used to improve yields of annual, herbaceous plants that provide little or no shade. We also assume that urban farms are less accessible to the public as the open green space it might replace (Garcia Street Urban Farm, for example, is a working commercial farm that is only accessible to the public in a limited capacity). In contrast, food forests are more passively managed and, when mature, provide ample shade and are accessible by the public. In many cases, the conversion of underutilized lands to either agricultural type involves replacing one form of green space (often grass) into agriculture. In summary, we have a priori expectations that urban farms, like typical farms, will provide food but perhaps have less capability to provide cooling services or improve water quality, whereas food forests would provide urban cooling and water quality benefits but perhaps less food.

In addition to individual case studies, we considered three different scenarios in which land shown in Figures 1-2 could be converted to each type of urban agriculture. A 'full conversion' scenario modeled the potential benefits associated with converting all available natural 'underutilized' land to urban agriculture. While this scenario is not particularly realistic, it provides an upper bound on what could be possible. In two additional scenarios we applied a cap to the maximum acreage that could be converted on a given parcel–20 acres and 40 acres. We explored these scenarios to reflect a 'reasonable size' conversion for urban agriculture.

Understanding yields from urban agriculture in San Antonio

We explored the potential benefits to people if urban farms and food forests thrived in underutilized lands throughout the city. We modeled both types of urban agriculture after existing efforts in San Antonio, with simplifying assumptions about crop diversity and yields made for modeling purposes. The urban farm design was based on a simple crop plan that assumed equal production (in terms of acreage) of eight important crops: eggplant, cabbage, potato, onion, tomato, squash, radish, and lettuce. Crop yields, and farming practices (e.g. compost application, irrigation, cover cropping) were based, in part, on the Garcia Street Urban Farm[9], a 4.1 acre diversified vegetable and flower farm in San Antonio. We modeled our Urban Food Forest template on the Tamōx Talōm urban food forest, again simplifying the crop plan to focus on four high-yielding fruits and nuts: pecans, figs, mulberries, and nopal. We discuss methods for modeling crop yields, including simplifying assumptions about crop production for the purposes of this analysis in detail in Appendix 2. An important consideration that was not explicitly accounted for in this analysis is that crop yields for urban food forests assumes mature trees, which take approximately 3-8 years to begin producing fruit (depending on the crop). Thus there is a time lag between the establishment of a food forest and its production. In contrast, an urban farm will begin producing food more quickly, though farmers will still have to improve the surface conditions. The crop yield estimates provided in this study assumed a fully mature farm or food forest.

In addition to estimating yield and attempting to capture demand for local fresh food through a diversity of metrics, we also linked supply and demand by estimating the annual fruit, nut, and vegetable needs for a typical household. To do this we used the USDA's dietary guidelines (2015-2020) to calculate the fraction of daily fresh food intake that should be vegetables (~56%, averaged between 'moderately active' male and female adults and children) and fruits (~43%). We then used the WHO's recommendation of 400g (0.88lbs) of fresh fruit and vegetables daily for an 'average person', to calculate the lbs of fruit and vegetables required per person, per day. We were able to do these calculations for nuts directly from the USDA as the recommended daily allotments are given in weight rather than cup equivalents. To estimate the amount of fruit and vegetables required to feed a household for a year, we assumed each household was composed of four people all consuming the recommended 400g (0.88lbs) of fresh fruit and vegetables per day. Because SNAP usage is measured by the household in the census, we were able to estimate the lbs of fresh fruit and vegetables required to feed each SNAP household for the year and assess how that compared with potential production from urban agriculture. For more details on this calculation see Appendix 2.

[9] San Antonio College. (2023). *Garcia Street Urban Farm.* Alamo Colleges District San Antonio College. https://www.alamo.edu/sac/about-sac/college-offices/eco-centro/eco-centro-garcia-street-urban-farm/

Estimating co-benefits

We used the Natural Capital Project's InVEST software suite (Natural Capital Project 2023) to estimate the additional ecosystem service co-benefits provided to people by the conversion of underutilized lands to urban farms or food forests. Using land cover and other environmental data, e.g., expected precipitation, as inputs, InVEST creates maps of urban cooling potential, flood retention, nutrient retention, and urban nature access. We compared the spatial patterns of each service supply under current land cover with the potential changes that would occur under the different scenarios of food forest and urban farms. We summarized the results at each of the three assessment scales.

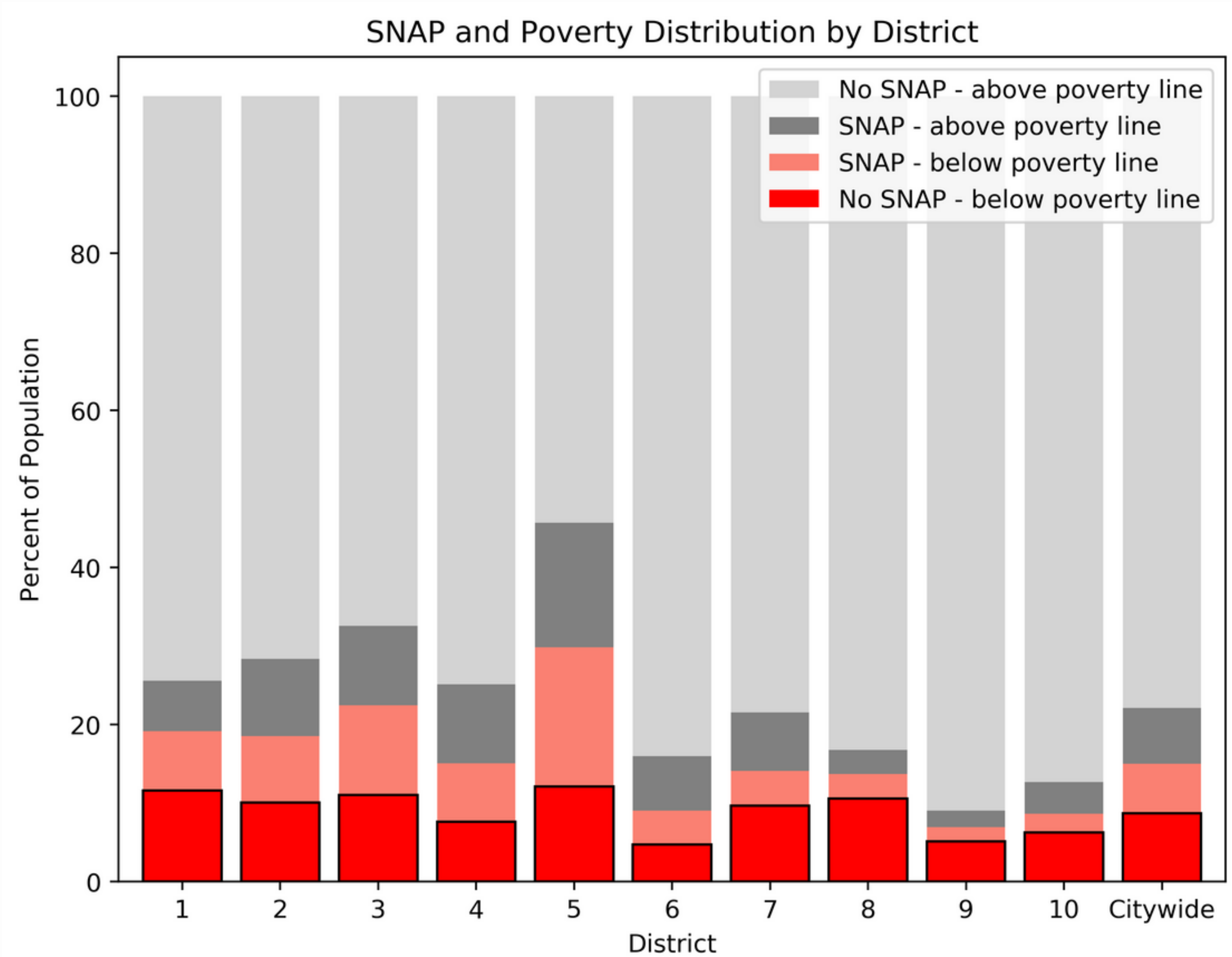


Figure 3. District and citywide distributions of poverty and SNAP benefits. Gray colors indicate households above the federal poverty line while red denotes those below. The percentage of households below the poverty line that do not receive SNAP benefits are outlined in black.

Metro Health Director Claude Jacob, Nadia Gaona, San Antonio Mayor Ron Nirenberg, and Mitch Hagney at the Tamox Talom Food Forest. 2022.

A focus on vulnerable populations and on equity

Food insecurity is highly correlated with negative health outcomes, such as diabetes in San Antonio (SA Forward Plan 2021 - 2026). The SNAP program has been very effective at mitigating food insecurity and improving health outcomes for participants (which, in 2022 was ~12% of the US population, and ~11% of Texas' population) (Center for Budget and Policy Priorities Texas SNAP Factsheet). Due in part to it being a comprehensive national program, SNAP usage has been used as a proxy measure of food insecurity across the U.S. (Feeding America) and in San Antonio (City of San Antonio Strategic Health Plan Dashboard). Building on this, we used information about the number of households receiving SNAP benefits in each US Census tract as a key proxy for food insecurity in this study (Figures 3,5a). In addition, we also used information on 'low income and low [food] access' census tracts mapped by the USDA (Figure 4). Formerly termed 'food deserts', this effort uses metrics related to income and distance from a supermarket, as well as vehicle access, to map accessibility to fresh and healthy food. Lastly, we used local information collected as part of the San Antonio forward planning initiative available on the City of San Antonio Strategic Health Plan Dashboard.

When going beyond food to explore broader environmental co-benefits provided by urban agriculture, we used both race (% people of color, Figure 5c) and income (% below poverty line, Figure 5b) reported in the 2020 American Community Survey (U.S. Census Bureau, 2021) as potential indicators of vulnerability–metrics similar to those used by the San Antonio Equity Atlas[10] . To assess the equitable distribution of co-benefits, we aggregated the total delivery of service by census tract and determined the correlation between services provided and socio-economic attributes at different scales (e.g., citywide, district). A significant correlation between the amount of environmental service delivered and socioeconomic variables indicates an inequity. For example, our results suggest an inequitable distribution of urban cooling services across the city, where census tracts that have higher fractions of non-white and poor residents experience hotter temperatures. Any reduction in the strength of the correlation between social vulnerability and heat that results from adding food forests or urban farms indicates a more equitable distribution of benefits from the landscape.

[10] City of San Antonio Diversity, Equity, Inclusion, & Accessibility. (2023). *Equity Atlas*. City of San Antonio. https://www.sanantonio.gov/Equity/Initiatives/Atlas

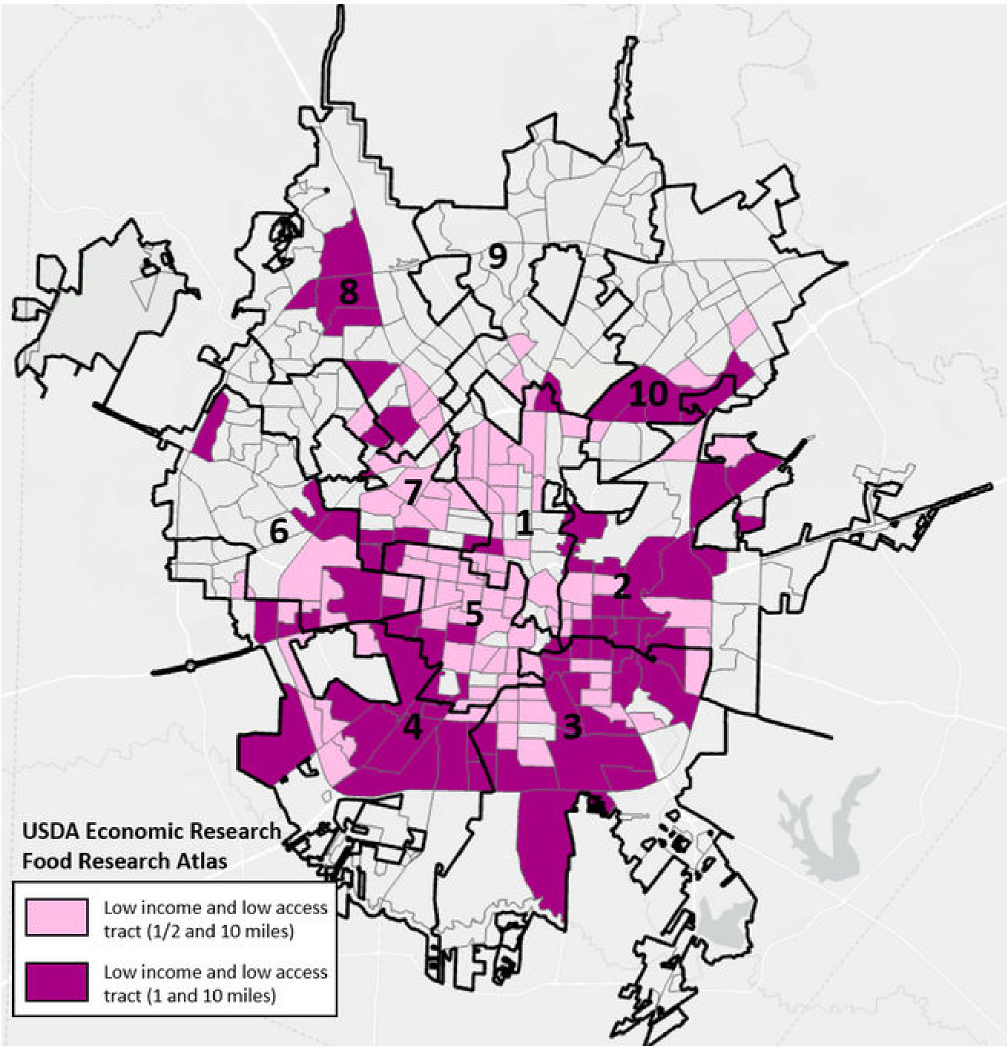


Figure 4. Census tracts considered low income and low access to healthy food by the USDA Economic Research Atlas (USDA ERS. 2019). Low income status is based on several tract-level statistics related to median income and poverty rate. Low access status is based on whether a significant portion of the tract's population (either >500 people or 33% of the total) lives within ½ a mile or 1 mile of a supermarket in an urban center, or 10 miles from a supermarket in a rural setting.

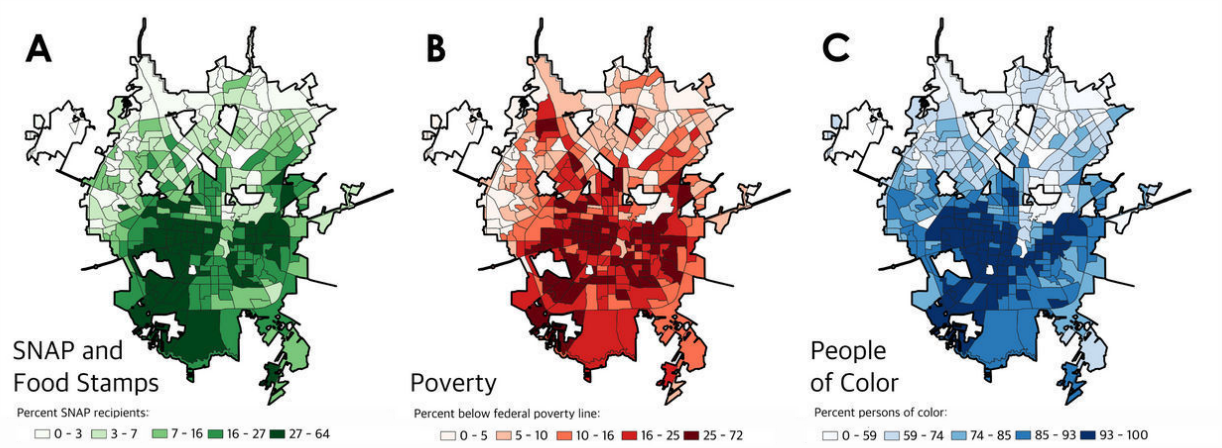


Figure 5. Maps of San Antonio census tracts reporting the percentage of (A) households that are SNAP recipients, (B) individuals below the federal poverty line, or (C) individuals that identify as people of color.

Results

Underutilized land available for urban agriculture

San Antonio has a total of 16,800 acres of publicly owned natural areas that could be converted to urban agriculture. This available space is not evenly distributed throughout the city, with Districts 1 and 5 having the least area and Districts 3 and 8 having the most (Figure 6).

District	Publicly owned undeveloped open space (acres)
1	544
2	1,021
3	4,323
4	2,178
5	237
6	869
7	687
8	3,607
9	1,914
10	1,420

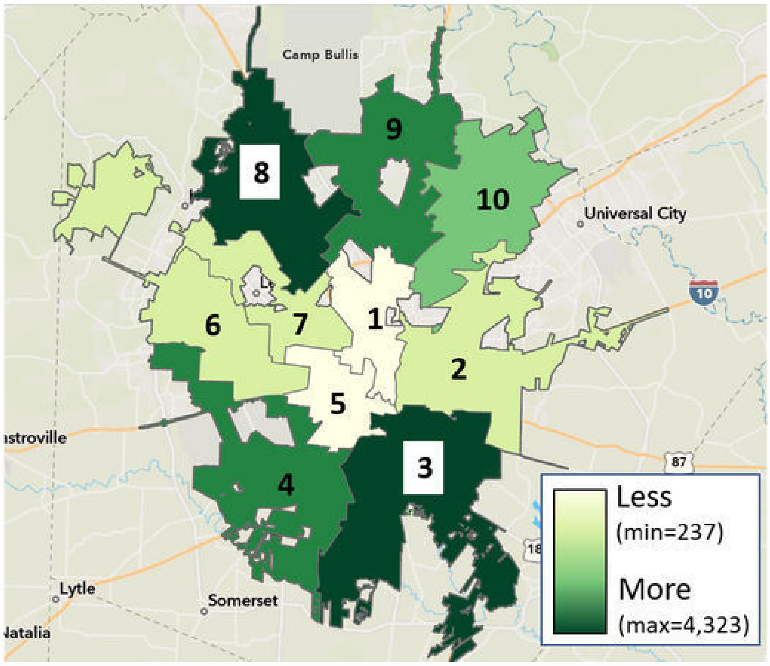


Figure 6. The amount of underutilized lands (publicly owned natural areas) by district.

Food and co-benefits provided by individual food forests: three case studies

This section presents results for a subset of specific parks that are being actively considered for conversion to urban agriculture.

Villa Coronado Urban Food Forest (District 3)

Figure 7. Villa Coronado Park (outlined in green) and surrounding areas. In the image on the left, some of the existing park features are visible. The solid circle in the image on the right shows the area surrounding the park in a 1-mile radius.

Villa Coronado is a park located in District 3. The park has ballfields, a sports complex and approximately 8.86 acres of undeveloped open space with a walking path that is being considered for conversion to an urban food forest (Figure 7). Villa Coronado is located in an area that is both low income and has low access to fresh food. Twenty-three percent of the households in the census tract in which Villa Coronado Park is located rely on SNAP benefits and 50% are low income according to the USDA Food Access Research Atlas [11] (USDA 2019). Furthermore, a significant number of the households in this tract are >1 mile from a supermarket and >10% of the households in this tract lack a vehicle (USDA 2019) (Table 1). Local work mapping food insecurity [12] in the city, conducted by Metro Health as part of the San Antonio Forward Plan [13] (2021-2016), found that >40% of kids in the zip code encompassing Villa Coronado Park (zip codes encompass a larger area than census tracts) reported no vegetable consumption the previous day and >20% reported less than an hour of physical activity in the previous week (SA Forward).

[11] United States Department of Agriculture, Economic Research Service. (2022). *Food Access Research Atlas*. United States Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/data-products/food-access-research-atlas/go-to-the-atlas/

[12] City of San Antonio Metropolitan Health District. *Food Insecurity & Nutrition.* SA Forward: Leading the Way to a Healthier Community. https://dashboards.mysidewalk.com/city-of-san-antonio-strategic-health-plan-dashboard-5bbc32e941c7/food-systems-nutrition

[13] City of San Antonio Metropolitan Health District. (2023). *SA Forward.* City of San Antonio. https://www.sanantonio.gov/Health/AboutUs/SAForward

We evaluated the potential benefits of developing an 8.86 acre urban food forest in the park, encompassing the current undeveloped open space. An urban food forest at this location would produce more >100,000 lbs of fruit and nuts per year, valued at ~$525,000. This could provide each of the 536 households relying on SNAP benefits in this census tract with an average of 3.64 lbs of fresh fruit and nuts per week (Table 1). Alternatively it could provide 178 households with the recommended daily allotment of fruit and 30 households with the recommended daily allotment of nuts each year.

In addition to fresh food, urban food forests provide other key ecosystem service co-benefits to people. In this case, co-benefits include 162 metric tons of carbon storage (over $8,400 in societal value), $2,300 per year in decreased cooling costs for communities within 1 km, and increased urban nature access by a small amount (less than ¼ acre per 100,000 people). Benefits of a food forest in this location also include a roughly 2.7% reduction in flood volume on-site in a 100-year storm, as well as a 3% reduction in annual stormwater phosphorus export (valued at $2,300 in terms of cost of treatment by structural stormwater practices), while nitrogen export from the site would likely be increase by about 7% versus baseline (at a cost of $8,700), likely due to an increase in leaf litter relative to the ball fields and grass at the site currently.

Tamōx Talōm Food Forest (District 3)

Tamōx Talōm Food Forest is a recently established food forest located in District 3. The food forest, which was established in 2021, is approximately 1.47 acres, in a larger park of 4 acres. The park connects directly to the Mission Reach section of the San Antonio River Walk, and contains a substantial drainage area. It borders Mission County Park II, and was the least visited of three contiguous county parks before the food forest was planted. Tamōx Talōm is located in an area that is both low income and has low access to fresh food. Fifty-one percent of the households in the census tract in which Tamōx Talōm is located rely on SNAP benefits, and 72% are low income according to the USDA Food Access Research Atlas (USDA 2019) (Table 1). Furthermore, a significant number of the households in this tract are >1 mile from a supermarket and >34% of the households in this tract lack a vehicle (USDA). Local work mapping food insecurity in the city, conducted by Metro Health as part of the San Antonio Forward Plan (2021-2016), found that more than 40% of kids in the zip code encompassing Tamōx Talōm Food Forest (zip codes encompass a larger area than census tracts) reported no vegetable consumption the previous day and >20% reported less than an hour of physical activity in the previous week (SA Forward).

We used the same approach to estimate the potential production of Tamōx Talōm food forest once mature, as the park is just recently established and not yet producing fruit. Once matured, a 1.47 acre food forest such as Tamōx Talōm could produce an estimated ~16,800 lbs

[14] United States Department of Agriculture, Economic Research Service. (2022). *Food Access Research Atlas.* United States Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/data-products/food-access-research-atlas/go-to-the-atlas/

[15] City of San Antonio Metropolitan Health District. *Food Insecurity & Nutrition.* SA Forward: Leading the Way to a Healthier Community. https://dashboards.mysidewalk.com/city-of-san-antonio-strategic-health-plan-dashboard-5bbc32e941c7/food-systems-nutrition

[16] City of San Antonio Metropolitan Health District. (2023). *SA Forward.* City of San Antonio. https://www.sanantonio.gov/Health/AboutUs/SAForward

lbs of fruit and nuts, valued at ~$87,000, annually. This could provide each of the 473 households relying on SNAP benefits in this census tract with 3/4 lbs of fresh fruit and nuts per week (Table 1). Alternatively it could provide 30 households with the recommended daily allotment of fruit, and 5 households with the recommended daily allotment of nuts each year.

In addition to fresh food, this urban food forest is expected to provide additional ecosystem service benefits to people which include 26 metric tons of carbon storage (over $1,350 in societal value), $430 per year in decreased cooling costs for communities within 1 km, and increased urban nature access by a small amount (less than ¼ acre per 100,000 people). The food forest also provides some benefits to stormwater-related services relative to existing land use, with a small reduction in flood volume on the site (~2% in a 100-year storm) and 9-10% reduction in annual nitrogen and phosphorus export in runoff (valued at roughly $10,600 in terms of cost of treatment with conventional stormwater practices).

It cost $25,000 to establish the Tamōx Talōm food forest; maintenance costs are expected to add an additional $45,000 over the first three years. The market value of the potential crop each year is estimated at $87,000 once mature with additional $430 in annual co-benefits associated with urban cooling, and $1,350 from carbon storage. Given this, the park 'pays for itself' once in production.

Garza and Linear Park Food Forest (District 7)

Garza and Linear Park Food Forest incorporates land associated with one park (Garza Park), and an intersecting Linear Park located in District 7. Garza Park has ball fields, tennis courts and approximately 25 acres of undeveloped open space with a walking path that is being considered for conversion to an urban food forest. It intersects Linear Park, a 39 acre park with some undeveloped open space and some concrete lined channels. This project would establish a large 64 acre food forest spanning the two parks. It would restore riparian areas to the creek banks in Linear Park, which would involve removing concrete in the southern extent of the park.

The Garza and Linear Park food forest is also located in an area that is both low income and has low access to fresh food. It spans two census tracts, of which 37% of the households in the lower income census tract rely on SNAP benefits and 65% are low income according to the USDA Food Access Research Atlas (USDA 2019) (Table 1). Furthermore, a significant number of the households in this tract are >0.5 mile from a supermarket and >12% of the households in this tract lack a vehicle (USDA 2019). Local work mapping food insecurity in the city, conducted by Metro Health as part of the San Antonio Forward Plan (2021-2016), found that

[17] United States Department of Agriculture, Economic Research Service. (2022). *Food Access Research Atlas.* United States Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/data-products/food-access-research-atlas/go-to-the-atlas/

[18] City of San Antonio Metropolitan Health District. *Food Insecurity & Nutrition.* SA Forward: Leading the Way to a Healthier Community. https://dashboards.mysidewalk.com/city-of-san-antonio-strategic-health-plan-dashboard-5bbc32e941c7/food-systems-nutrition

[19] City of San Antonio Metropolitan Health District. (2023). *SA Forward.* City of San Antonio. https://www.sanantonio.gov/Health/AboutUs/SAForward

more than 40% of kids in the zip code encompassing Garza and Linear Park reported no vegetable consumption the previous day, and 23% reported less than an hour of physical activity in the previous week (SA Forward).

We evaluated the potential benefits of developing an 64 acre urban food forest in this area, encompassing the current undeveloped open space. An urban forest at this location would produce more than 732,000 lbs of fresh fruit and nuts, valued at ~$3.8M, annually. This could provide each of the 624 households in the two census districts spanning the park that rely on SNAP benefits ~23 lbs of fresh fruit and nuts per week (Table 1). Alternatively it could provide 1,288 households with the recommended daily allotment of fruit, and 217 households with the recommended daily allotment of nuts each year.

In addition to fresh food, urban food forests provide other key ecosystem service co-benefits to people. In this case, co-benefits include 162 metric tons of carbon storage (over $8,400 in societal value), $2,300 per year in decreased cooling costs for communities within 1 km, and increased urban nature access by a small amount (less than ¼ acre per 100,000 people). Benefits of a food forest in this location also include a roughly 2.7% reduction in flood volume on-site in a 100-year storm, as well as a 3% reduction in annual stormwater phosphorus export (valued at $2,300 in terms of cost of treatment by structural stormwater practices), while nitrogen export from the site would likely be increase by about 7% versus baseline (at a cost of $8,700), likely due to an increase in leaf litter relative to the ball fields and grass at the site currently.

In addition to fresh food, an urban food forest in Garza and Linear Park would provide other key ecosystem service benefits to people including 271 metric tons of carbon storage (over $14,000 in societal value), $6,800 per year in decreased cooling costs for communities within 1km, and increased urban nature access by a small amount (less than ¼ acre/100,000 people). This food forest would provide a roughly 4% reduction in flood runoff from the site in a 100-year event, while annual stormwater retention could improve by about 15% for phosphorus (valued at roughly $66,000) and 5% for nitrogen (valued at roughly $34,000). Most of these flood and stormwater benefits arise from replacement of concrete in the linear park with trees; thus the result should be considered carefully as the linear park is a floodplain and stormwater conveyance, and vegetation placed near the channel might reduce erosion, but could also provide direct nutrient inputs to the waterway. Trees in the channel could also enhance infiltration (due to increased soil porosity from tree roots) and would reduce flow velocities, likely decreasing downstream erosion but potentially increasing upstream flooding in large events. Understanding tradeoffs among these hydrologic effects may require a more sophisticated hydrodynamic model.

Table 1. Potential production and market value from three urban food forest case study sites (in blue), demographic metrics related food access in surrounding census tract (yellow), and potential for urban food forests to support some of that need by providing fresh produce (green).

Urban food forest case study sites	Potential production of fruit and nuts (lbs/year)	Market Value of produce ($/year)	Fraction of census tract low income	Fraction of census tract using SNAP	Pounds of fruit and nuts for each SNAP household per week
Tomax Talom	16,813	$ 87,098	72%	51%	0.75
Villa Coronada	101,336	$ 524,955	50%	23%	3.64
Garza and Linear Park	732,000	$ 3,792,000	65%	37%	23

Case study summary

These case studies capture a range of size and potential production coming from individual proposed and implemented urban food forests. Even when constrained to smaller acreages, food forest production is quite high, and if effectively distributed, food forests can make sizable contributions to people in need of fresh food. Furthermore, the market value of these crops is high, such that the return on investment in food forests is achieved fairly quickly once trees mature. In addition, the ecosystem service co-benefits associated with replacing underutilized open space with canopy cover provided by trees and shrubs adds significant additional services in the form of urban cooling and carbon storage while also providing small benefits for green space access and flood and nutrient retention. Also, there are considerable benefits likely provided by urban food forests in the form of mental health and increased physical activity, as well as educational and community enrichment opportunities that are not explicitly quantified in this analysis.

Food and co-benefits provided by urban agriculture at city and district scales

City-wide food yield and a focus on two districts

If all 16,800 acres of publicly owned underutilized land across the city were converted to urban food forests they could produce an estimated 192 million pounds of fruit and nuts (mulberry, pecan, nopal, and fig) annually. This would be worth over $995 million per year if crops were sold at market value. If that acreage were to be converted to urban farms instead, they could produce an estimated 926 million lbs of vegetables annually, worth over $1.1 billion per year if crops were sold at market value. Crop yield is dependent on the area available for production such that districts with extensive underutilized lands, such as Districts 3, 4, and 8 (Fig. 4) would see higher yields in a 'full conversion' scenario.

The relationship between available green space and potential production (e.g., a positive linear one), neglects to account for a key additional component–demand for fresh food. Linking supply (underutilized publicly owned land for urban agriculture) with demand (households facing food insecurity) can help to guide decision-makers in an effort to implement urban agriculture where it will be most beneficial to vulnerable communities and continue building equity in the city. To highlight the differences in supply and demand in San Antonio, we explored two districts. Districts 5 and 3 both have less access to fresh healthy foods relative to other districts in the study, with a significant proportion of census tracts in each being considered low income and low [food] access by the USDA (Figure 4), and relatively high reliance on SNAP benefits (Figure 3). These districts also have variability in the extent of underutilized lands available for conversion, and considerable interest in the potential for urban agriculture to meet some of this need (Figure 6).

District 5

District 5 is an area of San Antonio with less access to fresh food and limited publicly owned underutilized land that could be converted to urban agriculture. District 5 has ~237 acres of publicly owned undeveloped green space (much of it within existing parks)–the least amount of land available for conversion to urban agriculture of any district in the city. If all 237 acres of underutilized land were converted to urban food forests, it could produce an estimated >2.7M lbs of fruit and nuts annually (>$14M/year market value), or an estimated > 13M lbs of mixed vegetables per year ($16.5M/year market value) if the land was converted to urban farms.

There is potentially significant demand for fresh, healthy food in District 5. Thirty five percent of households in District 5 receive SNAP benefits (6,060 households in 2020) (Figure 3) and most of the census tracts in the districts are considered 'low income and low [food] access' by the USDA (Figure 4). With appropriate distribution, these families could significantly benefit from the yields from new urban farms and forests. An estimated 4.1 million lbs of vegetables would meet the average recommended daily intake for the District's 6,060 families on SNAP benefits all year (see Appendix 2 for information on the nutritional conversion). Meeting the annual vegetable needs of the district's 6,060 households on SNAP benefits could be accomplished by converting ~80 acres of underutilized land (33% of the available total) in District 5 to urban farms. This underscores the highly productive nature of urban farms; even in an area of the city that is very highly developed, with relatively little underutilized land, there is still ample opportunity to address local demand for food with very local production of food.

If all 237 acres of underutilized land were converted to urban food forests, it would produce approximately 2.7 million pounds of fruit and nuts per year. This would provide ~8.6 lbs of fresh fruit and nuts to each of the 6,060 households relying on SNAP benefits every week, year round. Food forests in District 5 (the "full conversion scenario") could provide a host of ecosystem service co-benefits: an average temperature reduction of 0.07 ˚F, representing an annual savings of $210,000 on cooling energy costs and a 0.02% reduction in daily heat-based mortality risk; nearly 6,000 metric tons of carbon sequestration with a potential societal value of over $0.3 million, and an increase in urban nature access of 0.7 acres/100,000 people across the district.

District 3

At the other end of the spectrum, District 3 has the greatest area of publicly owned underutilized land in the city–more than 4,000 acres. District 3 also has high demand for better access to food, with more than half of census tracts in the district considered 'low income and low [food] access' by the USDA (Figure 4), and the second highest SNAP benefit usage rate (21%) in the city (Figure 3). It is a large district, with threefold the number of households on SNAP than District 5. Thus, District 3 has both high demand and potentially high capacity to meet that demand. To supply the yearly allotment of vegetables to all 15,323 households in District 3 that rely on SNAP benefits would require establishing ~200 acres of urban farms. Additionally, to supply the yearly allotment of fruit and nuts to all SNAP households would require ~840 acres dedicated to pecans, and ~140 acres dedicated to fruiting trees & cacti. Establishing all of this urban agriculture (both farms and food forests) would require converting only ~25% of the district's publicly owned underutilized land.

The ecosystem service co-benefits of fully converting all identified underutilized natural lands to food forests in District 3 are robust. Air temperatures could be reduced by an average of 0.21˚F for an annual energy savings of $683,000 and a 0.06% reduction in daily heat-based mortality risk. Food forests could also provide up to 120,000 metric tons of carbon sequestration with a potential societal value of over $6 million, alongside a 8.9 acre increase in urban nature access per 100,000 people across the district.

We can use information about supply and demand in Districts 5 and 3, as well as other districts in the city, to locate urban agriculture near the communities who need it most. For example, we can use our spatial results to help identify where urban farms and market stands could best be sited within walking distance of or near public transit to the communities with the highest SNAP usage in the district.

Ecosystem service co-benefits and tradeoffs of urban agriculture at scale

We explored the delivery of several key co-benefits provided by food forests and urban farms: urban cooling, carbon sequestration, access to green space, floodwater retention, and nutrient retention (Table 2). We summarized these citywide results across the 3 scenarios of converting a maximum of 20 acres/parcel, 40 acres/parcel, and then the "full conversion" scenario that assesses transitioning all of the underutilized lands to urban agriculture (Table 2). Overall, food forests provide significant food in addition to significant co-benefits with minimal nutrient pollution. Urban farms provide more food than urban forests, but this comes with tradeoffs of higher maintenance costs, potentially increased nutrient pollution (from over-application or inefficient use of compost, for example), as well as decreases in carbon storage and green space access as compared to the current baseline of underutilized lands. Of course, these are not all of the co-benefits of urban agriculture. Additional co-benefits that we have not quantified here include support of urban wildlife, increased aesthetics, the health benefits of access to nature (including improvements in mental health as well as improvements in physical health through increased physical activity), and more.

Table 2. A summary of the food and co-benefits provided by each of the conversion scenarios for food forests and urban farms. Cells shaded in gray represent little to no change from the baseline; pinks and reds represent small and large costs; light and dark greens represent large and small benefits.

	Crop Yield			Urban Cooling		Carbon storage	Access	Flood Retention	Nutrient Retention			
Scenario	Fresh food (lbs/yr)	Market value of fresh food ($/yr)	~# of households receiving daily allotment of fresh food from urban ag/yr	Annual savings on cooling ($)	Average change in relative mortality risk from heat (%)	Change in value of Carbon sequestered ($)	Change in green space access (acres/ 100,000 people)	Change in flood volume, 100-year storm (ft3)	Change in annual Nitrogen runoff export (%)	Annual cost of treating additional N in stormwater ($)	Change in annual Phosphorus runoff export (%)	Annual cost of treating additional P in stormwater ($)
Food Forests												
20-acre	~61M lbs	>$315M	~99,200	$ 1.6M	-0.01%	$4.2M	0.5	-0.14%	0.60%	$4.52M	0.10%	$0.41M
40-acre	~85M lbs	>$439M	~138,100	$ 2.0M	-0.02%	$6.1M	0.7	-0.16%	0.60%	$5.09M	0.10%	$0.47M
Full convert	>192M lbs	>$995M	~313,900	$ 3.5M	-0.04%	$17.6M	2	-0.40%	4.20%	$33.6M	1.00%	$4.55M
Urban Farms												
20-acre	294M lbs	>$370M	~403,200	$ 1.0M	0.00%	-$5.1M	-1	-0.06%	29%	$235M	95%	$440M
40-acre	409M lbs	>$515M	~561,280	$ 1.1M	0.00%	-$7.5M	-2	-0.07%	36%	$290M	117%	$541M
Full convert	>926M lbs	>$1.17B	~1,271,600	$ 1.8M	-0.01%	-$23.6M	-10.4	0.18%	241%	$1,937M	786%	$3,643M

Urban cooling

Green spaces help cool air temperatures by providing shade and evaporative cooling (from plant evapotranspiration) amidst a landscape of heat-retaining pavement and concrete. We used the InVEST Urban Cooling model to assess the local urban heat island using local geographic and climate datasets (Figure 8). We converted changes in temperature into changes in the energy expenditures on building temperature control and the mortality risk of heat-induced death (see Appendix 2 for more detail).

Under the "full conversion" scenario, food forests could reduce the average air temperature citywide by about 0.12 degrees F, providing up to $3.5M per year in urban cooling services, which translates to about $5-7 in savings/household/year, and reducing heat-based mortality by 0.04%, saving the statistical equivalent of approximately 600 lives, in the "total conversion" scenario. In the "full conversion" scenario urban farms could reduce the temperature by about 0.02 degrees F, providing up to $1.8M per year in urban cooling services and reducing mortality by 0.01% (saving the statistical equivalent of approximately 150 lives).

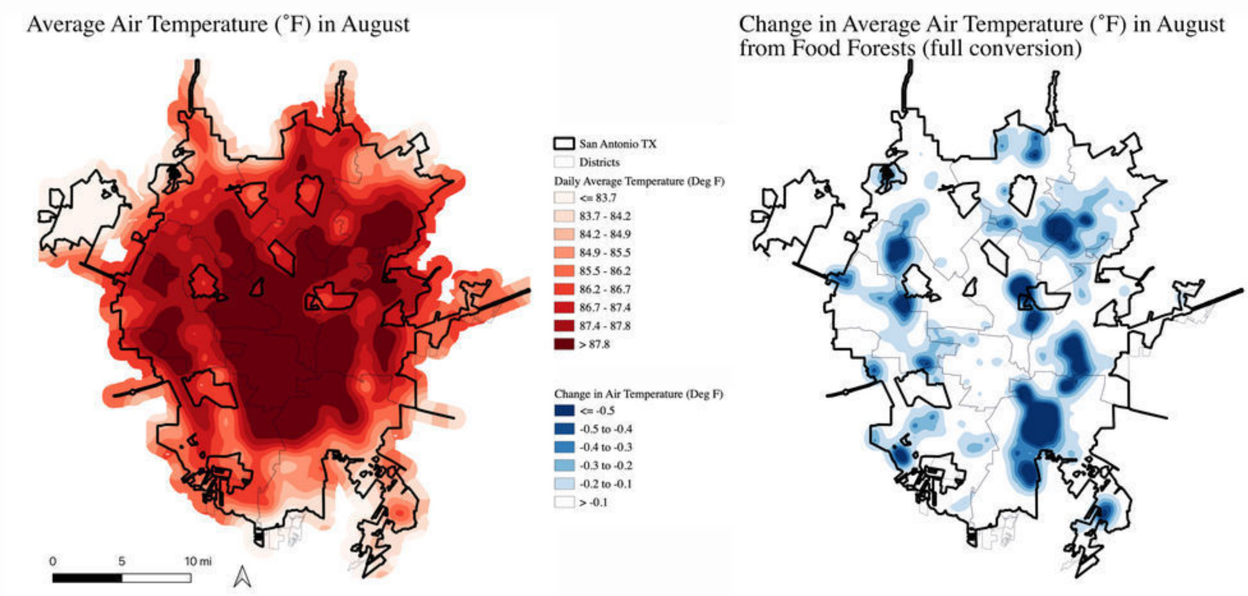


Figure 8. Urban heat in San Antonio (left) and urban cooling provided by food forests in the full conversion scenario (right).

Cooling services provided by the modeled food forests and urban farms are not evenly distributed throughout the city. For example, Districts 3 and 10 have the most potential for urban cooling through food forests while Districts 7, 8, and 9 have the least potential for cooling through urban farms (Figure 9).

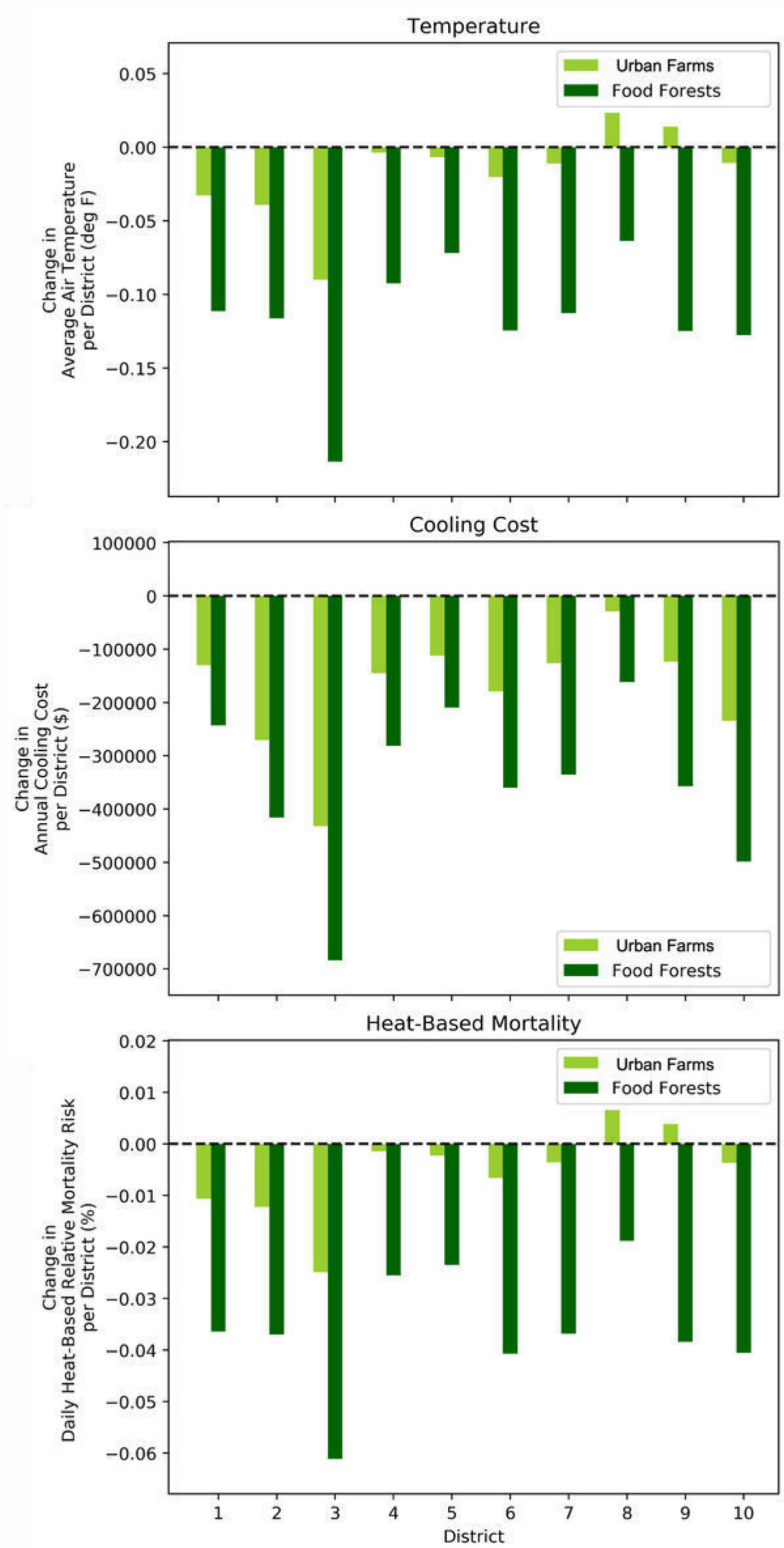


Figure 9. Changes in temperature, cooling costs, and heat-based mortality under the "full conversion" scenario for food forests (dark green) and urban farms (light green).

As in many cities throughout the US, the distribution of environmental amenities such as green space and disamenities such as urban heat are tightly correlated with measures of population vulnerability such as reliance on SNAP benefits. Figure 10 (panel A) shows the relationship between the percentage of households receiving SNAP benefits and temperature by census tract; panel B shows the location of the areas that have the highest proportion of SNAP benefits and the hottest temperatures. These are locations that would be good targets for investment in urban agriculture that provides both food and urban cooling.

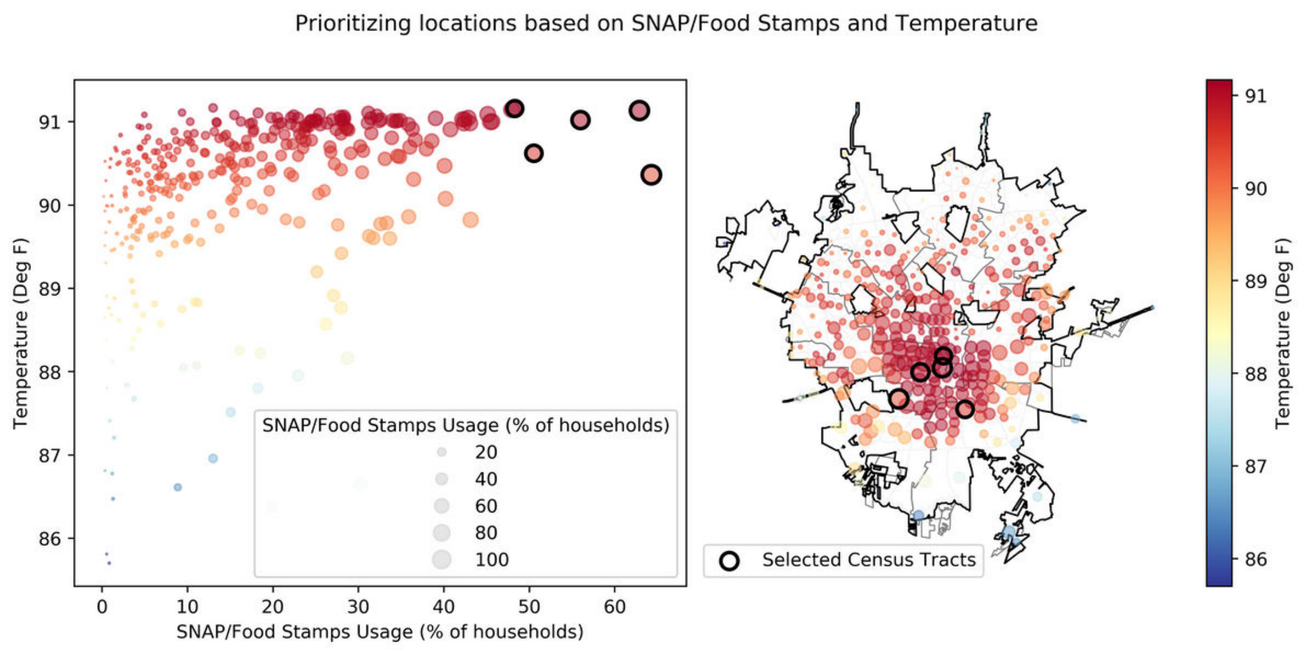


Figure 10. Equity prioritization mapping based on SNAP reliance and temperature. In both the scatterplot (left) and map (right) dots represent census tracts; dot size corresponds to SNAP/Food Stamp usage and dot color to temperature. High priority census tracts were selected based on a combination of high temperature and SNAP/Food Stamp usage.

We can measure the degree of inequity between socio-economic vulnerabilities and environmental amenities–and how those relationships change when installing food forests or urban farms–using graphs like Figure 10a. The slope of the line correlating a socio-economic metric and an environmental amenity indicates the degree of inequity; steeper slopes show deeper inequities. By repeating this analysis under our urban agriculture scenarios we can test for changes in these relationships. If the line flattens by installing urban agriculture across the city in a scenario, that intervention is helping to address an existing inequality. If the line steepens, the scenario is exacerbating current inequities.

Figure 11 highlights the correlation between impoverished populations and temperature under the current landscape (light gray) and full-conversion food forest scenario (black). The installation of food forests reduces the slope of the line. This reduction is small, however. Many factors unchanged by the addition of food forests underlie this relationship.

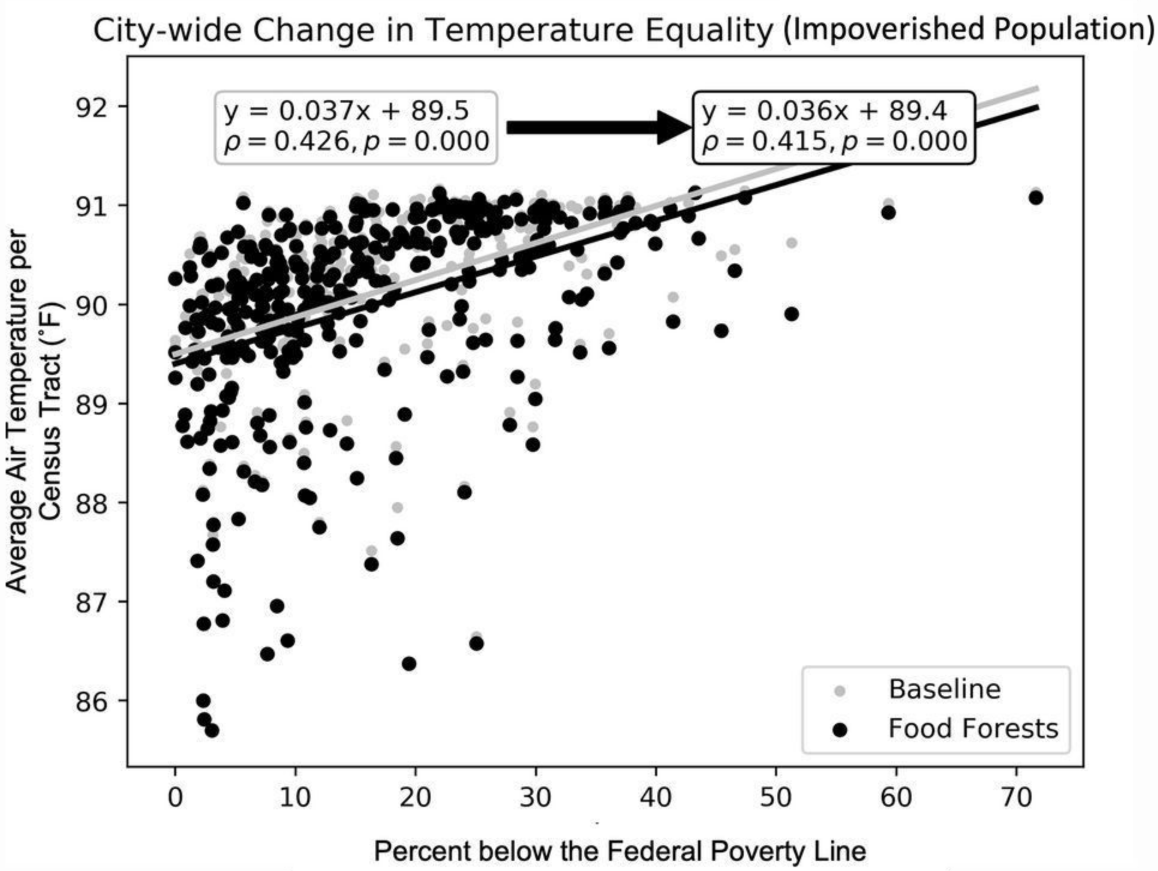


Figure 11. The relationship between modeled air temperature and poverty. Each point represents a census tract, with gray dots showing the results for the current landscape and black dots representing the food forests under the full conversion scenario. Correlation equations and significance levels are provided, with their outline color (gray, black) corresponding to their scenario.

Carbon sequestration

Cities are critical sources of climate emissions, with significant global carbon emissions coming from manufacturing and constructing built infrastructure. We linked changes in carbon stocks and emissions to global climate impacts and resulting economic damages through the social cost of carbon.

Food forests have the potential to increase carbon storage across the city by up to 340,000 metric tons, an equivalent value of $17.6 million using a conservative social cost of carbon ($53 per metric ton; Interagency Working Group on Social Cost of Greenhouse Gases, 2021). Conversely, urban farms could decrease carbon storage by over 450,000 metric tons at a social cost of $23.6 million—this is likely driven by the conversion of forested areas with already high carbon storage in our scenarios.

Green space access

Urban living is associated with heightened risk of cardiovascular and respiratory disease and a suite of mental disorders (Hartig et al. 2014, Kondo et al. 2018). A growing body of research demonstrates causal links between loss of nature experience and human health (Soga and Gaston 2016). We use green space access as a proxy for the mental and physical health benefits of nature to people. Citywide, food forests could increase the amount of urban green space accessible to San Antonians by 2.0 acres/100,000 people–with bigger changes possible in some districts (such as an increase of 8.9 acres/100,000 people in District 3. In contrast, urban farms decrease accessible green space by 10.4 acres/100,000 people because we assume that food forests are open to public access and urban farms are not. Any green space on the original vacant lands (as identified in the land cover data) was assumed to be accessible due to lack of granular data on each parcel's accessibility—if this assumption is incorrect and some of the vacant lands are inaccessible, transitioning them to urban farms would not change accessibility and transitioning them to food forests would provide even more green space access than reported here. Similarly, if some of the urban farms were accessible, the decrease in accessible green space wouldn't be as strong either.

Flood retention

Natural areas can play a critical role in storing floodwaters. Because they provide permeable surfaces in a sea of impermeable surfaces, urban farms and food forests will surely contribute to the retention of flood waters. While this analysis evaluates just flood retention changes from natural areas (already permeable surfaces) transitioning to farms and forests, any sites that transitioned from impermeable surfaces to farms or food forests would have large effects on water infiltration (San Antonio Cost Benefit Analysis of Climate Ready Strategies 2021).

The benefit to flood reduction in large storms provided by urban agriculture, whether food forest or urban farm, is going to be minimal in the scenarios considered here because the forests and farms are replacing existing green or barren space. Greater benefits would be observed in cases where these practices are replacing impervious cover types, which provide very little flood mitigation. However, services of annual stormwater nutrient retention illustrate an important tradeoff with other benefits of urban agriculture (e.g., food production, heat island mitigation). Specifically, while food forests typically produce a very small increase in nitrogen or phosphorus loading (due primarily to increased leaf litter, which is rich in nutrients), urban farms would represent a large increase in nutrient export to stormwater without careful consideration of compost use and management of site rainfall-runoff, especially given the proximity of these farms to stormwater drainage systems.

While we see some small reductions or increases in flood volume in the full food forest and urban farm scenarios, there is essentially no difference between expected flood retention in the urban agriculture scenarios versus the existing parks or vacant vegetated space (typically 1% or less across districts; see Appendix 1). During large storms, rainfall rates greatly exceed infiltration capacity of soils and interception by trees, so topography and blue-gray infrastructure (e.g., pipe size, reservoir placement) can become more important in the determination of flooding than the ability of the landscape to soak up runoff. While urban agriculture undoubtedly contributes more to floodwater retention than built land use types with impervious surfaces, the urban agriculture scenarios investigated here are swapping one green space for another, without changes to underlying soil or water storage capacity–critical elements driving flood retention.

Nutrient retention

Natural lands can play an important role in retaining nutrients that would otherwise end up in local–and distant–water bodies, causing nutrient pollution and eutrophication and incurring stormwater treatment costs. The close proximity of urban agriculture to elements of the drainage network (streets, ditches, storm drains) necessitates careful consideration of external nutrient inputs to these landscapes (e.g., compost, fertilizer) and practices to manage runoff and nutrient pollution sources to stormwater (e.g., vegetative litter, compost use, erosion control).

With respect to nutrient retention, the most important result here is the large potential increase in both nitrogen and phosphorus export associated with the urban farm scenarios (Table 3), resulting from the high nutrient inputs of compost. We used a moderate compost application scenario per Small et al. (2022; see Appendix 2) and assumed no fertilizer use; yet compost is nutrient-rich and typically over-applied to urban farms, creating a potential runoff pollution problem. We emphasize, however, that this issue can be greatly alleviated with responsible compost use and runoff management practices. The other conversion scenario, food forest, was associated with very little impact to nutrient retention, with increases of roughly 4% or less to total N or total P exported in runoff overall. This small effect is primarily due to the incorporation of litter dispersal over greater distances by trees compared to shrubs or grass in the model.

Table 3. Estimated nutrient export associated with urban farm and food forest conversion scenarios, relative to existing (baseline) conditions, using the InVEST Nutrient Delivery Ratio (NDR) model. The extremely high export numbers for the farm scenario are due to high nutrient content of compost, assumed to be used at moderate levels in a scenario without any particular management or regenerative practices (See Appendix 2 for further details of methods).

Scenario		Phosphorus Export		Nitrogen Export	
		Total kg	Diff vs. Base (%)	Total kg	Diff vs. Base (%)
Baseline		25,138	--	337,194	--
Food Forest	20-ac Conv	22	0.09%	1,899	0.56%
	40-ac Conv	25	0.10%	2,138	0.63%
	Full Conversion	247	0.98%	14,128	4.20%
Urban Farm	20-ac Conv	23,860	95%	98,678	29%
	40-ac Conv	29,355	117%	121,813	36%
	Full Conversion	197,550	786%	813,754	241%

We used the scenario assessments across the city to estimate the expected per acre benefits that could be provided with the incremental addition of urban agriculture and food forests (Table 4). To estimate these numbers, we divided the total benefits by the total acres changed. Note that the benefits are likely to vary from place to place depending on existing green space and distributions of people but this provides an estimate for a standardized unit of change.

Table 4. Estimated average food and co-benefits provided per acre of urban farm and food forest.

Scenario	Crop Yield			Urban Cooling		Carbon storage	Access	Flood Retention	Nutrient Retention			
	Fresh food (lbs/yr)	Market value of fresh food ($/yr)	~# of households receiving daily allotment of fresh food from urban ag/yr	Annual savings on cooling ($)	Average change in relative mortality risk from heat (%)	Change in value of Carbon sequestered ($)	Change in green space access (acres/ 100,000 people)	Change in flood volume, 100-year storm (ft3)	Change in annual Nitrogen runoff export (%)	Annual cost of treating additional N in stormwater ($)	Change in annual Phosphorus runoff export (%)	Annual cost of treating additional P in stormwater ($)
Food Forests												
per 1-acre	11,438	$59,250	19	$208	<-0.001 %	$1,047	<0.0001	-735 (-0.40%)	0.84	-$2,002	0.015	-$271
Urban Farms												
per 1-acre	55,140	$69,476	553	$107	0.00%	-$1,405	- <0.0001	326 (0.18%)	48	-$115,300	12	-$216,800

A note on modeled results

As with all modeling studies, these results are dependent on key assumptions built into our approach. We detail all methods in Appendix 2. Future work could involve updating or changing assumptions or parameters that could yield different results.

Conclusions

Urban food forests and urban farms

Urban food forests and farms are extremely productive. Even in areas of the city that are very highly developed and thus have relatively little underutilized land (such as District 5), there is still ample opportunity to address local demand for food with very local production of food. Linking supply (underutilized publicly owned land for urban agriculture) with demand (households facing food insecurity) can help to guide decision-makers in an effort to implement urban agriculture where it will be most beneficial to vulnerable communities and continue building equity in the city.

Food forests provide less food (by weight) than urban farms, but additional yields include increases in ecosystem service co-benefits such as urban cooling, carbon storage, flood retention, and green space access. Food forests do increase nutrient pollution relative to underutilized lands, but these increases are minimal and can be mitigated with management practices.

Overall, urban farms provide more food than food forests but fewer co-benefits and could add nutrient pollution to the water system, though on-farm practices can significantly mitigate this cost. Urban farms provide some cooling services, but they store less carbon than existing underutilized lands, decrease green space access, and decrease flood retention services as well.

The city of San Antonio could implement policies directed at increasing urban agriculture to take advantage of these benefits–drawing from current sites and the Cost Benefit Analysis of Climate Ready Strategies from the Office of Sustainability. Such policies could include: 1) expanding their existing Community Toolshed to include agricultural equipment like trenchers, tillers, tree augers, broadforks, and walk-behind tractors, 2) making certain public lots available for a long-term lease for urban farmers, and 3) integrating the installation and maintenance of food forests into land management plans for public space by the Parks and Public Works departments.

Case studies

The individual food forests that we examined indicate that small scale investments in food forests can yield significant benefits–in terms of food yields, urban cooling, green space access, and carbon storage, once the trees are mature. We see very small benefits in terms of flood retention compared to baseline underutilized lands, but this service is would likely be much more significant if parcels were converted from those with impervious cover.

City-wide

Although it is not a particularly likely outcome, the “full conversion” scenario provides a useful bookend for thinking about the potential large-scale benefits of urban agriculture. Converting all available underutilized lands:

- To food forests would
    - provide over 192 million pounds of food, worth $995M enough to feed nearly 314,000 households
    - provide enough urban heat island mitigation service to save $3.5M in cooling costs per year.
    - sequester more than 300,000 metric tons of carbon (worth nearly $18M)
    - increase access to green space
- To urban farms would
    - provide over 926 million pounds of food, worth $1.17B enough to feed 1.27 million households
    - likely increase nitrogen and phosphorus runoff into the city
    - potentially reduce access to green space if they are private facilities

District level

District 3 and 5 have the highest rates of food insecurity, according to SNAP usage, in the city and are thus good locations to invest in urban agriculture. These districts differ significantly in the amount of available underutilized lands with District 3 having the most publicly owned green space and District 5 having the least.

Urban agriculture is highly productive; even small areas can produce significant amounts of fresh food for people. In addition, food forests targeted in these areas will decrease inequities in the distribution of benefits from green space, such as urban cooling services. Creating maps that explore supply and demand can help make the case for establishing farms and food forests where it will be most meaningful to those who need it.

Next steps and future work

In future work, we plan to drill down further to assess the benefits of conversion of individual parcels. This will provide useful information to assist with prioritizing investments in urban agriculture that seek to provide multiple benefits in equitable ways. In addition, we have secured a grant from NASA’s Environmental Equity and Justice program to build a web-based tool that will allow users without particular expertise to change individual parcels or groups of parcels on a map and to then see how those changes might impact the delivery of selected benefits. We have a beta version of this tool that we look forward to sharing. Feedback now will help us to create a tool with maximum utility for informing urban planning decisions–regarding urban agriculture or other changes in land use–in San Antonio.

Appendices

Appendix 1: **More detailed results**

Appendix 2: **Methods**

Appendix 1: More detailed results

This section provides additional results on food production, urban cooling, carbon sequestration, urban nature access, flood volume, and nutrient runoff.

Food production

Table A1-1. Production of vegetables at different scales for urban farms in San Antonio (lbs/year)

Potential production by urban farms of differing sizes (lbs/year)				
	1 acre	5 acres	20 acres	40 acres
Eggplant	7,760	38,799	155,196	310,391
Cabbage	3,007	15,035	60,140	120,279
Potato	5,995	29,974	119,898	239,795
Onion	6,447	32,233	128,932	257,864
Tomatoes	11,071	55,357	221,426	442,853
Summer Squash	5,188	25,938	103,751	207,503
Radish	8,025	40,124	160,495	320,991
Lettuce	7,648	38,241	152,964	305,928
Total	*55,140*	*275,700*	*1,102,802*	*2,205,603*

Table A1-2. Estimated production for the 'total conversion' scenario, in which all 16,800 acres of underutilized natural lands in the city are transitioned to urban farms. This would produce an estimated 926 million lbs of vegetables per year, with an estimated >$1.1 billion in market value.

Lbs/acre/year	Potential production of urban farms across San Antonio
Eggplant	130,368,745
Cabbage	50,519,034
Potato	100,717,489
Onion	108,306,413
Tomatoes	186,004,388
Summer Squash	87,154,054
Radish	134,820,644
Lettuce	128,494,156

Table A1-3. Production of fruit and nuts at different scales for urban food forests in San Antonio (lbs/year).

Potential production by urban food forests of differing sizes (lbs/year)				
	1 acre	5 acres	20 acres	40 acres
Mulberry	1,500	7,500	30,000	60,000
Pecan	188	938	3,750	7,500
Fig	2,250	11,250	45,000	90,000
Nopal	7,500	37,500	150,000	300,000
Total	*11,438*	*57,188*	*228,750*	*457,500*

Table A1-4. Estimated production for the 'total conversion' scenario, in which all 16,800 acres of underutilized natural lands in the city are transitioned to urban food forests. This would produce an estimated 192 million lbs of vegetables per year, with an estimated $995 million in market value.

	Potential production of Urban Food Forests across San Antonio (lbs/year)
Nopal	25,200,857
Fig	3,150,107
Mulberry	37,801,285
Pecan	126,004,284

Urban Cooling

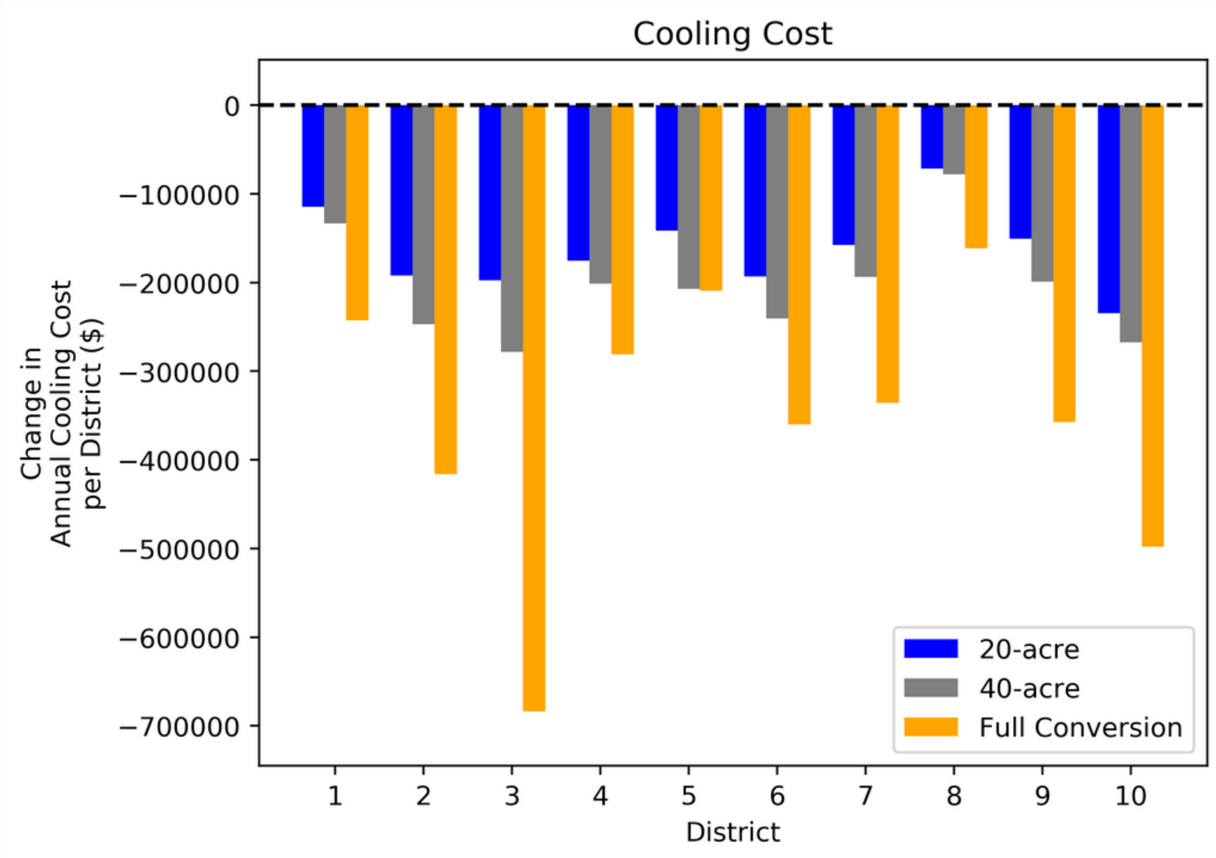


Figure A1-1. Change in annual cooling costs associated with the urban heat island per district for varying sizes of urban food forests. Cooling costs were calculated based on monthly temperature effects on cooling degree days per residential building.

Carbon

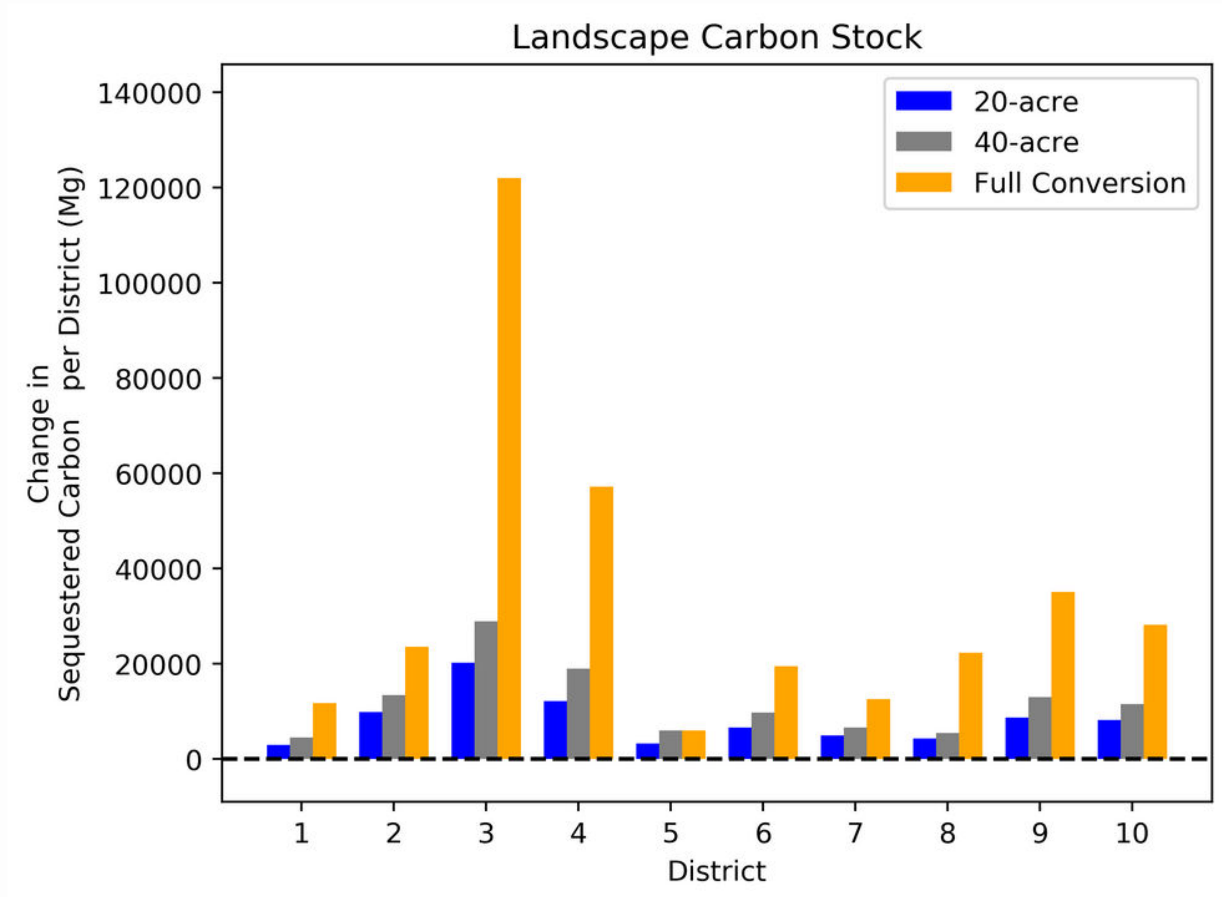


Figure A1-2. Change in sequestered carbon per district from varying sizes of urban food forests. District 3 has the most undeveloped open space for conversion, so converting it all has a large potential impact on carbon storage and sequestration. Every increase in 20,000 Mg (metric ton) of stored carbon is equivalent to removing approximately 16,000 cars for one year (EPA Greenhouse Gas Equivalencies Calculator).

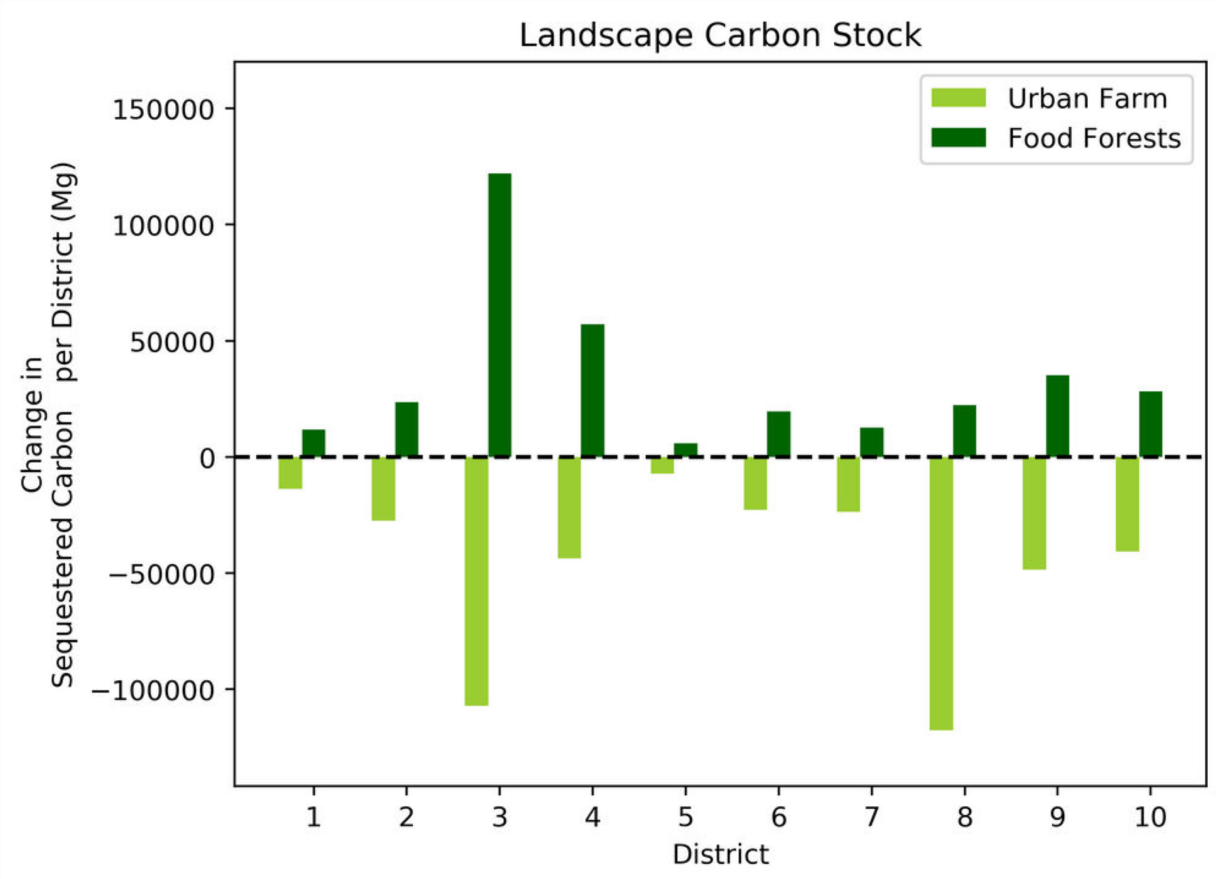


Figure A1-3. Change in sequestered carbon per district from food forests and urban farms under the full conversion scenario. Results here are driven primarily by the carbon sequestration potential of trees. We expect the trees that comprise food forests to sequester more carbon than the agricultural crops produced on urban farms. We also assumed that some currently forested land can be converted to food forests or urban farms, leading to a net loss of landscape carbon from the installation of urban farms.

Nature access

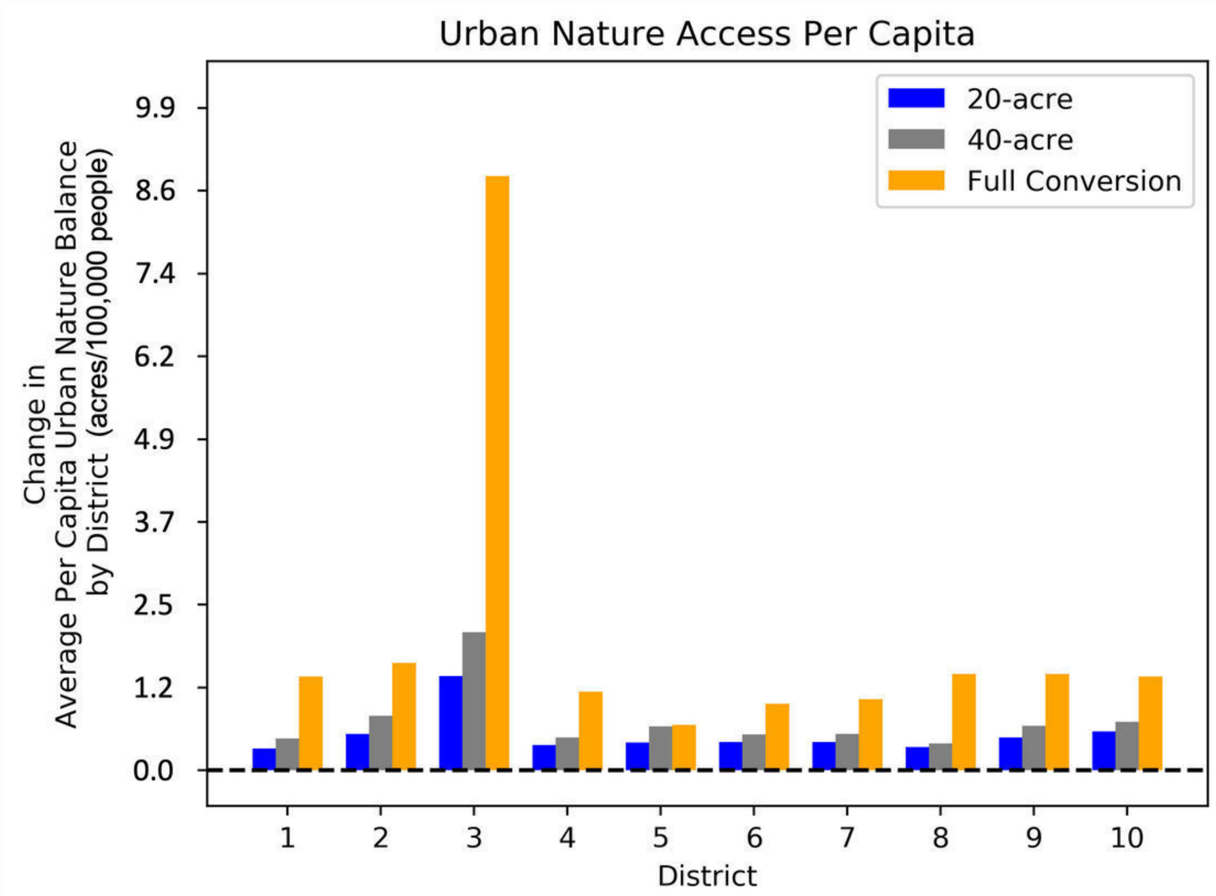


Figure A1-4. Change in urban nature access per district from varying sizes of urban food forests. District 3 has the most undeveloped open space for conversion, hence the relatively large potential increase in benefits shown here.

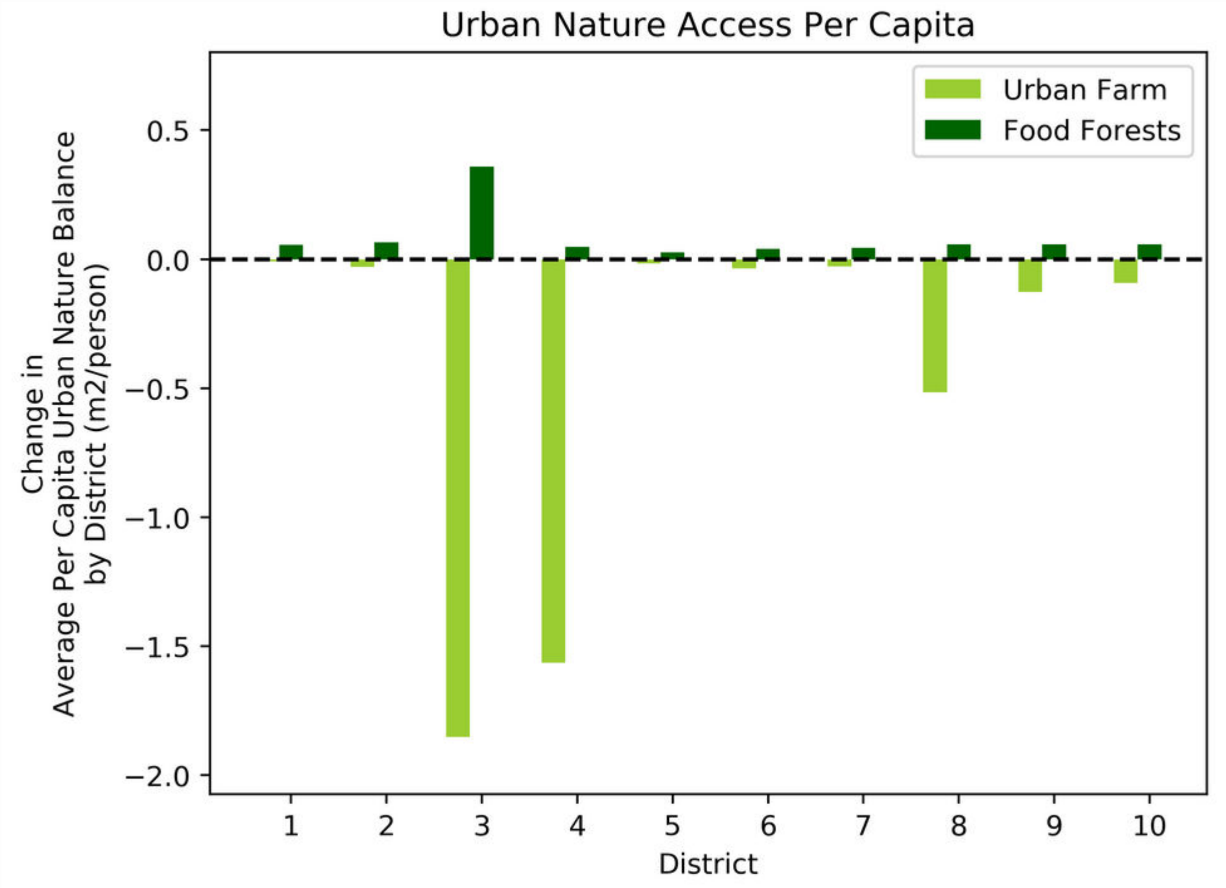
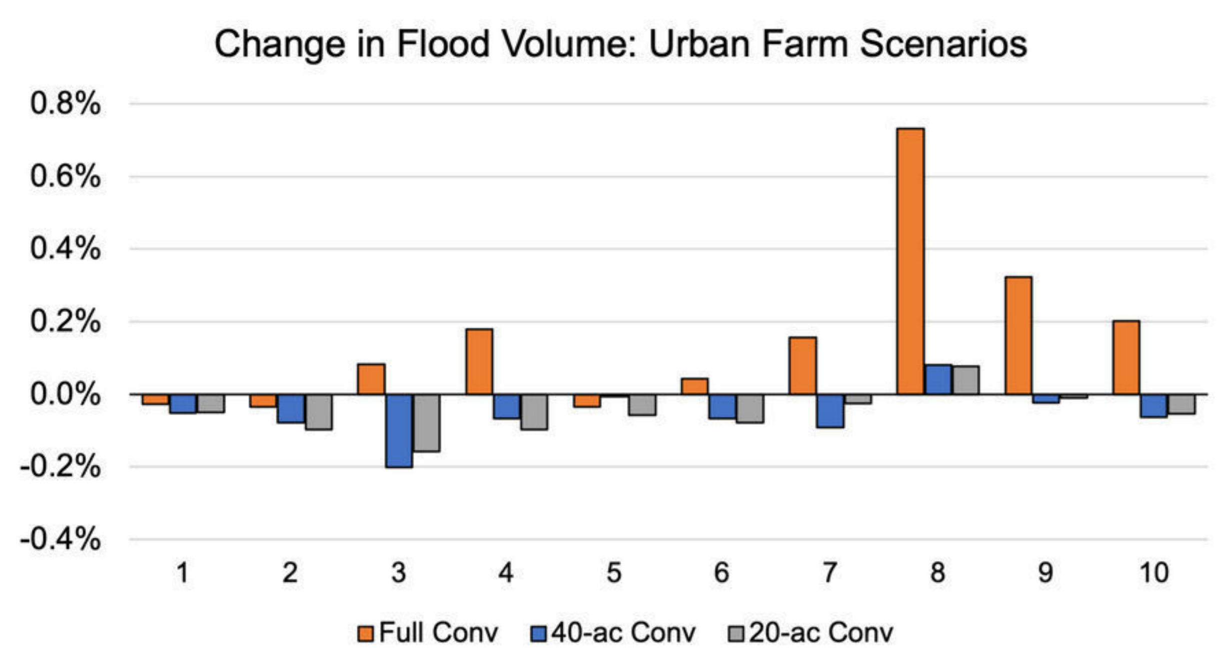


Figure A1-5. Change in per-capita urban nature access per district from urban food forests and urban farms under the full conversion scenario. These results reflect our assumptions that urban farms are closed to the public and replace existing accessible greenspace with inaccessible agriculture, whereas urban food forests are designed for public access and maintain or even increase the total amount of accessible green space across the city.



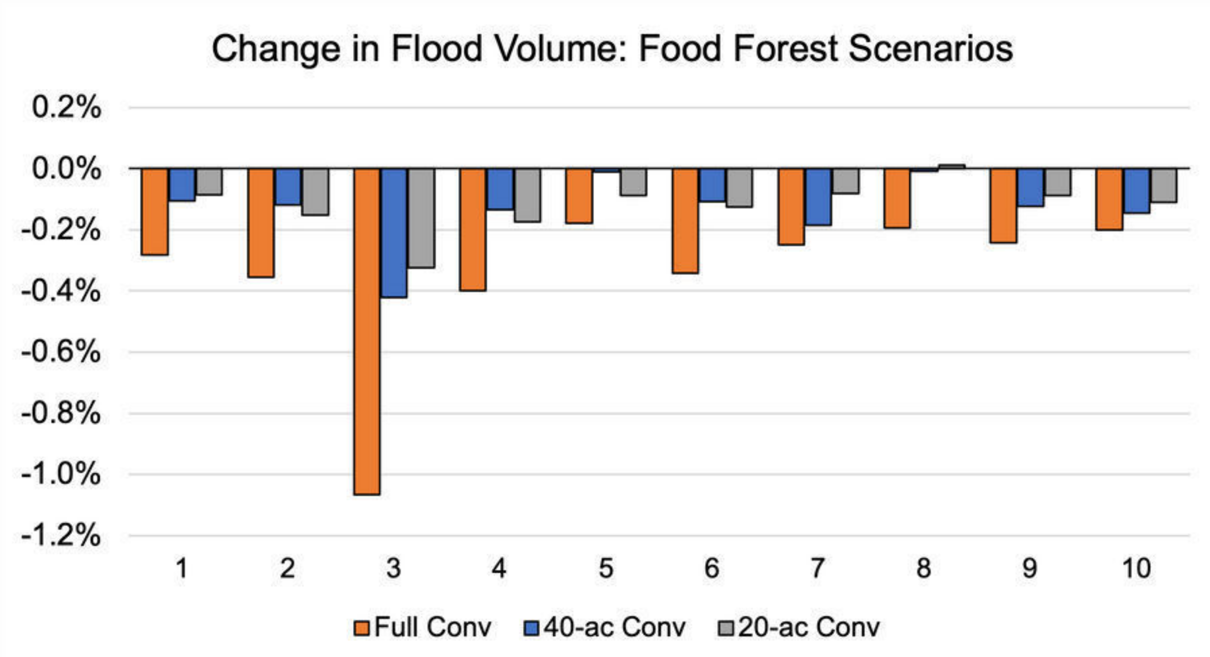


Figure A1-6. Flood mitigation impacts (as percent change in total flood volume, by district) of urban agriculture scenarios in San Antonio using the InVEST Flood Mitigation Model and a 24-hour, 100-year storm (11.8 inches). Top: urban farm scenarios; Bottom: food forest scenarios. Since conversion takes place on vacant and often vegetated spaces, flood volumes for the 100-year storm are largely unaffected by the various agriculture scenarios.

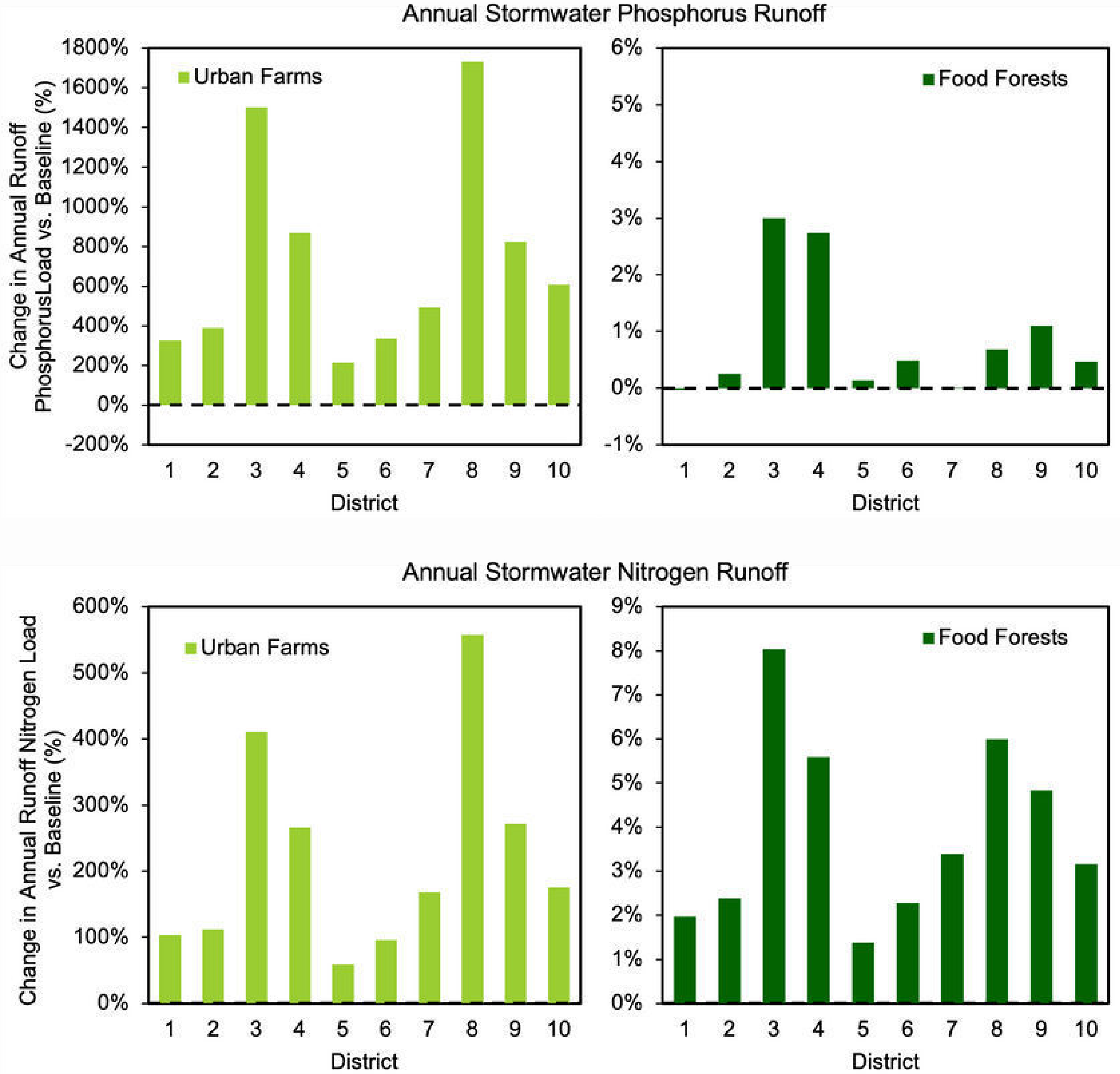
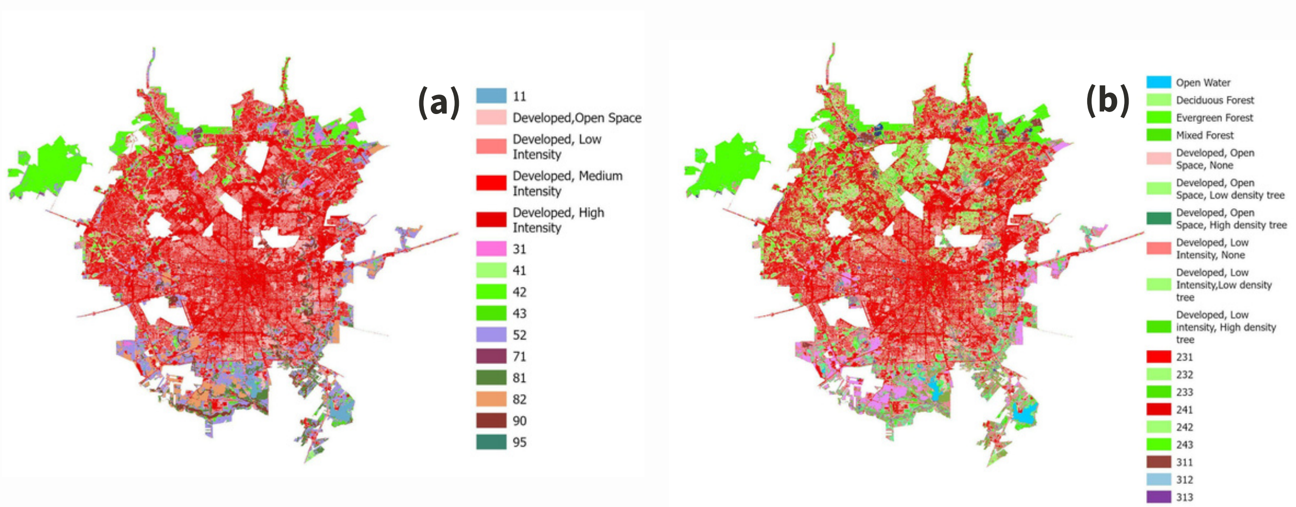


Figure A1-7. Stormwater nutrient runoff impacts (as percent change in rainfall-runoff export of Nitrogen or Phosphorus vs. baseline conditions, by district) of the "full conversion" urban agriculture scenarios in San Antonio using the InVEST Nutrient Delivery Ratio model. Top: Nitrogen runoff, Bottom: Phosphorus runoff. Given the inputs of nutrient-rich compost to the urban farms, and proximity of the farms to impervious drainage, potential nutrient export in stormwater (due to leaching and erosion) is high in this agriculture scenario, but can be greatly mitigated by on-site compost and stormwater management practices.

Appendix 2: Methods

Improved land cover data by integrating tree canopy

While the National Land Cover Data (NLCD) is available nationally, its spatial resolution (30 meters) and ability to represent green infrastructure are inadequate for many of the ecosystem services we will model. We supplemented the 30-meter NLCD with NASA tree canopy data to improve estimates of tree canopy, grass, and/or impervious surfaces percentages. Specifically, we added one tier in the existing land cover classes. For example, the class of Developed, Open Space in the NLCD data was reclassified into Developed, Open Space, None tree (0%), and Developed, Open Space, low density tree (1%-33%), and Developed, Open Space, high density tree (>33%) based on the percentages of tree canopy. The improved land cover data were used as inputs into our InVEST models.



NLCD data

New Land Cover with **tree canopy (30-m NASA)**

Figure A2-1. Spatial pattern of National Land Cover data (NLCD, a) and improved land cover by integrating tree canopy from NASA (b).

Identifying 'underutilized lands' in San Antonio

We used three criteria to create a map of land in San Antonio that could potentially be transitioned to urban agriculture from its current land use. The three criteria were 1) current land cover/land use type, 2) current land ownership, and 3) parcel size. The goal was not to exhaustively identify every potential parcel that could be converted, but rather to use available data and apply a simple, transparent approach to generate a map that had broad coverage city-wide which could then be used to explore the potential benefits of implementing urban agriculture at different scales.

Table A2-1 shows the land use/land cover types that were considered for conversion to urban agriculture in San Antonio and the acreage of each within the city boundary. Land cover was extracted from a 30m National Land Use Land Cover dataset (2019) (Dewitz and USGS 2021). All natural land cover types, except wetlands and existing cropland, were included as areas where urban agriculture could be implemented (Figure A2-2). The most extensive land cover type in the city was 'developed open space', which is primarily grass with little tree canopy cover. Including forested and scrub/shrub areas in the suite of possible land cover types for conversion to urban agriculture was based on local knowledge that in many areas of San Antonio these land cover types may be comprised of invasive species and could benefit from remediation activities.

Table A2-1. Natural lands of different types in San Antonio that could be converted to urban agriculture and the acreage of each within the city. We assume that urban agriculture could only occur on open space or natural land use classes including developed open space, forested areas, scrub/shrub, and grassland. We excluded woody wetlands and croplands.

Natural LULC types in CoSA subject to conversion to Urban farms/food forests	NLCD code	Total Acres in San Antonio
Developed Open Space	21	39,999
Deciduous Forest	41	5,169
Evergreen Forest	42	27,770
Mixed Forest	43	2,306
Scrub/shrub	52	32,303
Grassland	71	1,722

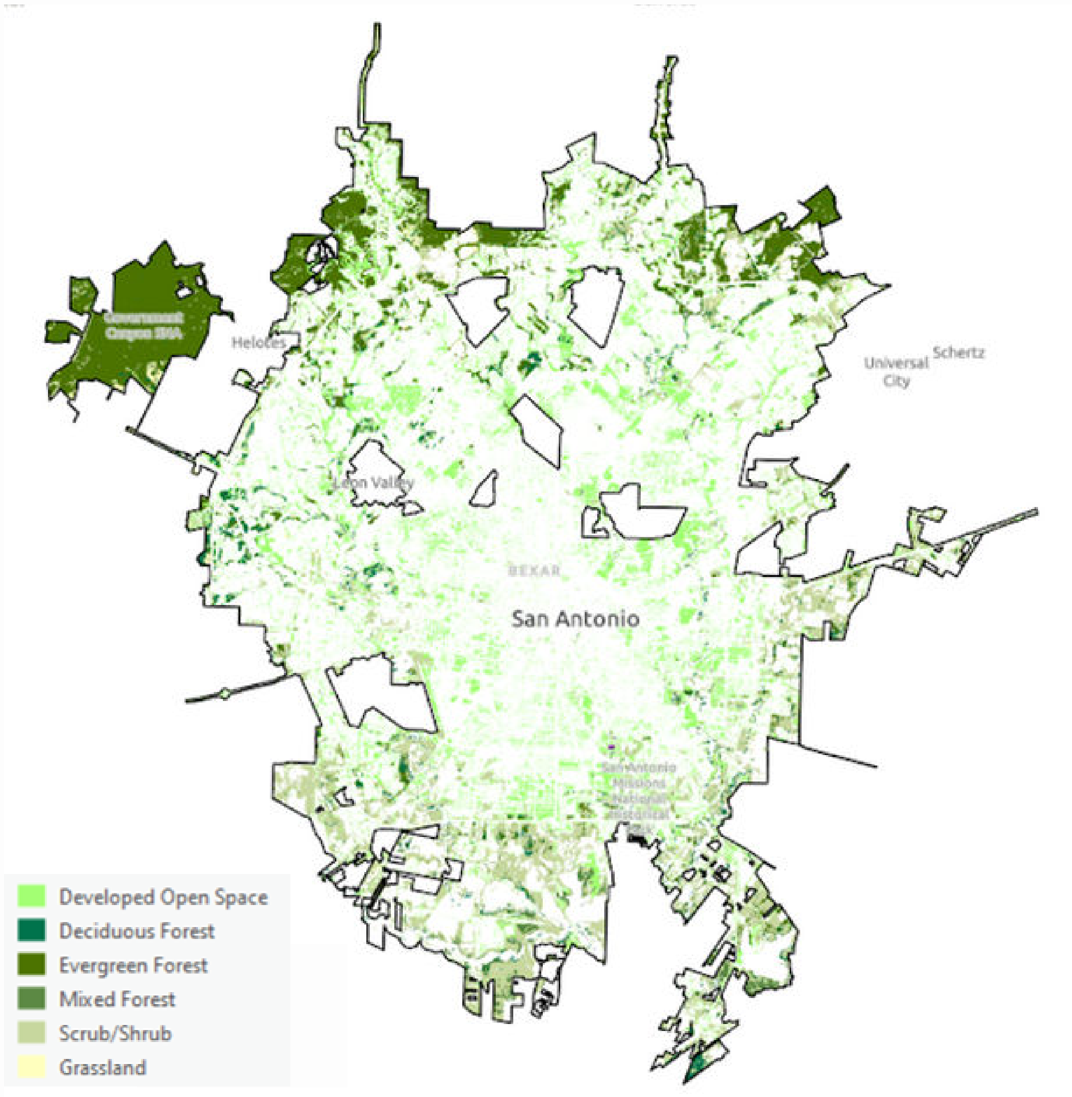


Figure A2-2. Natural lands of different types in San Antonio that could be converted to urban agriculture. We assume that urban agriculture could only occur on open space or natural land use classes including developed open space, forested areas, scrub/shrub, and grassland. We excluded woody wetlands and croplands.

The second criteria related to property ownership. In this analysis we explored the potential for expansion of urban agriculture on publicly owned lands, including city, county and state owned lands, as well as lands owned by utilities (e.g. San Antonio Water System) and the San Antonio River Authority. We excluded lands owned by the military and also excluded the airports. We also excluded other types of privately held land such as golf courses, country clubs and other significant tracts of green space, though we acknowledge the potential to collaborate with these landowners in the service of urban agricultural expansion. Table A2-2 lists the data sources that were used to identify publicly owned property. In particular the Bexar County Appraisal District had comprehensive parcel-level ownership data for the city and Table A2-3 lists the queries used to extract publicly owned parcels from this dataset. Putting this together with the natural lands layer, we created a map of publicly owned natural areas (Fig. A2-3).

Table A2-2. Data Sources used to identify publicly owned property in the city of San Antonio.

Data Type	Source
Park Boundaries	City of San Antonio GIS data portal[20]
Parcel Ownership	Obtained from the Bexar County Appraisal District[21] by partners on 11/10/2022
Vacant lots - miscellaneous city-owned property	Obtained from Bexar County Appraisal District and City of San Antonio partners

Table A2-3. Terms used to extract publicly owned parcel data from the Bexar County Appraisal District dataset.

Ownership Type	Attribute Column Query
County	Bexar County, Bexar County Properties LLC, Bexar Land Holdings Inc
City	City of San Antonio, City of San Antonio &, City of San Antonio Parks & Recreation Dept, City of San Antonio/Parks Dept
River Authority	San Antonio River Authority
Utilities	City of San Antonio/San Antonio Water System, San Antonio Water System, San Antonio Water Systems
State	State of Texas

[20] City of San Antonio. (2023). GIS Data. City of San Antonio. https://www.sanantonio.gov/GIS/GISData
[21] Bexar Appraisal District. (2023). Bexar CAD. Bexar Appraisal District. https://www.bcad.org/

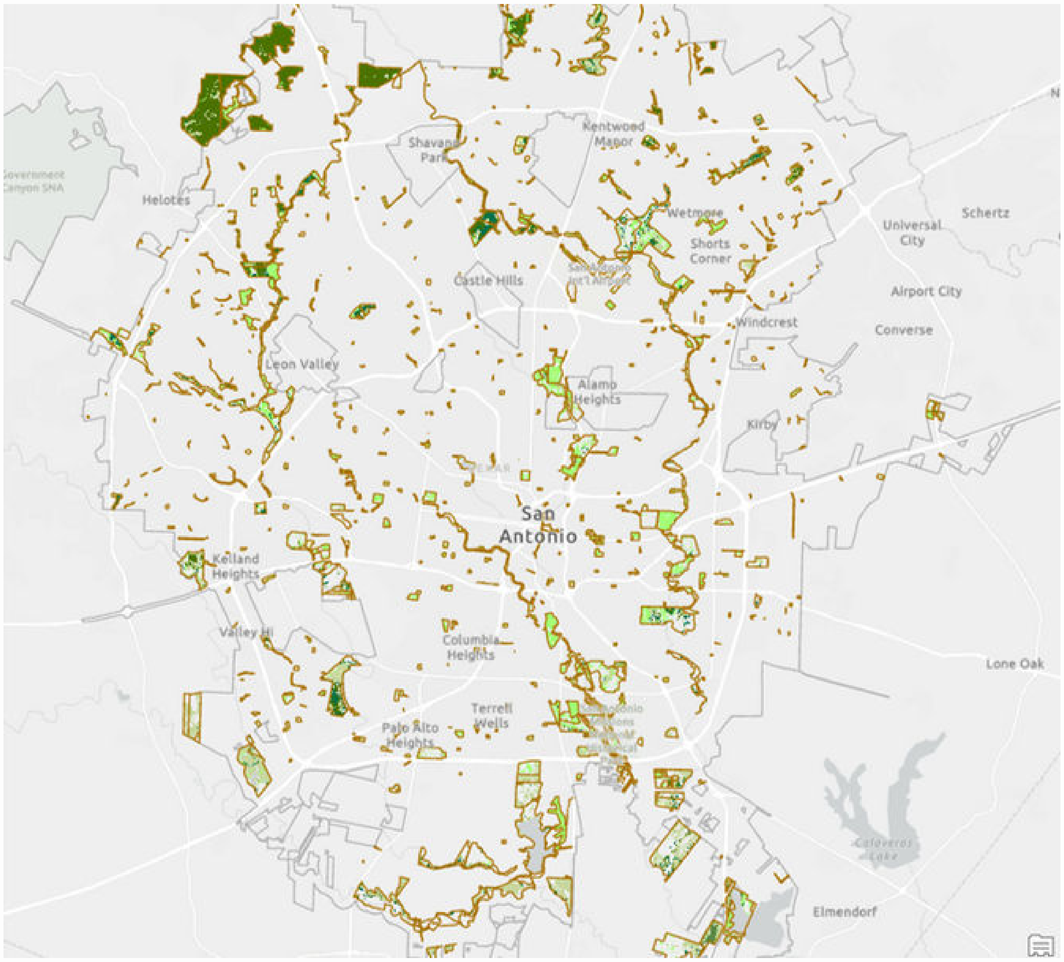


Figure A2-3. Natural areas on publicly owned lands. Brown outlines highlight publicly owned parcels throughout the city.

The third criteria we used to envision the area that could be used for expansion of urban agriculture is that of area. We used a minimum threshold of 1 acre of available space for a given parcel to be considered as suitable for conversion to urban agriculture. To understand the maximum benefits that could be provided if all underutilized land across the city was converted to urban agriculture, we first examined a “full conversion” scenario in which all natural lands that were publicly owned were converted to urban agriculture. We also explored the outcome of limiting the maximum area for any one parcel that might be converted to urban agriculture (20 acres and 40 acres). This is because we assumed that in large natural areas with, for example, many hundreds of acres of available green space, there may be an upper level cap on the acreage that can reasonably be converted.

Creating and selecting locations for the 20- and 40- acre farm and forest scenarios

To create the 20 and 40-acre scenarios, we randomly selected a 20 or 40-acre plot within each of the underutilized parcels that are at least that size. We created the potential farms or forests using the “Fishnet” tool in ArcGIS. We used this to split existing parcels into the 20- and 4-acre polygons and then randomly selected one polygon in each parcel for conversion. While an actual farm or forest in these parcels could be in a slightly different location, our goal was simply to provide an estimate for that area.

Modeling Crop Yields for Urban Food Forests and Farms

To estimate crop yields from urban food forests and urban farms we calculated an average per-area yield, in pounds, of selected crops for each scenario. This resulted in a yield (in pounds) per acre for urban food forests and urban farms that could be used to compute total yields for different extents of land converted (e.g., by district, by case study). This is a simple approach that assumes equal productivity across all converted land and is designed primarily to look at potential outcomes of land use change across the city. In reality, myriad factors beyond the scope of the study such as soil characteristics, drainage, exposure, will drive differences in productivity across sites. Thus, the results from this study should be used as a simple screen to identify opportunities based on land availability and a need for access to fresh food, which can then inform site selections to investigate in greater detail.

Urban Food Forest Yields and Value

For urban food forests, partners designed a scenario that reflected a simple intercropping of four highly adapted and low labor-input edible perennials: Mulberry, Pecan, Fig and Nopal. We assumed that food forests would dedicate equal amounts of space to each crop (e.g. each acre in cultivation would include a quarter acre for each crop). Yields, which are presented in Table A2-4, were taken from a variety of sources. These values all assume commercial production capacity which leverages machinery, harvesting efficiency, and often fertilizers and pest control techniques that will not be used by urban food forests. Thus we discounted the yields from urban food forests by 25% from those expected under commercial production. Based on the yields below, the estimated total annual production from one acre of food forests would be ~11,483lbs of fruit and nuts/year.

Table A2-4. Crop yields and sources for four crops in the Urban Food Forest scenario.

	Yield from commercial production (mature trees) lbs/quarter acre/year	Yield at 75% of commercial production (mature trees) lbs/quarter acre/year	Source
Mulberry	2,000	1,500	Flores-Hernández, et al (2004)
Pecan	250	188	Texas A&M (2015)
Fig	3,000	2,250	Stansel & Wyche (1932)
Nopal	10,000	7,500	https://journeytoforever.org/edu_silk_mulberry.html

Market value for each product are shown in Table A2-5. These were provided by Jamie Gonzalez of The Food Policy Council of San Antion, based on local going rates for fruit and nuts.

Table A2-5. Market value for four Urban Food Forest crops.

	Price per pound for local product (range)	Price per pound used in this study.
Mulberry	$10-15	$12
Pecan	$6-10	$9
Fig	$10-12	$11
Nopal	$2	$2

Urban Farm Yields and Value

For urban farms, partners designed a scenario that focused on eight staple crops: eggplant, cabbage, potato, onion, tomato, summer squash, radish, and lettuce. Like the urban food forest, for the purposes of this study we assumed that each crop would be allocated the same amount of space, such that for an acre 1/8th of the space would be cultivated with each crop (with the appropriate spacing and number of successions). In this case, we calculated yields from the average of four different sources. The first was harvest logs from four seasons (Spring/Fall 2021 and Summer/Fall 2021) from Garcia Street Urban Farm. The other three sources were non-local and included: a meta-analysis by Payen et al. (2022) surveying and documenting yields from 200 studies of urban agriculture, and information from Rutgers University (2012) and Louisiana State University Ag Extension (2007) providing typical expected yields from mixed stand small scale agriculture and gardens. Table A2-6 shows the yields/acre/year for each crop for the different studies, as well as the average value across studies, which was what was applied in this study. Based on the yields below, the estimated total annual production from one acre of an urban farm would be ~55,140 lbs/year.

Table A2-6. Estimated crop yields for eight crops in the Urban Farm scenario.

Crop Type	Garcia Street Urban Farm (lbs/acre/yr)	Rutgers (lbs/acre/yr)	LSU (lbs/acre/yr)	Payen et al. Meta Analysis (lbs/acre/yr)	Average value used in this study (lbs/acre/yr)
Eggplant	143,724	43,560	39,000	22,029	62,078
Cabbage	19,057	28,314	22,100	26,752	24,056
Potato	102,655	28,314	28,600	32,267	47,959
Onion	95,103	43,560	65,000	2,627	51,573
Tomatoes	248,138	34,848	20,800	50,496	88,571
Summer Squash	82,545	54,014	7,800	21,642	41,501
Radish	95,349	87,120	26,000	48,324	64,198
Lettuce	107,882	82,764	26,000	28,096	61,186

We got the market value for each crop from the USDA Agricultural Marketing Service, National Retail Report - Specialty Crops. These reports are produced biweekly, so prices below corresponded to the time period of Mar 11-23, 2023 (the reports also provide the previous year's price during that window for comparison). Table A2-7 shows the market prices from 2022 and 2023, as well as the average used in this study.

Table A2-7. Market value for eight Urban Farm crops.

Crop Type	Price per lb. for 3/11-3/23/2023	Price per lb. for 3/11-3/23/2022	Average price per lb.	Notes
Eggplant	$1.38	$1.30	$1.34	
Cabbage	$0.58	$0.52	$0.55	green cabbage
Potato	$1.08	$0.95	$1.02	average of four varieties: round red, round white, russet, yellow type
Onion	$0.75	$1.29	$1.02	yellow onions
Tomatoes	$1.32	$1.48	$1.40	avg. of misc. tomato varieties, vine ripened and roma
Summer Squash	$1.32	$1.34	$1.33	zucchini
Radish	$1.38	$1.94	$1.66	
Lettuce	$1.74	not reported	$1.74	average of romaine and iceberg

Calculating household consumption of fresh fruit and vegetables

To calculate the estimated household consumption of fresh fruit and vegetables, we used the USDA's dietary guidelines (2015-2020) to calculate the fraction of daily fresh food intake that should be vegetables (~56%, averaged between 'moderately active' male and female adults and children) and fruits (~43%) (Table A2-8). We then used the WHO's recommendation of 400g (0.88lbs) of fresh fruit and vegetables daily for an 'average person', to calculate the pounds of fruit and vegetables required per person, per day. We were able to do these calculations for nuts directly from the USDA as the recommended daily allotments are given in weights rather than cup equivalents. To estimate the amount of fruit and vegetables required to feed a household for a year, we assumed each household was composed of four people all consuming the recommended 400g (0.88lbs) of fresh fruit and vegetables per day (see Table A2-9). Because SNAP usage is measured by the household in the census, we were able to estimate the lbs of fresh fruit and vegetables required to feed each SNAP household for the year and assess how that compared with potential production from urban agriculture.

Table A2-8. Daily vegetable, fruit and nut requirements per the USDA[22]

	Estimated Daily caloric need	Demographic	Vegetable cup equivalents/ day	Fruit cup equivalents/ day	Nut ounce equivalents/ week	Vegetable / Total Produce	Fruit / Total Produce
Child 2-8	1,400	Moderately Active 4 yr old	1.5	1.5	3	50%	50%
Child 2-8	1,600	Moderately Active 8 yr old	2	1.5	4	57%	43%
Adult (F)	2,000	Moderately Active 40 yr old	2.5	2	5	56%	44%
Adult (M)	2,600	Moderately Active 40 yr old	3.5	2	5	64%	36%
Average values used in this study					***4.3***	***57%***	***43%***

Table A2-9. Estimating daily and yearly recommended vegetable, fruits and nuts in weight per person, and for a household of four.

*WHO: 400g/day recommendation[23] of veg (57%) and fruit (43%) (from Table A2-8)			
	Daily consumption of vegetables (grams)*	Daily consumption of fruit (grams)*	nuts (oz/wk) (USDA)
Per person	226	174	4.25
Per household of four	905	695	17
	Daily consumption of vegetables (pounds)	Daily consumption of fruit (pounds)	Daily consumption of nut (pounds)
Per person	0.50	0.38	0.04
Per household of four	2.00	1.53	0.15
	Yearly consumption of vegetables (pounds)	Yearly consumption of fruit (pounds)	Yearly consumption of nuts (pounds)
Per person	182	140	14
Per household of four	729	559	55

[22] U.S. Department of Health and Human Services and U.S. Department of Agriculture. (2015). 2015–2020 Dietary Guidelines for Americans. https://health.gov/sites/default/files/2019-09/2015-2020_Dietary_Guidelines.pdf

[23] World Health Organization. (2020). *Healthy diet*. World Health Organization. https://www.who.int/news-room/fact-sheets/detail/healthy-diet

Modeling Urban Cooling with InVEST

The InVEST Urban Cooling model converts maps of land cover and evapotranspiration into anticipated air temperature through a series of spatialized functions (Hamel et al. 2021). The input biophysical table (Table A2-10) relates land cover with solar reflectance (albedo), crop evapotranspiration, shade, building density, and its aggregation into larger green spaces. The model predicts cooling potential from these land cover-related parameters and applies that cooling to a map of temperature derived from a monthly average (82.7˚F for August in San Antonio) and a typical urban heat island for the city (6.4˚F in San Antonio). We derived land cover parameter estimates from previous studies (World Bank 2022). Many of these parameters are scarce in the published literature and are global in scope, so we rely on city-based temperature and urban heat island estimates to provision the model with locational specificity. For each combination of land cover and tree canopy classification (see Table A2-10) we calculated the average of the land cover's parameter and the "Mixed Forest" parameters weighted by the expected tree canopy cover percentage.

As our initial parameters were not tailored to food forests and urban farms, we extrapolated from the existing land cover classes to approximate these new land uses. For the urban cooling model, we assumed food forests were an average of the existing "cultivated crops" and "deciduous forests" layers. We approximated urban farms as 25% "herbaceous" and 75% "cultivated crops".

We converted air temperature into relative mortality risk following methods from a global analysis of mortality relative to a city's climate (Guo et al. 2014; World Bank 2022). A city has a "comfort" temperature around which the lowest deaths are reported; mortality rates increase above that temperature in non-linear and city-specific ways (Guo et al. 2014). We spatialized those increased mortality risks by applying functions from Guo et al. (2014) to the temperature maps output by InVEST (World Bank 2022). Mortality risk here is presented as relative risk, where a percent increase in risk is associated with a percent increase in mortality.

To assess impacts on energy costs, we converted air temperature into monthly cooling degree days (CDD) following methods from Roxon et al. (2020). Cooling degree days are a standard estimate of per-building energy use, representing the number of days a building had to cool itself a single degree Fahrenheit (if a building cooled 5˚F in a single day, it accrued 5 cooling degree days), and are directly related to energy use and its associated monetary cost (Roxon et al. 2020). We converted maps of air temperature into maps of cooling degree days and joined them to building footprint data across San Antonio (Microsoft 2023), calculating the monetary cost of cooling with a conservative rate of $0.14 per kWh (Energysage 2023).

Table A2-8. Daily vegetable, fruit and nut requirements per the USDA[22]

	Estimated Daily caloric need	Demographic	Vegetable cup equivalents/ day	Fruit cup equivalents/ day	Nut ounce equivalents/ week	Vegetable / Total Produce	Fruit / Total Produce
Child 2-8	1,400	Moderately Active 4 yr old	1.5	1.5	3	50%	50%
Child 2-8	1,600	Moderately Active 8 yr old	2	1.5	4	57%	43%
Adult (F)	2,000	Moderately Active 40 yr old	2.5	2	5	56%	44%
Adult (M)	2,600	Moderately Active 40 yr old	3.5	2	5	64%	36%
Average values used in this study					***4.3***	***57%***	***43%***

Table A2-9. Estimating daily and yearly recommended vegetable, fruits and nuts in weight per person, and for a household of four.

***WHO: 400g/day recommendation[23] of veg (57%) and fruit (43%) (from Table A2-8)**			
	Daily consumption of vegetables (grams)*	Daily consumption of fruit (grams)*	nuts (oz/wk) (USDA)
Per person	226	174	4.25
Per household of four	905	695	17
	Daily consumption of vegetables (pounds)	Daily consumption of fruit (pounds)	Daily consumption of nut (pounds)
Per person	0.50	0.38	0.04
Per household of four	2.00	1.53	0.15
	Yearly consumption of vegetables (pounds)	Yearly consumption of fruit (pounds)	Yearly consumption of nuts (pounds)
Per person	182	140	14
Per household of four	729	559	55

[22] U.S. Department of Health and Human Services and U.S. Department of Agriculture. (2015). 2015–2020 Dietary Guidelines for Americans. https://health.gov/sites/default/files/2019-09/2015-2020_Dietary_Guidelines.pdf

[23] World Health Organization. (2020). *Healthy diet*. World Health Organization. https://www.who.int/news-room/fact-sheets/detail/healthy-diet

Table A2-10. InVEST Parameter Values for the Urban Cooling, Carbon, and Urban Nature Access models by NLCD classification and tree canopy percentage.

NLCD Land Cover	Tree Canopy (%)	Urban Cooling					Carbon				Nature Access
		Shade (0 to 1)	Crop Evap. Coefficient (kC)	Albedo (0 to 1)	Green Area (0 or 1)	Building Intensity (0 to 1)	Aboveground Carbon (Mg)	Belowground Carbon (Mg)	Soil Carbon (Mg)	Dead Matter Carbon (Mg)	Urban Nature (0 or 1)
Open Water	0%	0	1.0000	0.0564	0	0	0	0	0	0	0
Open Water	14%	0.15	1.0006	0.0691	0	0	14.1669974	0	15.5679885	1.6	0
Open Water	40%	0.4	1.0016	0.0902	0	0	37.7786598	0	41.5146361	4.26666667	0
Open Water	66%	0.66	1.0026	0.1122	1	0	62.3347887	0	68.4991496	7.04	1
Perennial Ice/Snow	0%	0	0.0000	0.8000	0	0	0	0	0	0	0
Perennial Ice/Snow	14%	0.15	0.1506	0.7012	0	0	14.1669974	0	15.5679885	1.6	0
Perennial Ice/Snow	40%	0.4	0.4016	0.5364	0	0	37.7786598	0	41.5146361	4.26666667	0
Perennial Ice/Snow	66%	0.66	0.6626	0.3651	1	0	62.3347887	0	68.4991496	7.04	1
Developed, Open Space	0%	0	0.5160	0.1607	0	0	52.8896524	3.4	100.986275	4.4	0
Developed, Open Space	14%	0.15	0.5892	0.1577	0	0	59.1232019	2.89	101.406322	5.34	0
Developed, Open Space	40%	0.4	0.7112	0.1528	0	0	69.5124512	2.04	102.106401	6.90666667	0
Developed, Open Space	66%	0.66	0.8380	0.1477	1	0	80.3172705	1.156	102.834483	8.536	1
Developed, Low Intensity	0%	0	0.4296	0.2279	0	0.33	187.451856	2.93333333	78.014436	17.4800813	0
Developed, Low Intensity	14%	0.15	0.5157	0.2149	0	0.33	173.501075	2.49333333	81.8802591	16.4580691	0

		Urban Cooling					Carbon				Nature Access
NLCD Land Cover	Tree Canopy (%)	Shade (0 to 1)	Crop Evap. Coefficient (kC)	Albedo (0 to 1)	Green Area (0 or 1)	Building Intensity (0 to 1)	Aboveground Carbon (Mg)	Belowground Carbon (Mg)	Soil Carbon (Mg)	Dead Matter Carbon (Mg)	Urban Nature (0 or 1)
Open Water	0%	0	1.0000	0.0564	0	0	0	0	0	0	0
Open Water	14%	0.15	1.0006	0.0691	0	0	14.1669974	0	15.5679885	1.6	0
Open Water	40%	0.4	1.0016	0.0902	0	0	37.7786598	0	41.5146361	4.26666667	0
Developed, Low Intensity	40%	0.4	0.6593	0.1931	0	0.33	150.249773	1.76	88.3232977	14.7547154	0
Developed, Low Intensity	66%	0.66	0.8086	0.1705	1	0.33	126.06842	0.99733333	95.0240578	12.9832276	1
Developed, Medium Intensity	0%	0	0.3275	0.2082	0	0.66	171.901414	2.93333333	77.1556028	17.2634146	0
Developed, Medium Intensity	14%	0.15	0.4290	0.1981	0	0.66	160.283199	2.49333333	81.1502509	16.2739024	0
Developed, Medium Intensity	40%	0.4	0.5981	0.1813	0	0.66	140.919508	1.76	87.8079978	14.6247154	0
Developed, Medium Intensity	66%	0.66	0.7740	0.1638	1	0.66	120.781269	0.99733333	94.7320546	12.909561	1
Developed, High Intensity	0%	0	0.1789	0.1618	0	1	142.457512	2.93333333	78.8523753	17.2800813	0
Developed, High Intensity	14%	0.15	0.3027	0.1587	0	1	135.255883	2.49333333	82.5925075	16.2880691	0
Developed, High Intensity	40%	0.4	0.5089	0.1535	0	1	123.253167	1.76	88.8260613	14.6347154	0
Developed, High Intensity	66%	0.66	0.7234	0.1481	1	1	110.770343	0.99733333	95.3089572	12.9152276	1

NLCD Land Cover	Tree Canopy (%)	Urban Cooling					Carbon				Nature Access
		Shade (0 to 1)	Crop Evap. Coefficient (kC)	Albedo (0 to 1)	Green Area (0 or 1)	Building Intensity (0 to 1)	Aboveground Carbon (Mg)	Belowground Carbon (Mg)	Soil Carbon (Mg)	Dead Matter Carbon (Mg)	Urban Nature (0 or 1)
Open Water	0%	0	1.0000	0.0564	0	0	0	0	0	0	0
Open Water	14%	0.15	1.0006	0.0691	0	0	14.1669974	0	15.5679885	1.6	0
Open Water	40%	0.4	1.0016	0.0902	0	0	37.7786598	0	41.5146361	4.26666667	0
Barren Land	0%	0	0.6135	0.2320	0	0	6.8	0	25.5	0	0
Barren Land	14%	0.15	0.6720	0.2183	0	0	19.9469974	0	37.2429885	1.6	0
Barren Land	40%	0.4	0.7696	0.1956	0	0	41.8586598	0	56.8146361	4.26666667	0
Barren Land	66%	0.66	0.8712	0.1719	1	0	64.6467887	0	77.1691496	7.04	1
Deciduous Forest	0%	1	1.0039	0.1419	1	0	85.8849871	0	96.0899427	8.8	1
Deciduous Forest	14%	1	1.0039	0.1419	1	0	85.8849871	0	96.0899427	8.8	1
Deciduous Forest	40%	1	1.0039	0.1419	1	0	85.8849871	0	96.0899427	8.8	1
Deciduous Forest	66%	1	1.0039	0.1419	1	0	85.8849871	0	96.0899427	8.8	1
Evergreen Forest	0%	1	1.0039	0.1401	1	0	105.684987	0	96.0899427	14.4	1
Evergreen Forest	14%	1	1.0039	0.1401	1	0	105.684987	0	96.0899427	14.4	1
Evergreen Forest	40%	1	1.0039	0.1401	1	0	105.684987	0	96.0899427	14.4	1
Evergreen Forest	66%	1	1.0039	0.1401	1	0	105.684987	0	96.0899427	14.4	1
Mixed Forest	0%	1	1.0039	0.1410	1	0	91.7699743	0	119.179886	8.8	1

NLCD Land Cover	Tree Canopy (%)	Urban Cooling					Carbon				Nature Access
		Shade (0 to 1)	Crop Evap. Coefficient (kC)	Albedo (0 to 1)	Green Area (0 or 1)	Building Intensity (0 to 1)	Aboveground Carbon (Mg)	Belowground Carbon (Mg)	Soil Carbon (Mg)	Dead Matter Carbon (Mg)	Urban Nature (0 or 1)
Open Water	0%	0	1.0000	0.0564	0	0	0	0	0	0	0
Open Water	14%	0.15	1.0006	0.0691	0	0	14.1669974	0	15.5679885	1.6	0
Open Water	40%	0.4	1.0016	0.0902	0	0	37.7786598	0	41.5146361	4.26666667	0
Mixed Forest	14%	1	1.0039	0.1410	1	0	91.7699743	0	119.179886	8.8	1
Mixed Forest	40%	1	1.0039	0.1410	1	0	91.7699743	0	119.179886	8.8	1
Mixed Forest	66%	1	1.0039	0.1410	1	0	91.7699743	0	119.179886	8.8	1
Shrub/Scrub	0%	0	0.9677	0.1887	1	0	47.875	0	68.1547765	0	1
Shrub/Scrub	14%	0.15	0.9732	0.1815	1	0	54.8607474	0	73.4995485	1.6	1
Shrub/Scrub	40%	0.4	0.9822	0.1696	1	0	66.5036598	0	82.407502	4.26666667	1
Shrub/Scrub	66%	0.66	0.9916	0.1572	1	0	78.6122887	0	91.6717736	7.04	1
Herbaceous	0%	0	0.9315	0.1929	1	0	10.1066012	8	98.7926442	0	1
Herbaceous	14%	0.15	0.9424	0.1851	1	0	22.7576084	6.8	99.5417361	1.6	1
Herbaceous	40%	0.4	0.9605	0.1721	1	0	43.8426205	4.8	100.790223	4.26666667	1
Herbaceous	66%	0.66	0.9793	0.1586	1	0	65.7710331	2.72	102.088649	7.04	1
Hay/Pasture	0%	0	0.9315	0.1710	1	0	10.1066012	8	98.7926442	0	0
Hay/Pasture	14%	0.15	0.9424	0.1665	1	0	22.7576084	6.8	99.5417361	1.6	0
Hay/Pasture	40%	0.4	0.9605	0.1590	1	0	43.8426205	4.8	100.790223	4.26666667	0
Hay/Pasture	66%	0.66	0.9793	0.1512	1	0	65.7710331	2.72	102.088649	7.04	1

NLCD Land Cover	Tree Canopy (%)	Urban Cooling					Carbon				Nature Access
		Shade (0 to 1)	Crop Evap. Coefficient (kC)	Albedo (0 to 1)	Green Area (0 or 1)	Building Intensity (0 to 1)	Aboveground Carbon (Mg)	Belowground Carbon (Mg)	Soil Carbon (Mg)	Dead Matter Carbon (Mg)	Urban Nature (0 or 1)
Open Water	0%	0	1.0000	0.0564	0	0	0	0	0	0	0
Open Water	14%	0.15	1.0006	0.0691	0	0	14.1669974	0	15.5679885	1.6	0
Open Water	40%	0.4	1.0016	0.0902	0	0	37.7786598	0	41.5146361	4.26666667	0
Cultivated Crops	0%	0	0.7172	0.1607	0	0	4.79384016	0	65.7526342	0	0
Cultivated Crops	14%	0.15	0.7602	0.1578	0	0	18.2417616	0	71.4577276	1.6	0
Cultivated Crops	40%	0.4	0.8319	0.1528	0	0	40.6549639	0	80.9662167	4.26666667	0
Cultivated Crops	66%	0.66	0.9064	0.1477	1	0	63.9646943	0	90.8550452	7.04	1
Woody Wetlands	0%	1	1.1000	0.1605	1	0	33.5	0	716.913854	0	1
Woody Wetlands	14%	1	1.0856	0.1576	1	0	42.6419974	0	624.944765	1.6	1
Woody Wetlands	40%	1	1.0616	0.1527	1	0	57.8786598	0	471.662949	4.26666667	1
Woody Wetlands	66%	1	1.0366	0.1476	1	0	73.7247887	0	312.24986	7.04	1
Emergent Herbaceous Wetlands	0%	0	1.1000	0.1420	1	0	33.5	0	716.913854	0	1
Emergent Herbaceous Wetlands	14%	0.15	1.0856	0.1418	1	0	42.6419974	0	624.944765	1.6	1
Emergent Herbaceous Wetlands	40%	0.4	1.0616	0.1416	1	0	57.8786598	0	471.662949	4.26666667	1

		Urban Cooling					Carbon				Nature Access
NLCD Land Cover	Tree Canopy (%)	Shade (0 to 1)	Crop Evap. Coefficient (kC)	Albedo (0 to 1)	Green Area (0 or 1)	Building Intensity (0 to 1)	Aboveground Carbon (Mg)	Belowground Carbon (Mg)	Soil Carbon (Mg)	Dead Matter Carbon (Mg)	Urban Nature (0 or 1)
Open Water	0%	0	1.0000	0.0564	0	0	0	0	0	0	0
Open Water	14%	0.15	1.0006	0.0691	0	0	14.1669974	0	15.5679885	1.6	0
Open Water	40%	0.4	1.0016	0.0902	0	0	37.7786598	0	41.5146361	4.26666667	0
Emergent Herbaceous Wetlands	66%	0.66	1.0366	0.1413	1	0	73.7247887	0	312.24986	7.04	1
Urban Farm	0%	0	0.7708	0.1688	1	0	6.12203041	2	74.0126367	0	0
Urban Farm	14%	0.15	0.8058	0.1646	1	0	19.3707233	1.7	78.4787298	1.6	0
Urban Farm	40%	0.4	0.8640	0.1577	1	0	41.4518781	1.2	85.9222182	4.26666667	0
Urban Farm	66%	0.66	0.9247	0.1504	1	0	64.416279	0.68	93.6634461	7.04	1
Food Forest	0%	1	0.8606	0.1513	1	0	91.7699743	0	119.179886	8.8	1
Food Forest	14%	1	0.8821	0.1498	1	0	92.1714756	0	116.870891	9.08	1
Food Forest	40%	1	0.9179	0.1472	1	0	92.8406444	0	113.022567	9.54666667	1
Food Forest	66%	1	0.9552	0.1445	1	0	93.5365799	0	109.020311	10.032	1

Modeling Urban Carbon Storage

We analyzed landscape carbon storage using the InVEST Carbon model, fitted with parameters gathered in a global review of urban carbon storage estimates (World Bank 2022). Typically, in urban areas we amend the base model with estimates of annual emissions and with embedded emissions (the carbon cost of constructing and installing the built environment). However, as our scenarios here exclude any developed land cover categories and their associated emissions, we focused exclusively on landscape carbon storage as per the original InVEST model (Natural Capital Project, 2023). We converted carbon storage into monetary value using a $53 Social Cost of Carbon based on US government guidance using a 3% discount rate (Interagency Working Group on Social Cost of Greenhouse Gasses, 2021).

As in the parameterization for the Urban Cooling model, we approximated food forests and urban farms from the average of the existing “cultivated crops” and “deciduous forests” layers and the weighted average of 25% “herbaceous” and 75% “cultivated crops”, respectively.

Modeling Urban Nature Access

The InVEST Nature Access model estimates a city’s demand for and supply of accessible green space based on maps of land cover and population (Falcone 2016). The model uses a conservative per capita demand of green space (16.7 m2 per person) and calculates the total demand based on population density (e.g., places with higher population density will have a commensurately higher demand). It then contrasts this demand with the supply of green space within a 2230m radius. Comparing supply and demand helps identify areas with insufficient green space relative to their population density. For our application of this model, we considered any uncultivated green space classifications in the NLCD (Deciduous Forest, Evergreen Forest, Mixed Forest, Shrub/Scrub, Herbaceous, Woody Wetland, Emergent Wetland) as accessible green space; food forests were considered accessible but we considered urban farms to be inaccessible to the general public.

Modeling Hydrologic Ecosystem Services

The urban landscape provides important ecosystem services related to the fate of rainfall-runoff and to the associated transport of pollutants that affect water quality in lakes and streams that receive runoff. Thus, these services relate to both the quantity and quality of runoff water, with impacts at both the time scale of a single, large storm event (flood) as well as accumulated in multiple events over an annual period. In this work, we use the term “Flood” to refer to the services (and disservices) associated with a single large storm event, with the more general term “Stormwater” tending to refer to the services and disservices realized over annual periods.

In this work we employed two InVEST models for hydrologic ecosystem services: (1) Urban Flood Mitigation, and (2) Nutrient Delivery Ratio (NDR). Briefly, the Flood Mitigation model determines the amount of runoff generated during a single storm event as a function of land cover (e.g., imperviousness) and soil infiltration capacity using the US Department of Agriculture's Curve Number method (NRCS 2004). For each pixel in a simulation domain, the model determines the volume of rainfall that infiltrates into the ground (service) as well as the volume that runs off (disservice) during the event.

Runoff or retention volumes can be summed over the pixels in known watersheds to produce estimates of total flood volume, but the model does not attempt to simulate runoff "routing" (prediction of where the runoff ends up) and therefore does not produce maps of flood depth or velocity, which typically require much more sophisticated models and input data sets. Instead, the Flood Mitigation model provides an estimate of the "sponginess" of the landscape, or the ability to soak up rainfall during large storms. As events become larger and more intense, the sponginess of the landscape matters less than topography or gray infrastructure capacity (storm pipes, ditches, and channels) as rainfall rates will far exceed soil infiltration capacity.

The Nutrient Delivery Ratio (NDR) model produces annual-scale estimates of pollutant transport associated with rainfall-runoff as a function of pollutant inputs to the landscape ("input loads"), the ability of the landscape to retain or immobilize pollutants ("retention"), and the flowpath distance over which this retention is realized. For this study, we considered nitrogen (N) and phosphorus (P) as the pollutants of interest, as these were deemed important in previous studies (Lonsdorf et al. 2021, Hamel et al. 2021) due to the water quality problems (e.g., algae blooms) associated with excess levels of N and P in lakes and streams, especially in urban watersheds. The NDR model does consider routing by modeling flowpaths for surface runoff and the retention (removal) of nutrients that occurs as runoff flows along these paths. In urban watersheds, these flowpaths are typically streets and ditches, which have very low capacity for nutrient removal. NDR produces estimates of the nutrients infiltrated (service) and exported from the watershed in runoff (disservice) over an annual time scale, but does not include estimates of annual scale retention or runoff volumes. While NDR was originally developed for rural landscapes, we developed an implementation of NDR suitable for cities in a previous project (Lonsdorf et al. 2021), with the approach adapted by Small et al. (2022) in a recent study of urban gardens in St. Paul, MN.

Parameterization of the Hydrologic Models

Parameterization of the hydrologic models (Flood Mitigation and NDR) for cities was done in past projects (Lonsdorf et al. 2021, Hamel et al. 2021), and we refer readers to those documents for details. Briefly, the general input data to the models included the NASA tree cover-modified land cover layers, soil hydrologic group (SSURGO), and a digital elevation map (National Elevation Dataset). These raster layers were all resampled to the same resolution as the elevation map (3m). More specific biophysical parameters included nutrient loading and retention characteristics, and estimates of curve numbers for the various land cover classes (Tables A2-11 and A2-12). For the Flood Mitigation model, we used a “design” storm recommended by the Texas Department of Transportation’s Hydraulic Design Manual[3]: a 24-hour storm with a 100-year return period (11.8 inches per NOAA Atlas-14, area-adjusted to 6.98 inches per TxDOT).

Here we describe the modifications necessary to apply the NDR and Flood Mitigation models to the two unique land use scenarios in San Antonio: (1) food forests and (2) urban farms. First, for the NDR model, the food forest land use class was assumed to be fully mature trees and shrubs using minimal fertilization and composting, such that there was no difference between food forest and the existing “Deciduous Forest” land cover class. For parameterizing the urban farm land use class, we relied primarily on a study by Small et al. (2022) who used the NDR model to assess an expansion of urban gardens in a neighborhood of St. Paul, MN. In that study, the authors used three levels of compost input (low, medium, and high) that were based on usage rates from surveys of private and community gardens in the Minneapolis-St. Paul, MN metro area. They had also previously collected some leaching and runoff data from urban ag plots and observed substantial export of nutrients, yet given the difficulty in converting these data into the retention numbers needed for the NDR model, they instead ran NDR in a sensitivity analysis across a range of retention numbers (2.5% to 95%) for each compost input level. For application to San Antonio, we have used a moderate scenario, with medium compost application (1400 kg N/ha/yr and 300 kg P/ha/yr) and a relatively high retention value (75%). No fertilizer application was included in the estimates of nutrient inputs, yet it is important to note that these compost inputs are an order of magnitude higher than the inputs to any other land cover classes in the NDR model. Compost is incredibly rich in nutrients and is typically over-applied to gardens, far exceeding the uptake capacity of plants and potentially contributing to nutrient export that is generally poorly characterized or understood (Small et a. 2022). For this reason, the NDR results for the urban farm scenario should be considered in context as a worst-case scenario, and one which can be vastly improved with some attention to compost and runoff management practices at the farm scale.

For the Flood Mitigation model, we chose runoff curve numbers for the two urban agriculture practices from existing, similar classes compiled by the NRCS (2004). For urban farms, we used curve numbers for the “garden or truck crops” land use class (with a range of 45 to 83 across soil hydrologic groups, similar to scrub/shrub), and for the food forest we used the “good quality” (i.e., healthy) version of the “orchard or tree farm” class from NRCS (with curve numbers ranging from 32 to 79 across soil hydrologic groups, similar to deciduous forest). No other modifications were made to these classes for the Flood Mitigation model.

Table A2-11. Runoff Curve Numbers (NRCS 2004) used for the InVEST Flood Mitigation model as a function of NLCD Land Cover Class (lulc_desc), Tree Cover level, and Hydrologic Soil Group (HSG; A = highest infiltration capacity … D = lowest infiltration capacity). Note that the two urban agriculture practices specific to San Antonio are at the bottom of the table.

lulc_desc	Tree Cover	lucode	Curve Number per HSG (A, B, C, D)			
			A	B	C	D
Open Water	na	11	100.0	100.0	100.0	100.0
Perennial Ice/Snow	na	12	40.0	40.0	40.0	40.0
Developed, Open Space	None	211	49.0	69.0	79.0	84.0
Developed, Open Space	1-33%	212	46.7	66.3	76.6	81.9
Developed, Open Space	>33%	213	44.5	63.7	74.4	79.9
Developed, Low Intensity	None	221	77.0	86.0	91.0	94.0
Developed, Low Intensity	1-33%	222	69.9	80.4	86.6	90.2
Developed, Low Intensity	>33%	223	63.3	75.1	82.4	86.6
Developed, Medium Intensity	None	231	89.0	92.0	94.0	95.0
Developed, Medium Intensity	1-33%	232	79.9	85.4	89.1	91.0
Developed, Medium Intensity	>33%	233	71.3	79.1	84.4	87.2
Developed High Intensity	None	241	98.0	98.0	98.0	98.0
Developed High Intensity	1-33%	242	87.4	90.4	92.4	93.5
Developed High Intensity	>33%	243	77.4	83.2	87.1	89.3
Barren Land	None	311	77.0	86.0	91.0	94.0
Barren Land	1-33%	312	69.9	80.4	86.6	90.2
Barren Land	>33%	313	63.3	75.1	82.4	86.6
Deciduous Forest	na	41	32.0	48.0	57.0	63.0
Evergreen Forest	na	42	39.0	58.0	73.0	80.0
Mixed Forest	na	43	46.0	60.0	68.0	74.0

Dwarf Scrub	None	511	49.0	68.0	79.0	84.0
Dwarf Scrub	1-33%	512	46.7	65.5	76.6	81.9
Dwarf Scrub	>33%	513	44.5	63.1	74.4	79.9
Shrub/Scrub	None	521	49.0	68.0	79.0	84.0
Shrub/Scrub	1-33%	522	46.7	65.5	76.6	81.9
Shrub/Scrub	>33%	523	44.5	63.1	74.4	79.9
Grassland/Herbaceous	None	711	64.0	71.0	81.0	89.0
Grassland/Herbaceous	1-33%	712	59.2	67.9	78.3	86.0
Grassland/Herbaceous	>33%	713	54.6	65.1	75.7	83.2
Sedge/Herbaceous	None	721	49.0	62.0	74.0	85.0
Sedge/Herbaceous	1-33%	722	46.7	60.5	72.5	82.7
Sedge/Herbaceous	>33%	723	44.5	59.0	71.0	80.5
Lichens	None	731	49.0	62.0	74.0	85.0
Lichens	1-33%	732	46.7	60.5	72.5	82.7
Lichens	>33%	733	44.5	59.0	71.0	80.5
Moss	None	741	49.0	62.0	74.0	85.0
Moss	1-33%	742	46.7	60.5	72.5	82.7
Moss	>33%	743	44.5	59.0	71.0	80.5
Pasture/Hay	None	811	44.0	65.0	76.5	82.0
Pasture/Hay	1-33%	812	42.6	63.0	74.5	80.2
Pasture/Hay	>33%	813	41.2	61.0	72.7	78.5
Cultivated Crops	None	821	68.5	78.5	85.5	88.8
Cultivated Crops	1-33%	822	62.9	74.2	82.0	85.8
Cultivated Crops	>33%	823	57.6	70.1	78.7	83.1
Woody Wetlands	None	901	88.0	89.0	90.0	91.0
Woody Wetlands	1-33%	902	88.0	89.0	90.0	91.0
Woody Wetlands	>33%	903	88.0	89.0	90.0	91.0
Emergent Herbaceous Wetlands	None	951	89.0	90.0	91.0	92.0
Emergent Herbaceous Wetlands	1-33%	952	89.0	90.0	91.0	92.0
Emergent Herbaceous Wetlands	>33%	953	89.0	90.0	91.0	92.0
SA Food Forest	na	998	32.0	58.0	72.0	79.0
SA Urban Farm	na	999	45.0	66.0	77.0	83.0

Table A2-12. Biophysical parameters used by the InVEST NDR Model as a function of NLCD Land Cover Class ("lulc_desc") for three levels of Tree Cover (No Canopy, Medium Canopy (< 33%), and High Canopy (> 33%)). "Load" is the input load of either Nitrogen ("n" suffix) or Phosphorus ("p" suffix) to the given land cover type, "Eff" is the retention efficiency associated with that land cover type (i.e., how much of the load is retained by the landscape during runoff events), and "crit_len" is the flowpath distance over which the retention is realized. Notes are provided for assumptions of land use, management, or input loads specific to the land cover classes. Note that the two urban agriculture classes specific to San Antonio are at the bottom of the table.

lulc_desc	lucode	load_n	load_p	eff_n	eff_p	crit_len_n	crit_len_p	Notes
Open Water	11	14.49	0.63	0.95	0.95	1.0	1.0	unchanged vs original
Perennial Ice/Snow	12	14.49	0.63	0.95	0.95	1.0	1.0	unchanged vs original
Dev, Open, No Canopy	211	41.10	0.80	0.83	0.44	5.0	5.0	100% grass; 100% non-res urban
Dev, Open, Med Canopy	212	41.10	0.80	0.82	0.44	7.0	7.0	composite, trees + grass; 100% non-res urban
Dev, Open, High Canopy	213	41.10	0.80	0.79	0.44	9.0	9.0	composite, trees + grass; 100% non-res urban
Dev, Low Int, No Canopy	221	94.11	1.46	0.93	0.44	10.0	10.0	100% grass; assumed 100% res LU
Dev, Low Int, Med Canopy	222	94.11	1.46	0.93	0.44	12.0	12.0	composite, trees + grass; assumed 100% res LU
Dev, Low Int, High Canopy	223	94.11	1.46	0.93	0.44	14.0	14.0	composite, trees + grass; assumed 100% res LU
Dev, Med Int, No Canopy	231	67.61	1.13	0.88	0.44	15.0	15.0	100% grass; assumed 50% res and 50% non-res urban LU

Dev, Med Int, Med Canopy	232	67.61	1.13	0.87	0.44	17.0	17.0	composite, trees + grass; assumed 50% res and 50% non-res urban LU
Dev, Med Int, High Canopy	233	67.61	1.13	0.86	0.44	19.0	19.0	composite, trees + grass; assumed 50% res and 50% non-res urban LU
Dev, High Int, No Canopy	241	54.35	0.97	0.86	0.44	20.0	20.0	100% grass; assumed 25% res and 75% non-res urban LU
Dev, High Int, Med Canopy	242	54.35	0.97	0.85	0.44	22.0	22.0	composite, trees + grass; assumed 25% res and 75% non-res urban LU
Dev, High Int, High Canopy	243	54.35	0.97	0.82	0.44	24.0	24.0	composite, trees + grass; assumed 25% res and 75% non-res urban LU
Barren, No Canopy	311	14.49	0.63	0.83	0.80	20.0	20.0	100% bare soil
Barren, Med Canopy	312	18.56	0.59	0.85	0.79	23.4	23.4	composite, bare soil + trees (other)
Barren High Canopy	313	30.55	0.46	0.91	0.77	33.4	33.4	composite, bare soil + trees (other)
Deciduous Forest	41	57.89	0.88	0.88	0.55	40.0	40.0	Average of Residential, Non-residential Urban, and Other Tree categories; no distinction between deciduous or coniferous
Evergreen Forest	42	57.89	0.88	0.88	0.55	40.0	40.0	Average of Residential, Non-residential Urban, and Other Tree categories; no distinction between deciduous or coniferous
Mixed Forest	43	57.89	0.88	0.88	0.55	40.0	40.0	Average of Residential, Non-residential Urban, and Other Tree categories; no distinction between deciduous or coniferous
Dwarf Scrub, No Canopy	511	28.64	0.37	0.91	0.72	25.0	25.0	alaska only; given same parameters as shrub/scrub

Dwarf Scrub, Med Canopy	512	30.31	0.37	0.92	0.72	27.6	27.6	alaska only; given same parameters as shrub/scrub
Dwarf Scrub, High Canopy	513	35.22	0.37	0.94	0.75	35.1	35.1	alaska only; given same parameters as shrub/scrub
Shrub/Scrub, No Canopy	521	28.64	0.37	0.91	0.72	25.0	25.0	used 75% grass (other) - 25% trees (other) for SA
Shrub/Scrub, Med Canopy	522	30.31	0.37	0.92	0.72	27.6	27.6	weight grass (other) and trees (other) proportional to tree cover (in addition to original weighting for 'no' tree cover)
Shrub/Scrub, High Canopy	523	35.22	0.37	0.94	0.75	35.1	35.1	weight grass (other) and trees (other) proportional to tree cover (in addition to original weighting for 'no' tree cover)
Grassland, No Canopy	711	25.36	0.37	0.90	0.70	20.0	20.0	100% grass (other)
Grassland, Med Canopy	712	27.59	0.37	0.91	0.71	23.4	23.4	grass (other) + trees (other) proportional to tree canopy
Grassland, High Canopy	713	34.14	0.37	0.93	0.74	33.4	33.4	grass (other) + trees (other) proportional to tree canopy
Sedge/Herbaceous, No Cpy	721	25.36	0.37	0.90	0.70	20.0	20.0	alaska only; given same parameters as grassland/herbaceous
Sedge/Herbaceous, Med Cpy	722	27.59	0.37	0.91	0.71	23.4	23.4	alaska only; given same parameters as grassland/herbaceous
Sedge/Herbaceous, High Cpy	723	34.14	0.37	0.93	0.74	33.4	33.4	alaska only; given same parameters as grassland/herbaceous
Lichens, No Canopy	731	25.36	0.37	0.90	0.70	20.0	20.0	alaska only; given same parameters as grassland/herbaceous

Woody Wetlands, No Cpy	901	14.49	0.63	0.95	0.95	1.0	1.0	unchanged vs open water
Woody Wetlands, Med Cpy	902	14.49	0.63	0.95	0.95	1.0	1.0	unchanged vs open water
Woody Wetlands, High Cpy	903	14.49	0.63	0.95	0.95	1.0	1.0	unchanged vs open water
Emergent Herbaceous Wetlands, No Cpy	951	14.49	0.63	0.95	0.95	1.0	1.0	unchanged vs open water
Emergent Herbaceous Wetlands, Med Cpy	952	14.49	0.63	0.95	0.95	1.0	1.0	unchanged vs open water
Emergent Herbaceous Wetlands, High Cpy	953	14.49	0.63	0.95	0.95	1.0	1.0	unchanged vs open water
SA Food Forest	998	57.89	0.88	0.88	0.55	40.0	40.0	100% Deciduous (NLCD Class 41)
SA Urban Farm	999	1400.0	300.0	0.75	0.75	5.0	5.0	100% Urban Garden (per Small et al. 2022); moderate compost, no fertilizer

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