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# Optimizing the co-benefits of food desert and urban heat mitigation through community garden planning

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## HIGHLIGHTS

- Optimizing community gardens could ensure equal access to food and cooling benefits during urban sprawl.
- Compared to ad-hoc planning, optimization systematically identifies the optimal number and locations of gardens.
- In warm/hot arid climates, more gardens are needed to mitigate urban heat than food-desert.
- Food-desert or heat mitigation alone cannot optimize either's challenge.
- Tradeoffs between the two are critical, especially when a small number of gardens are sited.

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## ABSTRACT

Urban community gardens can reduce food insecurity and serve as green spaces alleviating extreme temperatures. Such co-benefit synergy may prove especially significant for arid-land metropolises. Despite these synergistic roles, planning for community gardens is largely undertaken in an ad-hoc manner. To date, few studies have addressed the full potential (co-benefits) of developing urban vacant land into community garden-green spaces. We addressed this in a spatially-optimized way, developing a model seeking to mitigate food desert and urban heat, and applied it to the fast sprawling Phoenix metro-area, Arizona (USA). Examining more than 5,000 vacant parcels for potential garden-green spaces, we found that the optimal number and locations of community gardens needed for different mitigation goals can vary significantly. In the Phoenix metro-area, the gardens required for extreme heat mitigation is about twice the number for food desert mitigation because high-temperature areas are more prevalent and expansive in semi-arid desert environment compared to the relatively small number low income, food desert areas. Furthermore, we found that the existing 76 community gardens were mostly clustered around urban cores, leaving two-thirds of the metro-area underserved. If sited in a spatially-optimized way, the co-benefits gained from the 76 gardens could be doubled, and covering more high-need neighborhoods. Integrating fine-scale vacant parcel data, our model identified high potential community garden-greening sites in priority neighborhoods with a precision not capable in conventional planning methods. Our findings demonstrate that spatially-optimized planning is of particular importance to avoid clustering of community gardens and ensure more equal access to local food and outdoor cooling benefits.

## 1. Introduction

Sustainability is increasingly one challenge confronting a changing climate and the unintended consequences of the legacies of past urban planning and development decisions (Murray, 2020). These challenges are sufficiently numerous and complex to warrant solution synergies. Improving human well-being through nutrition and extreme heat mitigation constitute two such challenges that are potentially linked. Many urban areas maintain "food deserts" and the urban heat island effects amplified by climate change. Community gardens constitute multi-functional green infrastructure with the potential to address food security and nutrition and ameliorate extreme temperatures—the synergy in

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question—while also providing a host of other social and environmental services (or "co-benefits) (Nicholls et al., 2020; Russo et al., 2017; Smith et al., 2021).

Among the many services provided by community gardening is its potential to supply local fresh and nutritious food. As such, these gardens are frequently developed in food deserts, or low-income neighborhoods in which residents have inadequate access to affordable fresh, nutritious food options. The term food desert was originally developed and has been primarily applied in regard to urban North America and the United Kingdom (Furey et al., 2001; Karpyn et al., 2019). That it is applicable globally, foremost within the developing world, is contested (Battersby & Crush, 2014; Wagner et al., 2019). Where the term is applied, disagreement exists regarding which metrics should be used to identify and delineate food deserts. Multiple factors are linked to food deserts, foremost disparities in access to food as a function of the physical distance to quality food retailers, the potentially prohibitive cost of healthier food options for low-income households, or some combination of both (Bao et al., 2020; Lucan & Chambers, 2013, Rhone et al., 2019). These disputes notwithstanding, various governmental agencies, NGOs, and urban researchers worldwide recognize the existence of urban areas lacking sufficient access to nutritious foods, if variously defined (Walker et al., 2010).

Importantly, community gardens, also hold the potential to mitigate extreme temperatures, given their greening of spaces among the impervious land covers of urban areas. Cities, particularly the sprawling metropolises of the Sun Belt of the United States, experience increasingly elevated daytime and nighttime temperatures due to the urban heat island (UHI) effect (Chow et al., 2012; Hunt et al., 2017). As cities continue to expand and agglomerate, in conjunction with a warming climate, the impacts of the UHI (i.e., extreme above-ground air temperature and land surface temperature) are felt by residents in the form of increased utility expenditures and heat-related morbidity (Ebi et al., 2021; Fraser et al., 2017; Guhathakurta & Gober, 2010; Jay et al., 2021). These impacts can be particularly significant in lower-income neighborhoods where vegetation may sparse compared to wealthier communities (Harlan et al., 2013). The increased green cover gained from community gardens (or any vegetated space) holds the potential to cool an area beyond the infrastructure itself, extending into surrounding neighborhood parcels (Declet-Barreto et al., 2013; Du et al., 2017) through evapotranspiration and reduction of reradiated heat, providing both local and, when incorporated into sustainable urban planning practices, cumulative cooling impacts across a warming urban landscape (Oliveira et al., 2011; Zhang, Murray & Turner, 2017; Ossola et al., 2021).

The integration of community gardens and urban greening into land-use planning is advocated as a means of promoting urban sustainability goals (Albright, 2020; Du & Zhang, 2020; Nicholls et al., 2020). The heretofore community garden focus, however, has been on their social and nutritional co-benefits (Bleasdale, 2015; Guitart et al., 2012; Russo et al., 2017; Saha & Eckelman, 2017; Uludere Aragon et al., 2019) as well as the varied motivations of individual gardeners, politicization of the problem, and "placemaking" (Andreotta et al., 2019; Barron, 2017; Sbicca, 2019; Wesener et al., 2020). Attention grows, however, regarding the environmental services that community gardens can provide as a multifunctional green infrastructure (Clinton et al., 2018; Russo et al., 2017), including the biophysical and social connectivities among garden locations (Egerer et al., 2020). The synergy of mitigating food deserts and extreme heat for urban sustainability with "community gardens" amplifies the role of garden locations and patterns as their spatial allocation impacts the cumulative benefits within the metro-area. Furthermore, siting based primarily on either mitigating goal may inadequately serve the other. As such, the trade-offs and synergies between the two needs to be carefully evaluated in order to achieve balanced solutions. It is interesting, therefore, why minimal attention has been paid to the spatial arrangement of community gardens and how their distribution across the urban landscape can be optimized to best serve high-priority neighborhoods and achieve full heat mitigation potential at-large (Mack et al., 2017; Tong et al., 2020).

Inadequate data of potential site inventory are one obstacle to addressing the co-benefits challenge. Conventional community garden siting has been undertaken on an ad-hoc basis, typically in incremental fashion. In contrast, increased access to high-resolution areal imagery and various remote sensing or geo-design tools allow for systematized assessments of metro-areas, addressing substantial inventories of potential urban community garden sites (e.g., Saha & Eckelman, 2017; Smith et al., 2017). Such assessments have largely been utilized to examine vacant parcel distribution and the potential area of cultivatable land (Clinton et al., 2018; Smith et al., 2017).

While underexplored, spatial optimization as it relates to urban community gardening and to green infrastructure (J. Wang et al., 2020; Y. C. Wang et al., 2018) has also garnered recent attention. In particular, the maximal covering location problem (MCLP) has been used to support community garden site selection (Mack et al., 2017; Tong et al., 2020). Broadly, the MCLP allocates a predefined number of facilities to maximize the total covered demand for some given objective(s) (Church & ReVelle, 1974; Murray et al., 2010). Recognizing the advantages of MCLP approaches, Mack and associates (2017) employed an extensive inventory of vacant parcels to establish a network of potential community gardens within the Phoenix metro-area, seeking to maximize the number of food desert residents covered. Vacant land identified in the county cadastral data with a minimum area threshold of 464.5 $m^2$ (5,000 $ft^2$) and within one mile or less from the population centroid of a given census tract designated as a food desert by the U.S. Department of Agriculture (USDA) was employed as potential garden sites. That study, however, did not consider the geographic setting of prospective locations (e.g., whether or not the parcel was located proximate to a residential area) or incorporate other potential environmental services that the community gardens could provide beyond food production, such as heat mitigation. A similar coverage assessment undertaken by Bao and colleagues (2020) sought to maximize food desert coverage in Tucson, AZ, through the use of hypothetical small, independent food retailers. Lastly, Tong and associates (2020) developed a series of models to maximize overall food production of community gardens in Tucson by selecting the optimal sites (public vacant parcels) as well as different forms of renewable water use (i.e., rainwater harvesting and utilizing reclaimed water). Potential sites were identified through county cadastral data and were aggregated at the block group-level. While the study established an optimized community gardening scheme, synergy with environmental services was not considered.

Given the increasing focus of urban areas worldwide to become more sustainable, our study explores the integration of the dual benefits of community gardens to improve food access and as green infrastructure for urban cooling. Specifically, we address three questions regarding spatially-optimized garden siting compared to conventional ad-hoc planning:

1. How does the total number of community gardens sited affect the overall benefits and spatial pattern of food desert and urban heat mitigation?
2. How do synergies in the co-benefits of community garden siting differ from maximizing benefit for either food desert or urban heat mitigation?
3. What are the differences in the spatial pattern and the co-benefits achieved between the spatially-optimized method and the conventional ad-hoc planning approach?

To address these questions, we developed a new variant of the MCLP model, the Community Garden Coverage Model (CGCM), which optimizes both the social-nutritional and environmental services. The model is used to evaluate the optimal number and distribution of community gardens in the Phoenix metro-area employing an extensive inventory of "vacant parcels for potential gardening" (VPPGs) that serve as candidate locations (Uludere Aragon et al., 2019). Throughout our reference to gardens or to sites connotes the dual benefits in question unless otherwise noted.

## 2. Study area, data, and methods

### 2.1. Phoenix metro-area

The Phoenix metropolitan area is located in the northern Sonora Desert in Maricopa County, AZ, and maintains a population of 4.8 million (U.S. Census Bureau, 2019). Like many other American Sunbelt metropolises, this clustering of cities has experienced substantial growth from the second half of the twentieth century to present, yielding a sprawling expanse covering over 3,200 $km^2$ (Fig. 1). Its “leapfrog” pattern of development has resulted in extensive, low-density suburban and *peri*-urban communities and sparse infill of existing vacant properties within the metro’s urban core (Gober & Burns, 2002). This process, coupled with the adverse economic conditions of the mid to late 2000 s, resulted in large quantities of undeveloped or underutilized vacant land across the metropolis (Smith et al., 2017). Even with the post-2008 Great Recession recovery, many open parcels remain within the urban core and along the urban fringe (Smith et al., 2021; Uludere Aragon et al., 2019). The overwhelming majority of these undeveloped parcels constitutes rather homogenous Sonoran Desert conditions.

In this study, food deserts are delineated at the census tract-level. Identified food deserts are commonly isolated in the metro-area, consisting of highly localized clusters of a few census tracts, many of which exist within the larger urban core. These designated tracts hold approximately 12% of residential population of the metro area (Rhone et al., 2019). Affected households in the associated neighborhoods are disproportionately racial/ethnic minorities and have household incomes well below the study area’s median value of $57,935 (U.S. Census Bureau, 2019). Additionally, the Phoenix metropolis maintains areas with low food retailer access (see 2.2) but with medium incomes that places them beyond the fiscal criterion of the USDA (2017) food desert identity. Some of these areas include several former agricultural tracts on the urban fringe that have converted to low- or moderate-income subdivisions where commercial development (e.g., supermarket construction) may be lagging. These areas have been included in this study.

Unlike the location-specific distribution of food deserts, the UHI effect is pervasive across the Phoenix metro-area (Chow et al., 2012; Hunt et al., 2017). Green spaces variously distributed across the built environment influence above-ground air temperature and land surface temperature (LST) at both micro and macro scales (Heris et al., 2020; Li et al., 2016). While cooling via evapotranspiration and shade of vegetation is primarily associated with above-ground air or mean radiant temperature (Spronken-Smith & Oke, 1998), its documentation across the Phoenix metro-area is insufficient to address the fine-grain level of VPPGs used in this study. In contrast, LST, correlated with immediate above-ground air temperature (Good, 2016), can be calculated for every pixel (and parcel) with various remote sensing data. It is also noteworthy that neighborhoods experiencing food desert conditions tend to have less vegetative cover and bear disproportionate impacts from extreme heat as well as other implications detrimental to human health and overall quality of life (Guhathakurta & Gober, 2010; Harlan et al., 2013). As such, mitigating the UHI is essential within the metro-area, recognized by the various cities and towns of the metro area and Maricopa County itself (e.g., Zhang et al., 2017). Indeed, the City of Phoenix has recently created the Office of Heat Response and Mitigation to address the growing public health and environmental issues posed by urban heat.

As of 2017, the metro-area held 76 active community gardens of

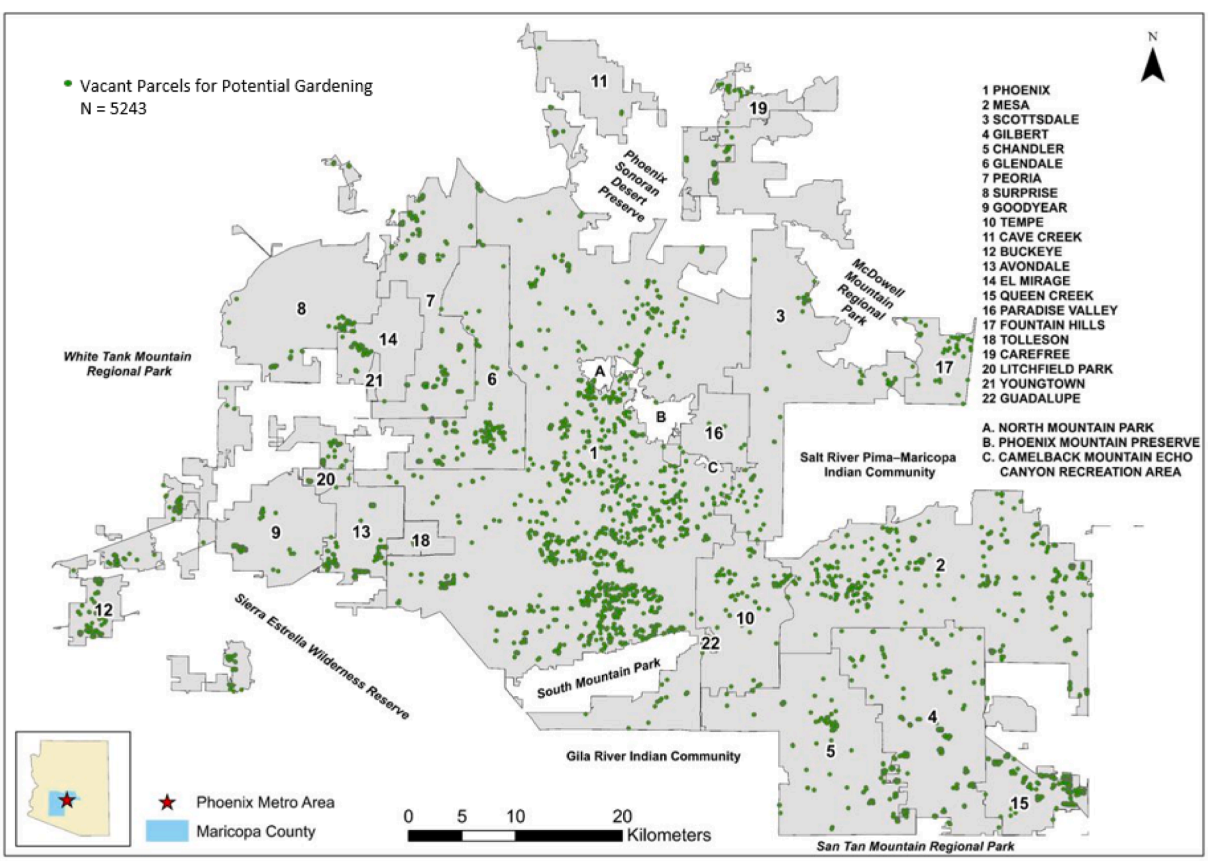


**Fig. 1.** Phoenix Metropolitan Area and Vacant Parcels for Potential Community Gardening.
Adapted from Smith et al. (2017)

varying sizes (Community Gardeners of Maricopa County, 2017; Mack et al., 2017). Prior work (Mack et al.,2017) found that the tracts within the vicinity of a community garden typically had populations with greater racial/ethnic diversity and lower socioeconomic characteristics (e.g., educational attainment and median household income). Of these land uses, ~ 46% are located within the metro's "urban core" (i.e., the portion of the region centralized around the City of Phoenix proper). Underserved areas include not only more affluent suburbs but also multiple middle-to-lower-income communities beyond the urban core, both of which may also hold aspirant community gardeners, and many of experience extreme heat with its implications for water and energy use.

### 2.2. Data

A 2017 shapefile inventory of 38,993 VPPGs (Aragon, Stuhlmacher, Smith, Clinton, & Georgescu, 2019) within the metro-area was employed to identify potential urban community garden sites. VPPGs represent undeveloped or open parcels according to Maricopa County cadastral data and were reevaluated and filtered using 1-m remote sensing data. These parcels largely maintain homogenous land-cover conditions, dominated by either barren, often rock-strewn surfaces, and scattered native vegetation of the Sonoran Desert, such as brittlebush (*Encelia farinosa*) with occasional Palo Verde trees (*Parkinsonia aculeata* or *Parkinsonia florida*). Virtually all parcels have access to water service infrastructure for irrigation. The overwhelming number of vacant parcels are privately owned, some of which have never been developed for unknown reasons and many of which await development. Residential yards, public parks, school grounds, and unused parts of commercial spaces were not included in the inventory because they have assigned uses and an objective of the initial VPPG assessment—and ours—is to convert underutilized, open land in a metro-area. Private property may be considered a constraint on public uses, such as that of community gardens. Many such parcels, however, especially those in the urban core of the City of Phoenix and the larger, older cities of the Phoenix metroplex, have been undeveloped for decades, suggesting opportunities for access as they have in New York City (below) and elsewhere.

The 2017 VPPG inventory was further refined based on siting potential and size. To represent the candidate community gardens social and geographical context, we developed a parcel's siting index ($S_i$*) that integrates its size, accessibility, and the neighborhood context. The index is modified from Smith and associates (2020) that uses multicriteria decision analysis and employs stakeholder-derived weights. Applying the weights established by community gardening stakeholders, our index combines five criteria in order of stakeholder priority: VPPG proximity to residential areas, census tract population density, VPPG proximity to community spaces (i.e., schools, community centers, religious institutions, and parks), area bikeability, and mass transit access. The number of parcels evaluated across the metro-area constrained an accounting of site-specific conditions (e.g., utility access or soil contamination) beyond validation of the sites being "open" that was part of the original VPPG inventory. Despite these limitations, the garden siting index provides site characteristics beyond whether or not a parcel is vacant and allows for further discrimination considering the thousands of potential sites (additional details in Appendix A).

Only those VPPGs scoring moderate to high ($\geq$ 0.5 on a scale of 0 to 1) were used in the study. Additionally, minimum and maximum area thresholds of 697 $m^2$ (7,500 $ft^2$) and 2,090 $m^2$ (22,500 $ft^2$) were used to discriminate for parcels maintaining an area sufficient for community garden facilities (e.g., multiple garden plots, tool sheds, and pathways) but not of a size representing land awaiting major development. Such dimensions are consistent with those applied other studies of urban community gardens (Bowman & Pagano, 2004; Mack et al., 2017). As well, parcel areas above the maximum threshold are commonly held by developers awaiting development or constitute city, county, state, or federal lands serving as parks and educational and training facilities and are not considered vacant or open lands in the cadastral data employed in this study. Given the min–max parameters, the 2017 inventory of parcels generated 5,243 VPPGs (median size of 957 $m^2$) that were ultimately used in the CGCM.

In addition to the parcels' siting score, we also composed the neighborhood priority score (Cj) Cj = food and Cj-heat to indicate each tract's priority in food desert and the urban heat reduction (Fig. 2). Regarding the Cj-food computation, the conceptualization of what constitutes and how to best represent a food desert spatially varies (Lucan & Chambers, 2013; Walker et al., 2010). Our study adopts the USDA metric that is frequently used by municipal governments in the United States; a census tract is considered to be a food desert if it is both low-income and has low-access to food retailors (i.e., $\geq$ 33% of the population must travel >1 mile [1.6 km] from a major food retailer) (USDA, 2017). Under this definition, 95 of the metro's 904 census tracts are classified as food deserts (Fig. 2a). The region contains other pockets of residents which have low-access and low-income, however, although their tracts are above the 33% threshold. To capture these households, our study uses the percentage of a tract's population experiencing food desert conditions (Cj-food) altering the formal USDA designation (USDA, 2017; Smith et al., 2021).

For the urban heat mitigation priority ($C_{j\_heat}$) (Fig. 2b), mean temperatures for each tract $j$ were computed by spatially aggregating the summer daytime LST using zonal statistics tool based on the 30-m Landsat Provisional Surface Temperature imagery dated August 16, 2017 (USGS, 2019). The data were derived from the Landsat Level-1 thermal infrared bands, ASTER Global Emissivity Database (GED) and NDVI data using a single channel algorithm (Cook 2014). Under no cloud conditions, the average error in the surface temperature was $-0.26^{\circ}$C based on North America measurements (Laraby & Schott 2018). Higher temperature tracts represent higher priority locations for community garden development. Both food desert and LST values were normalized across the study area using a linear scale transformation wherein larger values correspond to higher priority tracts. In addition to tract priority regarding the co-benefits, the assessment also incorporated the potential population covered by community gardens. A normalized population multiplier ($P_j$) was calculated and applied to tract priority values (see Eqs. (10) & (11)). With this consideration, the resultant priority values account for where community gardens could potentially have a greater impact. All the analysis were implemented using ArcGIS.

### 2.3. The community garden coverage model

Existing models developed to site community gardens have primarily focused on addressing food deserts (Mack et al. 2017; Tong et al. 2020). In contrast, our variant of the MCLP, the CGCM seeks to mitigate food deserts and urban heat simultaneously. We introduce new assignment variables $Z_{ij}$ to associate a garden to a particular neighborhood because the amount of benefit provided by community gardens to different tracts may vary due to neighborhood characteristics. Meanwhile $Z_{ij}$ permits a practical site consideration that prioritizes locations better-suited for sustaining the co-benefits among the multiple nearby parcels available. With this enhanced analytical ability, the model is able to represent spatial heterogeneity in the food desert and urban heat patterns and assign the highest quality sites to the most needed tracts.

The CGCM notation follows:

$i$ = index of VPPGs.
$j$ = index of census tracts to be covered.
$B_{ij\_food}$ = the benefit value of food desert reduction that census tract $j$ receives from VPPG $i$ if $i$ is developed into a community garden.
$B_{ij\_heat}$ = the benefit value of urban heat reduction that census tract $j$ receives from VPPG $i$ if $i$ is developed into a community garden.

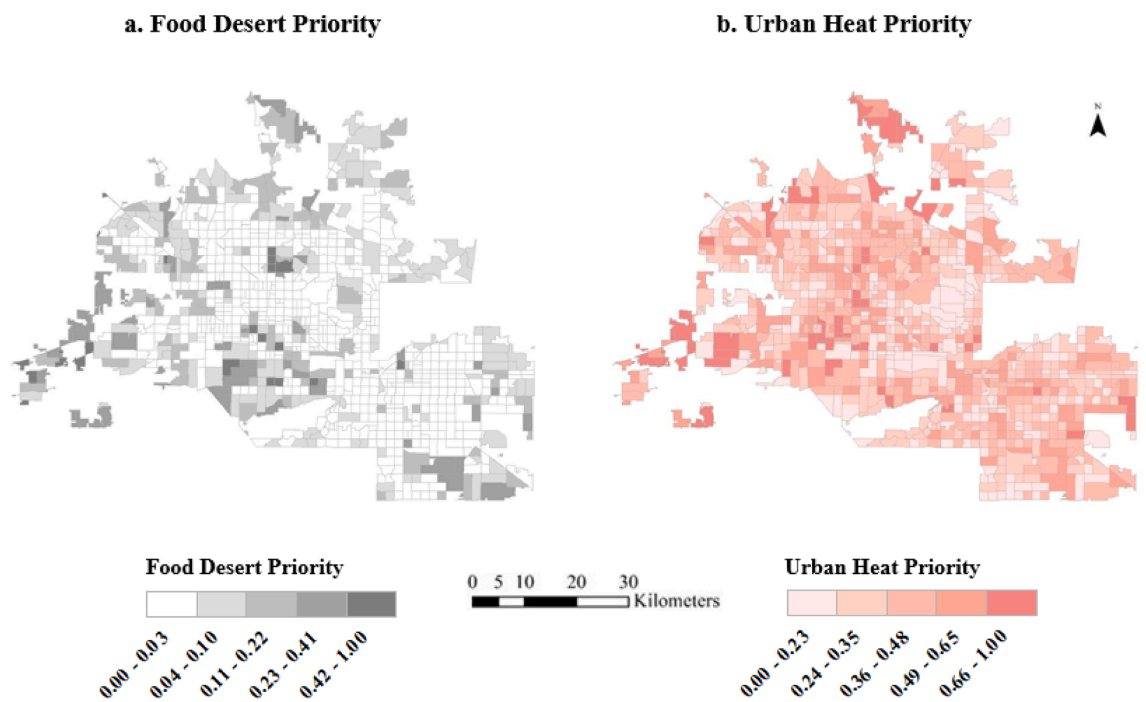


**Fig. 2.** Census Tract Priority of Potential Community Garden Development. Priority values represent the percentage of tract residents experiencing food desert conditions (a) and the average urban heat condition for the tract (b). Values have been normalized and adjusted for population (see Section 2.2). Darker colors represent higher priority tracts for community garden development.

$\Omega_{food}$ = the summation of all food desert reduction benefit values received by the covered census tracts.

$\Omega_{heat}$ = the summation of all urban heat reduction benefit values received by the covered census tracts.

$d_{ij}$ = the distance between the centroids of VPPG $i$ and tract $j$.

$D$ = the distance threshold of the urban community garden coverage.

$$y_{ij} = \begin{cases} 1 \text{ if the distance, } d_{ij}, \text{ between VPPG } i \text{ and census tract j is less than D} \\ 0 \text{ if not} \end{cases}$$

$p$ = number of community gardens to be developed.

$$X_i = \begin{cases} 1 \text{ if VPPG } i \text{ is developed into a garden} \\ 0 \text{ otherwise} \end{cases}$$

$$Z_{ij} = \begin{cases} 1 \text{ if census tract } j \text{ is covered by VPPG } i \\ 0 \text{ otherwise} \end{cases}$$

The model is specified as:

$$Maximize\ \Omega_{food} = \sum_{ij} B_{ij\_food} Z_{ij} \tag{1}$$

$$Maximize\ \Omega_{heat} = \sum_{ij} B_{ij\_heat} Z_{ij} \tag{2}$$

Subject to:

$$Z_{ij} \leq y_{ij} X_i \qquad \forall i,j \tag{3}$$

$$\sum_i Z_{ij} \leq 1 \qquad \forall i,j \tag{4}$$

$$\sum_i X_i = p \qquad \forall i \tag{5}$$

$$X_i \in \{0,1\} \qquad \forall j \tag{6}$$

$$Z_{ij} \in \{0,1\} \qquad \forall i,j \tag{7}$$

The model aims to maximize the sum of community garden benefits (food desert and heat mitigation, respectively) received by census tracts (model objectives in eq.1 and 2). To incorporate the *Zij*'s in the CGCM, we introduce constraints (3) and (4) to ensure appropriate garden-tract assignments. Constraints (3) define census tract $j$ will not be covered by VPPG $i$, unless $i$ is developed into a community garden and the distance between $i$ and $j$ is less than or equal to the service distance of a community garden, $D$. Constraints (4) specify census tract $j$ will be assigned to no more than one garden. Constraint (5) specifies the number of community gardens to be developed. Constraints (6) and (7) impose binary restrictions on the decision variables $X_i$ and $Z_{ij}$.

The benefit variables $B_{ij}$ are the key feature that integrate the community garden's area-adjusted siting score $S_i^*$ with the tract's population-weighted priority value $C_j^*$. In this way, $B_{ij\_food}$ and $B_{ij\_heat}$ specifically track which garden serves which tract and cumulate the corresponding benefit value in the model objective. This model design ensures that the highest quality sites will serve the most needed tracts. For example, the hottest tracts with dense population will be assigned to the largest and nearest candidate parcel within the distance threshold to maximize the overall benefit. The detailed equations for the $B_{ij}$ calculation are:

$$B_{ij\_food} = C^*_{j\_food} \times S^*_i \tag{8}$$

$$B_{ij\_heat} = C^*_{j\_heat} \times S^*_i \tag{9}$$

Where:

$C_j^*$ is the adjusted priority score of census tract $j$ (Eqs. (8) & (9)) and is calculated based on either the normalized food desert or urban heat priority of tract $j$ ($C_j$), respectively, multiplied by the normalized population of tract $j$ ($P_j$):

$$C^*_{j\_food} = C_{j\_food} \times P_j \tag{10}$$

$$C^*_{j\_heat} = C_{j\_heat} \times P_j \tag{11}$$

And:

$S^*_i$ is the adjusted siting score of VPPG $i$ that incorporates both parcel's siting score ($S_i$) and an area adjustment score ($A_i$) (Eq.12). This incentivizes the CGCM to not only select VPPGs with higher siting potential scores but also provides a slight bonus to larger parcels when multiple sites with similar siting values are in close proximity:

$$S^*_i = S_i \times A_i \tag{12}$$

The original VPPG siting scores ($S_i$) were converted from [0.5, 1] to [0.8, 1.2] with the median siting score (0.69) was rescaled to 1. In this way, higher-scoring VPPGs are slightly rewarded and more moderately scoring parcels are slightly penalized in the CGCM. The area multiplier ($A_i$) was created by reclassifying VPPG area into three values, centered at 1 (Eq. (13)). In the equation, 1,407 m$^2$ and 887 m$^2$ are the top and bottom 20$^{\text{th}}$ area percentiles, respectively, in the inventory:

$$A_i: \text{ Area adjustment score of VPPG } i; \quad A_i = \begin{cases} 0.8, & \text{if } i < 887 \text{ m}^2 \\ 1, & \text{if } 887 \text{ m}^2 \le i \le 1,407 \text{ m}^2 \\ 1.2, & \text{if } i > 1,407 \text{ m}^2 \end{cases} \tag{13}$$

### 2.4. Model implementation

The CGCM was developed and solved using the ArcGIS and Gurobi Python API. We chose $D = 1.5$ miles (2.4 km) as the community garden's service distance threshold, a distance suitable for 96% of the tracts in the study area. While it is slightly larger than the USDA food desert standard of one mile (which only achieved 87% tract coverage), considering the car-oriented design of Sun Belt metro-areas like Phoenix, a somewhat relaxed $D$ is a reasonable threshold.

The selection of $p$ (i.e., the number of sites to be developed) in the CGCM is key due to the reality of limits on resources for urban community garden planning. To address the first research question-determining the number of the gardens to be sited-we solved the model iteratively with a range of different $p$ values for both food deserts and urban heat to observe how the cumulative benefit changes with additional community gardens, eventually reached the largest $p$ necessary to achieve the maximum possible objective benefit (Max Ω) (i.e., every census tract within the study area that could feasibly be covered by a given VPPG is covered).

To address the second research question—distinctions in placements by maximizing benefits for food desert or/and urban heat mitigation—we solved the bi-objective CGCM using the weighted sum method (Eq. (14)) and further assessed the trade-offs between the two objectives $\Omega_{food}$ and $\Omega_{heat}$:

$$Maximize \ w\Omega_{food} + (1 - w)\Omega_{heat} \tag{14}$$

$$w \in [0, 1]$$

The CGCM was solved for different values of $w$ in increments of 0.01 to evaluate the trade-offs between food desert and LST benefit at $p = 50$, 76, 100, and 125. For the last research question—differences in the spatial distribution and the co-benefits between the spatially-optimized method and conventional site selection methods—we estimated the benefit value of the study area's current community garden network ($p = 76$), largely an ad-hoc effort, and compared that with the spatially-optimized scenarios. Recognizing that the existing 76 community gardens in the metro-area are likely to remain operative, we also implemented the model to create the optimal distribution of additional sites relative to the layout of the existing community gardens.

## 3. Results

Fig. 3 summarizes the trade-offs between the number of community gardens to be sited ($p$) and the overall optimal benefit achieved in food desert and heat mitigation ($\Omega_{food}$ and $\Omega_{heat}$). Max Ω (Y-axis) indicates the maximum possible benefit value that can be reached. When all the census tracts in the study area are covered, Max Ω is achieved; increasing $p$ will not yield any additional benefit. Once establishing the Max Ω, we standardized all the optimal Ω values to the relative percentage of the Max Ω and plotted them against the corresponding $p$ values.

As shown by Fig. 3, for both objectives, $\Omega_{food}$ and $\Omega_{heat}$, values grew as $p$ increased. The marginal benefit gains diminished gradually, however, with the addition of each new garden. For example, siting 50 gardens achieved about 77% of the food desert mitigation potential, whereas doubling the number of sites to 100 only gained 18% more benefit. For $\Omega_{heat}$ (Eq. (2)), due to the wide-spread nature of the UHI effect across the study area compared to the clustered food deserts, more spaces were required to achieve a comparable percentage of Max Ω. As a result, 50 gardens reached 58% of the maximum heat mitigation potential and 24% more benefit was achieved with an increase to 100 gardens (Fig. 3b). The trend curves provide important insights in determining the suitable range of community gardens to be sited when allocating limited land resources.

For illustrative purposes, we mapped the optimized garden locations for $p$ equals to 50 and 100 for both objectives to explore the spatial pattern differences between two reasonably-sized community garden networks. Compared, the optimal locations of the two objectives varied at both the urban core and fringe (Fig. 4). For solutions with lower values of $p$ (e.g., $p = 50$), tracts with the highest priority values were covered first. The food desert site locations appeared to be scattered both within the urban core and in communities nearer to the urban fringe (Fig. 4a). In contrast, the urban heat optimized site locations concentrated more within the urban core and other "inner" suburban communities, with very few sites sited towards the fringe (Fig. 4b). For higher values of $p$ ($p = 100$), the distributions of both objectives generally expand outwards, covering more medium to low level priority areas. The food desert locations continued to maintain a greater presence on the fringe (Fig. 4c), however, compared to the more "evenly" distributed heat mitigation locations (Fig. 4d).

We then solved the bi-objective CGCM under different priority weighting scenarios (Eq. (14)) and assessed the co-benefits that could be reached food deserts and heat mitigation for $p = 50$, 76, 100, and 125 (Fig. 5). Those $p$ values were selected based on the $p$-optimized benefit value curves shown in Fig. 3. When $p$ ranges from 50 to 125, approximately 60% to 90% of the Max Ω can be reached for both the food desert and heat objectives. $w = 1$ is the equivalent of solving for the food desert objective alone, and $w = 0$ is the equivalent of solving only for heat. Under all weighting schemes for $w$, benefits accrued for both objectives to varying degrees. The values of $w$ that produced the highest co-benefits (i.e. the most balanced benefit, purple marker in Fig. 5) for both objectives ranged from 0.63 to 0.67. For example, at $p = 50$, $w = 0.67$ achieved 57% Max $\Omega_{food}$ and Max $\Omega_{heat}$. For $p = 125$, $w = 0.66$ yielded

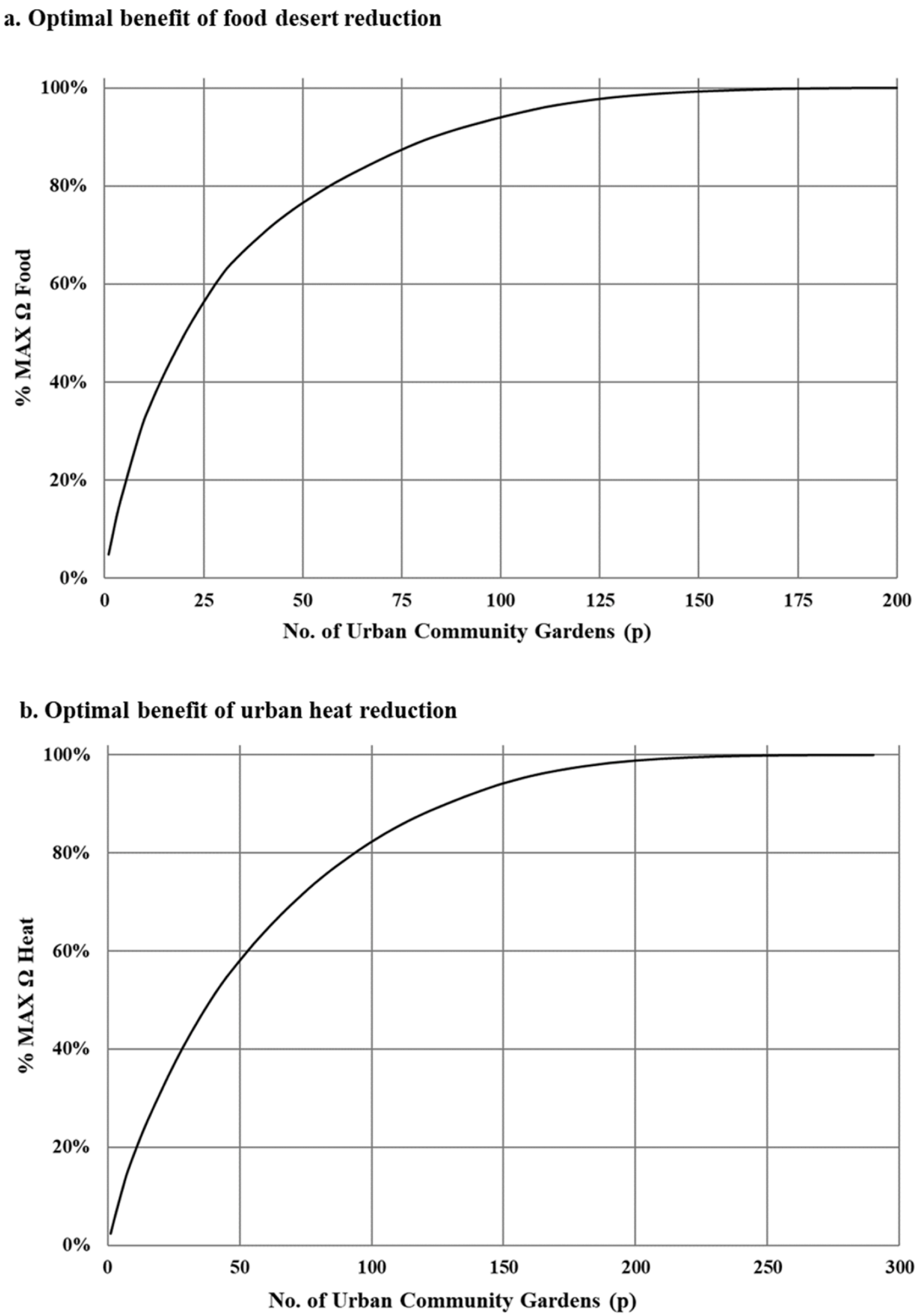


**Fig. 3.** Trade-off Curves between the Total Number of Community Gardens (p) and Their Corresponding Optimal Benefit Values: (a) Food Desert and (b) Urban Heat Reduction Objectives.

89% of Max $\Omega_{food}$ and Max $\Omega_{heat}$, respectively. These results suggest that when both co-benefits are equally desired, weighing food deserts slightly more than LST actually produces a more balanced outcome.

Lastly, we computed and plotted the maximum potential benefits of the 76 current community gardens in the Phoenix metro-area. We assumed that each garden has a service distance of 1.5 miles (2.4 km), held the highest possible adjusted siting score (i.e., $S_i^* = 1.44$), and followed Equations (1) and (2), accordingly. We found that even under these ideal conditions, the current community garden network only provided 37% Max $\Omega_{food}$ and 43% Max $\Omega_{heat}$ for the study area (blue marker in Fig. 5). As shown in Fig. 5, the current community garden network's benefit values are substantially less than the optimal solutions (i.e., the $p = 76$ curve) produced by the CGCM. By comparison, when the two objectives are solved separately at $p = 76$, the CGCM yielded 88%

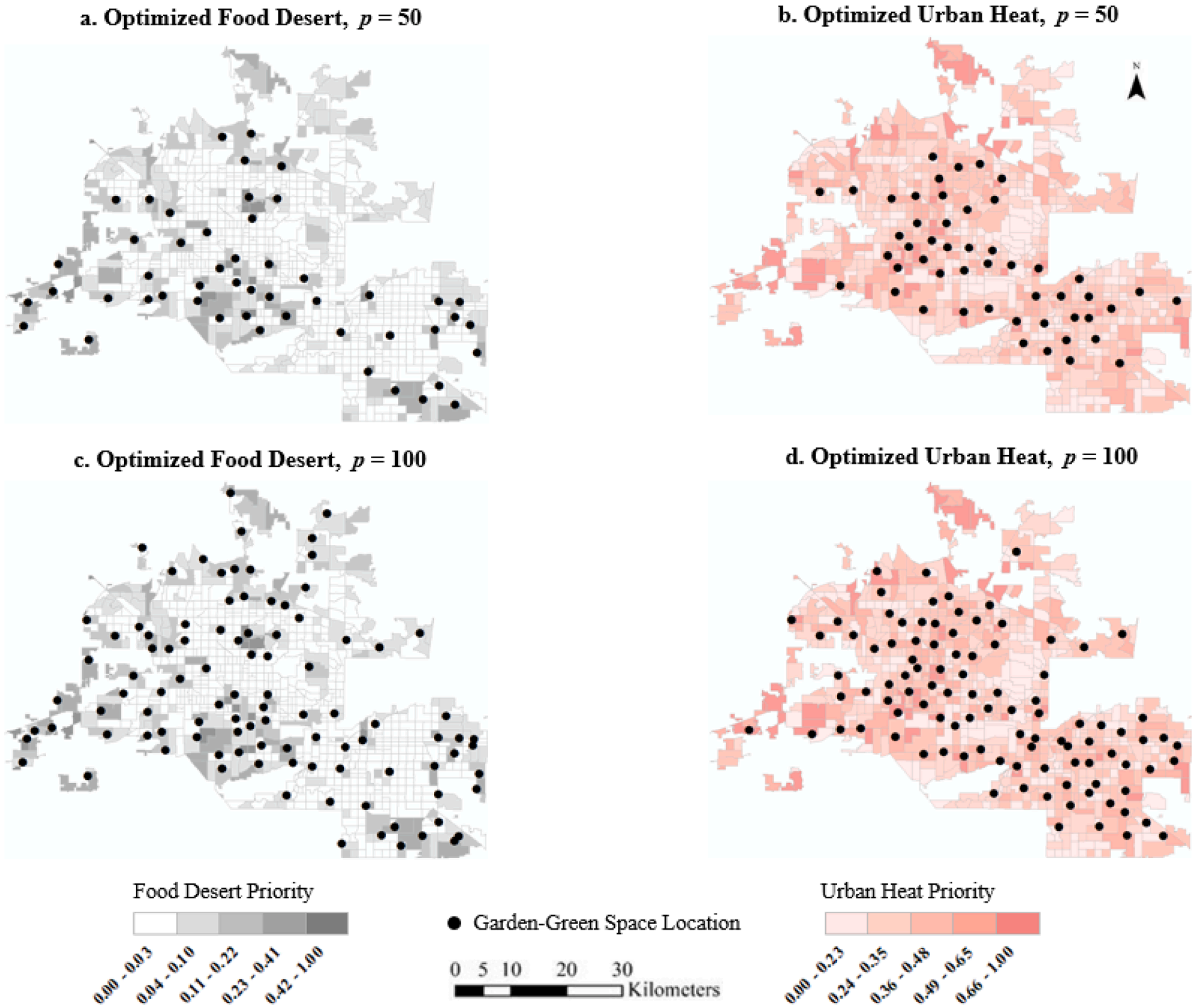


**Fig. 4.** Optimized Community Gardens Locations for Food Desert and Urban Heat Mitigations. The total number of community gardens p = 50 and 100. The grey backgrounds of (a) and (c) show the population weighted food desert priority; the red backgrounds of (b) and (d) show the population weighted urban heat priority. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Max $\Omega_{food}$ (green maker in Fig. 5) and 73% Max $\Omega_{heat}$ (red maker in Fig. 5). Also, the balanced solution of the benefits trade-off scenario for the bi-objective CGCM ($p = 76$ and $w = 0.63$) achieved higher co-benefit results with 71% for Max $\Omega_{food}$ and Max $\Omega_{heat}$, respectively (purple maker in Fig. 5). We further mapped the current and optimized community garden locations in Fig. 6. To better compare the location-induced garden performance differences, we made the backgrounds to represent the overlapping priorities of food desert and urban heat mitigation. Compared with the existing and single benefit scenarios (Fig. 6a-c), the co-benefit scenario (Fig. 6d) covers the largest number of darker color tracts, which have the highest priority for both mitigation goals.

The existing 76 community gardens are clustered in central Phoenix and only reach 37% of Max $\Omega_{food}$and 43% of Max $\Omega_{heat}$. Accounting for the distribution of existing gardens, how might additional sites improve the spatially unequal distribution? To address this query, we resolved the model to estimate 1) the number of additional gardens needed to reach above 80% of Max $\Omega_{food}$and Max $\Omega_{heat}$, and 2) the corresponding trade-off weight. The results indicate that 60 additional gardens were needed and the trade-off weight is 0.6. In sum, existing plus the additional community gardens could yield 80% Max $\Omega_{food}$ and 83% Max $\Omega_{heat}$. The optimal locations of the additional 60 gardens are mapped in Fig. 7.

## 4. Discussion

The food desert and UHI challenges confronting urban areas are commonly siloed from one another in research and applications, including those involved in community garden issues addressed in this study. The co-benefits derived from the use of the same urban space can help to unlock the silo. Optimization modeling facilitates assessment of co-benefit synergies, in our case to mitigate food desert and extreme heat through systematic planning of community gardens. Our model demonstrates how metropolitan-level garden networks can be tailored specifically to optimize the use of gardens' dual function. Examining more than 5,000 vacant parcels in the Phoenix metro-area, the results of the optimal garden numbers and locations were demonstrated. While the outcomes will surely differ by urban context, the findings provide insight into how two benefits may ultimately be complementary if weighted accordingly. Furthermore, our study illustrates that, when subject to the same constraints and criteria as the CGCM, the Phoenix metro-area's current urban community garden network leaves much of the study area's high-priority neighborhoods underserved compared against our optimized scenarios. We discuss these results through the three initial questions guiding our study.

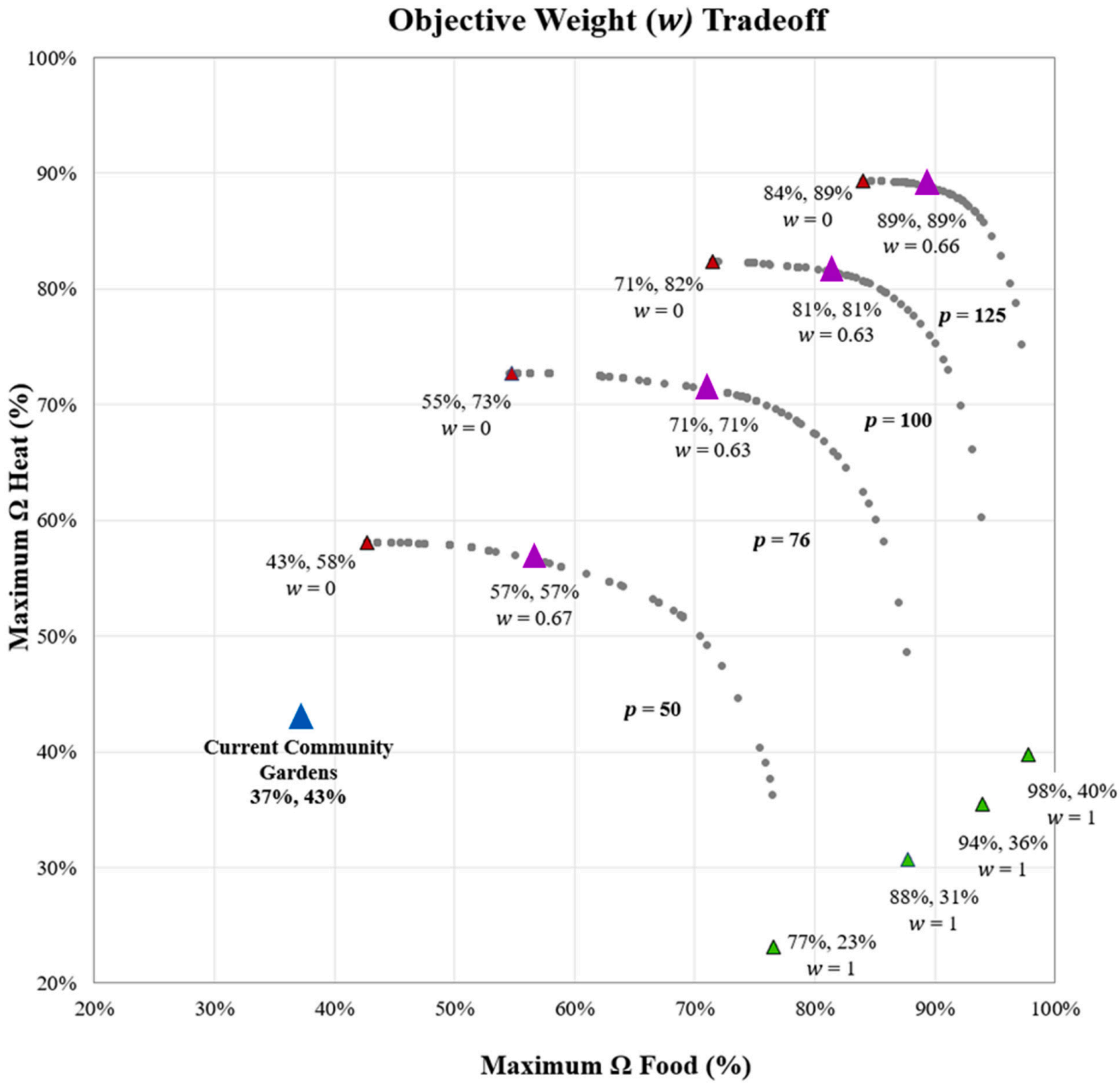


**Fig. 5.** Trade-off Curves with the Number of Community Gardens p = 50, 76, 100, and 125 (weight,w ranging from 0 to 1). Note that coordinates for each marker are ordered as (% Max $\Omega_{food}$, % Max $\Omega_{heat}$). Color of the markers represent: blue–current community garden settings; red–optimal food deserts settings; green–optimal urban heat settings; purple—optimal co-benefits balanced setting between the two mitigation goals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

*4.1. How does the total number of community gardens sited affect the overall benefits and spatial coverage of food desert and urban heat mitigation?*

The optimal number of community gardens needed to meet different mitigation goals can vary significantly. Assuming 1.5-mile (2.4 km) service distance, approximately 150 and 250 gardens are needed to achieve the full potential of food desert and urban heat mitigation in the Phoenix metro-area, respectively (Fig. 3). As demonstrated by the trade-off curves in Fig. 3, however, an increase in the garden number generates less marginal benefit per garden added, resulting in an increasingly flat curve. Therefore, when sited optimally, substantial benefits can be reached with a relatively low number of gardens. For example, 50 and 100 sites can achieve 80% of the food desert and urban heat mitigation potential, respectively.

We also conclude, that more gardens are needed to mitigate urban heat than reduce food desert in the Phoenix metro-area, which may be the case for other desert cities experiencing extreme heat. Considering increasing risks in heat-related health issues (Ebi et al., 2021; Jay et al., 2021), cities like those in the Phoenix metro-area are, in fact, seeking to heat mitigation, in some cases more so than food security, and are open to co-benefits. This observation follows from the abundance and spatial heterogeneity differences of the two phenomena (Fig. 2). While food deserts pose a major challenge for the Phoenix metro-area, the actual number of tracts in the study area with food priority score , $C^*_{j\_food}$ greater than zero is 431 (out of 897), and in only 161 of those tracts does $C^*_{j\_food}$ exceed 0.1. Therefore, relatively few community gardens are necessary to achieve decent coverage (Fig. 3a), whereas, the CGCM solution focuses on the scattered high-priority food desert hot spots. This result translates into spatially-optimized food desert locations appearing somewhat strewed across the metro-area, especially when $p$ is low (Fig. 4a). The overall pattern remains dispersed when additional sites are added (Fig. 4c).

Conversely, the ubiquity of the UHI effect produces an elevated LST gradient that spans numerous tracts throughout the study area (espe-

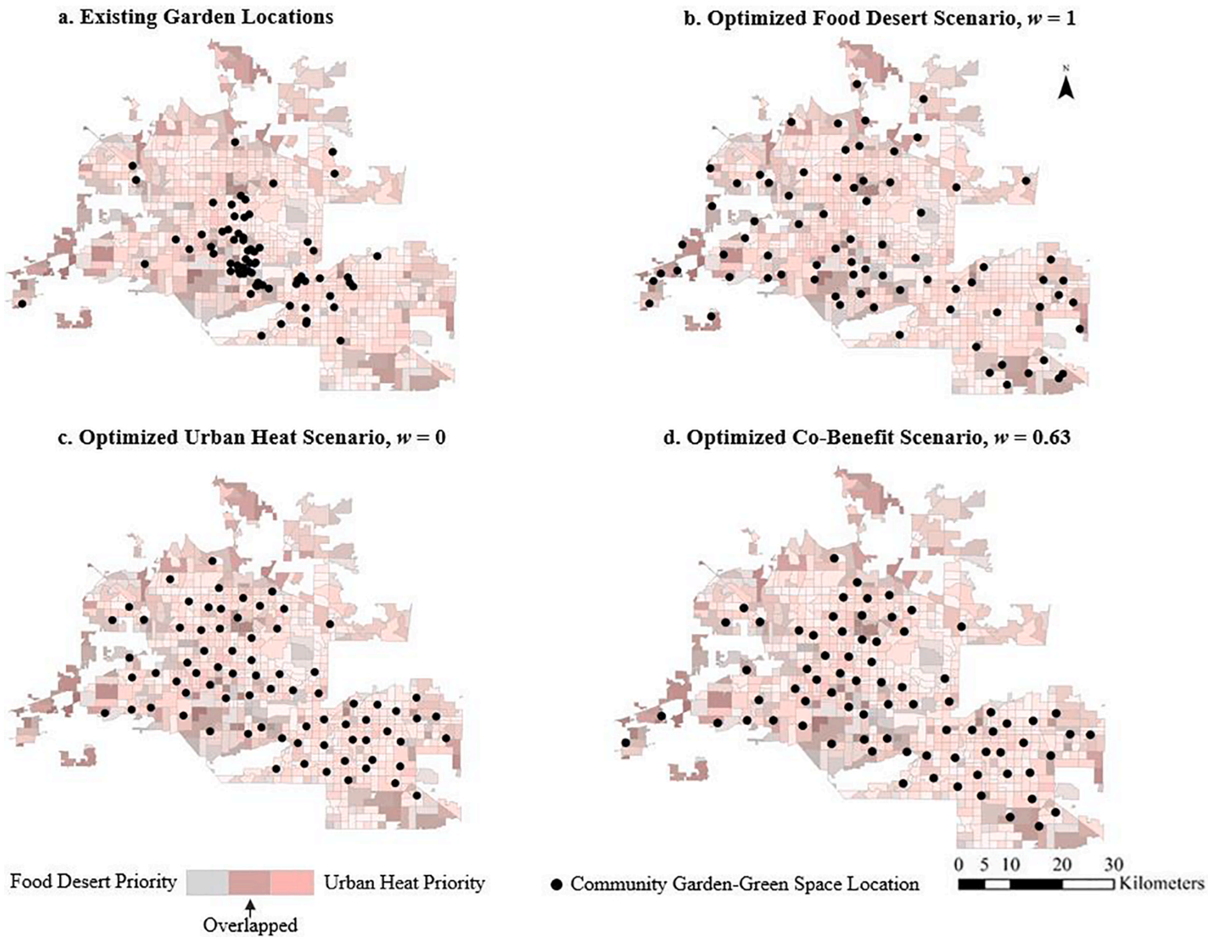


**Fig. 6.** Comparisons between the Existing Community Garden Locations and Three Optimized Scenarios. Total number of gardens p = 76 for all four maps. The grey-red mixed color scheme backgrounds show the overlapped food desert and urban heat priorities. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cially in the densely-developed areas in the southeastern part) (Fig. 2b). As a result, in heat-optimized solutions, more community garden-green spaces are necessary to attain similar percentages of Max $\Omega_{heat}$ (Fig. 3b). The distribution of these spaces generally appears more uniform than the optimized food desert results. Potential community garden locations tend to be concentrated in densely developed urban and suburban communities within the study area's interior where the UHI effect is most prolific. This is particularly evident with a small number of gardens (Fig. 4b). As $p$ increased from 50 to 100, the network eventually radiates outwards into communities located on the urban fringe (Fig. 4d). These tracts may also have elevated LSTs but hold smaller populations, reducing the priority of heat mitigation, compared to those hot and dense population tracts. It warrants noting that the number of sites estimated is based on the assumption that a community garden's service distance is 1.5-mile (2.4 km). Shortening the distance (e.g., 0.5 or 0.25 mile) will increase the total number of gardens needed. Nevertheless, the general trend of marginal benefits declining identified by the trade-off curve holds. More importantly, the method can be used to determine suitable ranges of gardens to be sited when planning for multiple mitigation goals.

### *4.2. How do synergies in the co-benefits of community garden siting differ from maximizing benefit for either food desert or urban heat mitigation?*

We observed that the synergies between the social and environmental services is constrained by the total number of community gardens sited. As demonstrated by the purple markers in Fig. 5, more gardens lead to a higher synergy potential, but a limit to the co-benefit's growth exists. For example, when sites increased from 50 to 100, the co-benefit achieved rose from 57% to 81%, whereas continuously adding sites from 100 to 125, the co-benefit only increased from 81% to 89%.

Spatial heterogeneity of the two services also strongly affects their synergies. Locations optimized for heat mitigation are distributed across the study area in a fairly even pattern that cover many high-priority food desert tracts (Figs. 4 & 6). Consequently, as shown in Fig. 5, when $w$ is weighted fully on heat, the solution yields high heat mitigation benefit and moderate food desert benefit. In contrast, if $w$ is weighted fully on food deserts, the solution produces high-food desert benefit but very low-heat mitigation benefit. To achieve a balanced trade-off or improved synergy, food desert was weighted slightly more than urban heat, resulting in a $w$ value of approximately 0.6. For example, for $p = 76$, when $w$ changes from 0 to 0.63, the food desert benefit increases significantly from 55% to 71% Max $\Omega_{food}$, compared to the relatively minor drop in the heat mitigation benefit (from 73% to 71% Max $\Omega_{heat}$).

This relationship is also visible in Fig. 6. The co-benefit scenario (Fig. 6d) looks more similar to the heat scenario (Fig. 6c) versus the food scenario (Fig. 6b). The overall co-benefit garden distribution maintains its uniform pattern covering the highest-priority tracts for heat mitigation, but the few outlying high-priority food desert tracts are served as well, which were missed in the heat scenario (Fig. 6c). The ability of the CGCM to redistribute potential garden locations to achieve some desired outcome demonstrates the flexibility of the model. In our case, we solved $w$ iteratively to achieve the balanced co-benefits, but the weighting scheme is inherently flexible to meet the needs of the user. By affording

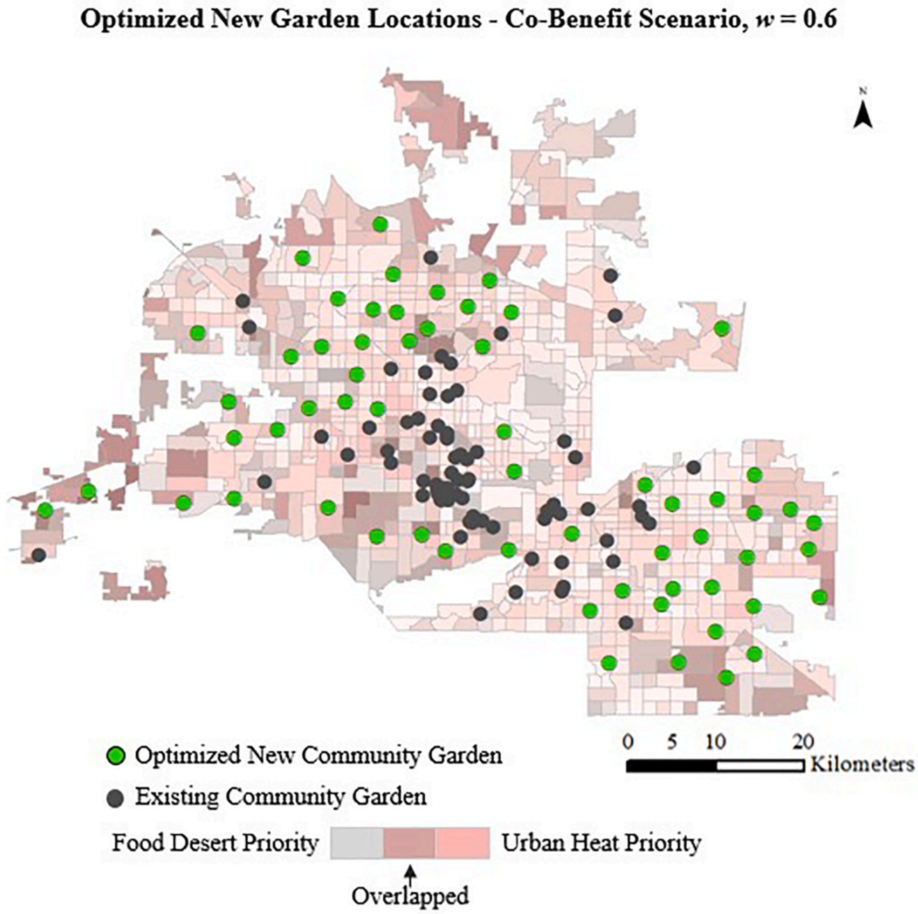


**Fig. 7.** Optimal Locations of 60 New Community Gardens (reaching an overall benefit above 80% of Max $\Omega_{food}$ and Max $\Omega_{heat}$, weight, w = 0.6). The grey-red mixed color scheme backgrounds show the overlapped food desert and urban heat priorities. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

decision-makers the capability to consider trade-offs between the two objectives, the CGCM provides yet another layer of nuance not present in the conventional, ad-hoc community garden siting process.

### *4.3. What are the differences in the spatial pattern and the co-benefits achieved between the spatially-optimized method and the conventional ad-hoc planning?*

Unlike the spatially-optimized scenarios, which are more evenly distributed across the metro-area (Fig. 6b-d), existing community gardens cluster around urban cores, leaving the majority of the study area, primarily suburban and urban fringe communities, underserved (Fig. 6a). As a result, the current 76 gardens only cover 55% of the USDA-defined food desert tracts, a result consistent with another community garden-only assessment which identified inadequate coverage in the majority of Phoenix-area neighborhoods experiencing food desert conditions (Mack et al. 2017). Besides spatial coverage, we further estimated the co-benefit differences provided by the existing and the optimal garden scenarios. In the result shown by Fig. 5, existing ad hoc-planned community gardens achieved only 37% of food desert reduction benefit and 43% of the heat reduction benefit in the most ideal conditions. In contrast, the spatial optimized 76 gardens reached 71% of both benefits simultaneously (w = 0.63), a result two times higher than the existing siting.

The issue of urban sprawl is not unique to Phoenix but is a characteristic increasing in cities across the globe (d'Amour et al., 2017; Liu & Meng, 2020; Stuhlmacher et al., 2022) which in many cases exacerbates UHI and food desert conditions. In sprawling cities in particular, clustering of community gardens due to ad-hoc planning may result in more severe coverage gaps, leading to poor and unequal mitigation of urban heat and food deserts. While it is infeasible to rebuild the current community garden network in the Phoenix metro area, optimizing new gardens in future planning could potentially improve the unequal spatial distribution of existing gardens. Fig. 7 shows the optimal locations of the 60 new community gardens to achieve above 80% of the maximum co-benefits. Most of new sites were located in the cities other than Phoenix, such as Mesa, Gilbert, Chandler, Glendale, and Goodyear, improving their access to local food and outdoor cooling features. On the northern edge of the metro-area, Cave Creek is both high in food desert and heat priorities, but did not receive new garden assignments, in part because of the few vacant parcels identified there.

Additional five new community gardens were assigned to the South Phoenix area (nearby South Mountain Park), which is highly consistent with the previous optimization results. South Phoenix is dominated by lower-income, Hispanic neighborhoods, which are disproportionately exposed to food deserts and temperature extremes but have the least access to mitigating features, exacerbating heat related and other health problems (Harlan et al., 2007). As identified by the optimization model, community garden planning in these neighborhoods can achieve more significant cooling and health benefits. Our assessment suggests that the evident disparity between the populations covered and the underserved areas could potentially be abated in the future through a systematic siting-approach as illustrated in Fig. 7. This possibility may prove especially advantageous as major cities explore the role of community-driven agriculture as part of a more resilient urban food system (Albright, 2020; Nicholls et al., 2020).

In sum, this study highlights at least three important insights about sprawling cities in warm-to-hot desert environments in which food security issues are at play. (1) More community gardens may be needed to mitigate extreme heat than to increase food security owing to the spatial expansiveness of the heat problem relative to low-income, food desert areas. (2) Increasing food desert and heat mitigation alone cannot optimize either challenge. If weighted properly, the two services could complement each other. Trade-offs between the mitigation of the two problems is invariably required, especially when only a small number of gardens is sited. (3) Spatially-optimized site planning is of special interest to avoid clustering of the garden-food role relative to the spatially expansive heat mitigation one.

### *4.4. Implications for urban planning*

With the growing impact of citizen science, GIS and open-source tools are increasingly used by park and recreational agencies (Gittleman et al., 2012). For example, the NYC Parks GreenThumb website maps more than 550 community gardens in New York City to find, join, or start a garden. The majority of the community gardens were derelict vacant lots renovated by volunteers (https://greenthumb.nycgovparks.org/gardensearch.php). Our optimization model could be incorporated into similar web or mobile applications for systematic community garden planning. Using the interactive maps, residents could view and rate potential sites, add comments or photos of the vacant parcels to facilitate site evaluation and future garden development. On the planner-end, citizens volunteered geographic information (VGI) provides valuable feedback in updating potential sites. Urban planners could then generate new optimal scenarios to redesign the metro-level community garden distribution for equality and inclusion goals and tracking cumulative benefits of various kinds. These updates can then be viewed from the citizen-end for iterative assessments.

On a broader perspective, our CGCM provides a systematic approach for vacant parcel usage of interest to urban planning beyond the specific problem for food desert and heat mitigation to which it has been applied in this study. Focusing on our problem at hand, however, several insights emerge for planning application. Foremost among them is that relevant for the global phenomenon of the melding of cities into urban conglomerations (Seto et al., 2011). In such cases, the optimal impacts of the co-benefits are obtained at the metro-level of planning as opposed to the individual city. This should prove to be the case for environmental services, such as heat or flood mitigation or maintenance of biodiversity, in which the metro-level impacts follow from the spatial distribution across the metropolis of parcel uses (Li et al., 2016). The role of such systematic planning is apparently heightened when the co-benefits involve the mix of more (community gardens) and less (green space cooling) local siting needs. In addition, the buy-in by communities to undertake one objective, for example our community gardens with their provisioning and social functions, may be enhanced if other functions are also derived, for instance the heat mitigation impact.

### *4.5. Limitations and future research avenues*

Recall that this study is exploratory, seeking to develop a model that can site community gardens based on the optimization of co-benefits—mitigating food and heat issues—and can serve an expansive metropolitan area with thousands of open parcels from which to choose. We aimed to achieve a flexible model in which decision makers could manipulate the relative attention to either benefit. Given the limitations in the data applied, our CGCM is not meant to be the final authority on the locational specifications of community garden sites, but is intended to demonstrate the potential of a systematic co-benefit approach to urban community garden development. Greater precision in siting would await additional data, as noted below, to be employed.

As with any model, a number of simplifications and omissions are involved. Foremost, the identification of a neighborhood as high-priority does not necessarily translate into its desire for a community garden (Bleasdale, 2015; Diaz et al., 2018). A well-intentioned project may ultimately fail due to insufficient buy-in from residents (Draus et al., 2014; Rosan & Pearsall, 2017). Community support, along with considerations regarding green gentrification, the equitable distribution of resources, sufficient gardening education, and local priorities, makes engagement with a diversity of stakeholders throughout all stages of garden development paramount (Barron, 2017; Meenar, 2017; Sbicca, 2019). Ideally, the site selection process would be conducted in tandem with the local community members as buy-in is fundamental to the long-term viability of any community garden (Draus et al., 2014).

Additionally, in terms of model design, the CGCM differs from the MCLP in that it introduces assignment variables to reflect the fact that the benefit a neighborhood receives varies with the particular garden to which it is assigned. In the model, only one garden is assigned to a census tract . The model could be designed to serve communities, particularly high-priority neighborhoods, being covered by multiple gardens rather than just one. In addition, a more generalized maximum coverage model is possible so that benefits received from gardens within the coverage threshold vary with distance. Determining the appropriate benefit decay function for such access points to a future research direction.

The various parcel simplifications employed can be improved with expanded data sets, such as biophysical and socioeconomic constraints on parcels. For example, soil contamination (McBride et al., 2014) and other biophysical conditions constraining or enhancing land-uses assets of the VPPG (i.e., whether or not it's compatible to transfer into gardens) are not captured in the CGCM. Sampling has shown lead concentrations to be low in current community gardens in Phoenix metropolis (Holmes et al., 2018), although slightly elevated levels of lead have been found in older neighborhoods' soils (but below remedial action levels) (Zhuo et al., 2012). In addition, the cooling effect of an garden is strongly affected by the composition and configuration (e.g., density, shape, and connectivity) of greenery and vegetation type (Middel, Chhetri & Quay, 2015; Li et al., 2016). It is noteworthy that accounting for 3D features predict human thermal comfort better than 2D landcover alone at the micro level (Zhang, Middel & Turner, 2019; Turner et al., 2022). Therefore, strategic placement of tree canopies among the cultivated vegetation is critical for the daytime cooling of community gardens. In Phoenix, cultivation is possible almost all year-round if water is available, thus there is minimal seasonal variation in greening if the garden is used. The median size of the optimal gardens is approximately 1,400 $m^2$, which may result in limited cooling coverage. Small green space, however, cools by creating significant localized LST reductions (Ossola et al., 2021). Given the challenges of developing large gardens, it is likely more cooling efficient to have many small green spaces.

Additional uncertainties, like those related to land tenure, also pose siting issues, both in terms of initial development and overall lifespan (Diaz et al., 2018). Public lands or underused commercial lands of sufficient size could be added to the private parcels we considered. Factors such as tax delinquency, parcel value, local ordinances, neighborhood association restrictions, development cost, existing municipal land use plans, infill and gentrification, and an absence of municipal or policy protections can affect the availability of parcels as well as shorten the ability of a site to maintain a community garden in the long-term (Sbicca, 2019). Among those, one salient challenge is the land tenure condition, such as parcels in tax delinquency or being held by developers with specific near-term development plans. For the most part, however, identification of long-term vacant parcels within otherwise developed neighborhoods warrant consideration in our effort. Much of the VPPGs near the older urban centers have the potential to be reclaimed by community garden-green space programs. For example, partnering with USDA-NRCS and the City of Phoenix, community gardens were successfully built on vacant lots in South Phoenix to mitigate food desert (https://tigermountainfoundation.org/our-initiatives-community-growing-project/). Unfortunately, our VPPG data did not have the detailed land tenure information. These considerations add another level of complexity to the community garden planning process that is beyond the scope of the CGCM, but some of which could be entered into the model when data is available.

## 5. Conclusion

The variety of co-benefits that urban community garden-green spaces offer makes their development an advantageous strategy to advance urban sustainability goals. Despite this array, community garden planning has been largely ad-hoc, focused on one or the other benefit, in some cases not necessarily focused on high-priority neighborhoods, and rarely based on the use of spatial optimization insights of co-benefits. Our approach offers a remedy for these shortcomings, recognizing that it entails a level of long-term planning that may prove difficult for urban planning. The urgency of sustainability challenges, however, necessitates consideration of more strategic planning methods.

Our study demonstrates that spatially-optimized community garden planning is of particular importance to avoid clustering of garden resources and ensure more equal access to local food and outdoor cooling benefits. Inspired by the classic MCLP model, our CGCM demonstrates how the optimal coverage of high-priority neighborhoods varies based on the number of community gardens proposed. Through its application, we demonstrate how the nearly two-thirds of the census tracts that are presently underserved by the Phoenix metro-area's community garden network could be covered more effectively. The targeted nature of the CGCM makes it capable of identifying high potential sites in priority census tracts with a precision not capable in more conventional planning methods.

The co-benefits selected in our study target priority issues for the Phoenix metro-area, but the CGCM's approach can be used to promote any of the social-environmental services that community gardens offer. Furthermore, through its ability to weight multiple objectives and the adjustability of other components, such as the coverage distance or the scale of the assessment (e.g., regional or neighborhood), the CGCM allows users the ability to customize various co-benefits. Ultimately, our approach demonstrates how micro-scale land-use decisions can be incorporated to strategically optimize metro-level urban landscape, potentially yielding both local and regional impacts.

## CRediT authorship contribution statement

**Yujia Zhang:** Conceptualization, Methodology, Model Implementation, Analysis, Writing. **Jordan Smith:** Conceptualization, Methodology, Analysis, Writing, Funding acquisition. **Daoqin Tong:** Conceptualization, Methodology, Writing. **B.L. Turner II:** Conceptualization, Writing, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2022.104488.

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