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Optimize urban food production to address food deserts in regions with restricted water access

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ABSTRACT

Adequate access to healthy, affordable food remains a great challenge in many urban areas. Among a range of interventions, urban agriculture has been identified as an important strategy to help address urban healthy food access. While urban food production is growing in popularity, the use of potable water in traditional urban agricultural installations will exacerbate gaps in water demand and availability in water-stressed cities. This paper examines the sustainable capability of urban agriculture through an integration of alternative water resources, urban vacant land and local nutritional needs. A spatial optimization model is developed to best allocate limited resources for maximal food production to address urban food deserts. The new model is applied to test the capability of relocalized food production in Tucson, Arizona, a semi-arid region with the longest continuously farmed landscape in North America. Results highlight that urban areas with restricted water access can substantially enhance their local food production capacity in an ecologically responsible manner.

1. Introduction

Adequate access to healthy food remains a great challenge for those of lower socioeconomic status. The concept of "food desert" was introduced to identify disadvantaged neighborhoods where access to healthy, affordable foods (especially fruits and vegetables) is limited or non-existent. In the United States, lack of healthy food access has been correlated with diet related diseases, such as heart disease, obesity and high blood pressure (Cummins & Macintyre, 2006; Wing et al., 2016; Suarez et al., 2015). The food desert concept has also been widely used in the U.S. to inform government agencies and public health professionals in their efforts to improve health outcomes in low-income neighborhoods.

To address food deserts and alleviate the healthy food access issue, efforts have focused on introducing healthy food retailers such as supermarkets or large grocery stores. However, studies indicated that such an intervention may not necessarily work. For example, food desert residents in Philadelphia (Cummins, Flint, & Matthews, 2014), New York (Elbel et al., 2015), and Pittsburgh (Dubowitz et al., 2015) reported no dietary change after new supermarkets were introduced. Based on an analysis of 1914 supermarkets opened from 2004 to 2015, Allcott et al. (2017) showed that supermarket entry had no or little effect on the healthy eating of food desert residents. All these findings suggest that healthy food access in food deserts goes beyond the availability of healthy food retailers; other barriers including poverty, education and nutritional knowledge may play an important role (Allcott et al., 2017; Wolfson, Ramsing, Richardson, & Palmer, 2019).

Among many alternative interventions for improving healthy food access in food deserts, urban agriculture has recently received an increasing amount of attention. Benefits of urban agriculture have been broadly reported, ranging from healthy food access, aesthetics, community building to physical and mental health (Brown & Jameton, 2000; Hynes & Howe, 2004). For example, community gardeners are found to be less food insecure and tend to consume more fruits and vegetables (Alaimo, Packnett, Miles, & Kruger, 2008; Carney et al., 2012; Litt et al., 2011; Barnidge et al., 2013). This is particularly true for food desert residents (Corrigan, 2011). Studies also showed that food sharing/donation, which is often practiced in urban agriculture, increases healthy food access at the community or a larger scale (Armstrong, 2000; Corrigan, 2011; Wakefield, Yeudall, Taron, Reynolds, & Skinner, 2007; Burdine & Taylor, 2018).

However, the success of urban agriculture is not always guaranteed.

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Among others, land access and security of tenure have been frequently reported as a primary issue in urban agriculture (Armstrong, 2000; Hess & Winner, 2007; Guitart, Pickering, & Byrne, 2012; Drake & Lawson, 2014; Angotti, 2015). On the other hand, vacant land has become a widespread issue in many cities (Smith, Li, & Turner, 2017). In the U.S., about 15% of urban land is deemed vacant or abandoned (Pagano & Bowman, 2000), presenting threats to public health and community safety (Garvin, Branas, Keddem, Sellman, & Cannuscio, 2013; Spelman, 1993; Cohen et al., 2003). To solve the land access issue in urban agriculture while addressing problems associated with vacant land, there has been increasing interest in transforming vacant land into urban agricultural sites (Bonham, Spilka, & Rastorfer, 2002; Schilling & Logan, 2008; Atkinson, 2012; Carlet, Schilling, & Heckert, 2017; Mack, Tong, & Credit, 2017).

While much urban agriculture research has focused on the issues associated with land availability, very few studies have examined water access. As urban water stress becomes an increasing global challenge, it is important to practice urban food production using sustainable water resources. This is especially critical for regions with restricted water access, such as the Southwest U.S. where a more arid climate and higher risk of water shortages are expected in the coming century (Seager et al., 2007). Meanwhile, although urban agriculture has been widely associated with healthy food access improvement, most existing studies are qualitative with results that are difficult to generalize (Ellis & Sumberg, 1998; Zezza, 2010; Badami & Ramankutty, 2015). Limited quantitative studies along with the challenges faced by urban agriculture may undermine the validity and significance of urban agriculture. This research introduces a quantitative method to study the sustainable capacity of urban agriculture initiatives. The method integrates alternative water resources and public vacant land availability to assess the capability of urban food production for meeting food desert nutritional needs. Varying levels of collaboration among neighborhoods and communities are considered to examine their impacts on food production. The approach has been applied to study the relocalized food production in a medium-sized Southwest U.S. city, Tucson, Arizona, where healthy food access and water scarcity have been serious issues.

2. Background

In the past century, worldwide urbanization and agriculture industrialization processes have made food production limited to mainly rural areas. The urban–rural divide along with specialization and globalization has resulted in a tremendous increase in food miles (Pirog, van Pelt, & Enshayan, 2001). Recently, urban agriculture has gained increasing popularity as a way to reconnect urban residents with land and promote local food production (Mok et al., 2014). Various forms of food production have been practiced in the urban setting, including urban farms, community gardens, community-supported agriculture, rooftop gardens, and vertical gardens (Horst, McClintock, & Hoey, 2017).

A large number of studies discussed the multidimensional benefits of urban agriculture, ranging from healthy food provision, community building, economic development, to climate change mitigation (Golden, 2013; Draper & Freedman, 2010; Kulak, Graves, & Chatterton, 2013). Among all these benefits, one major focus has been on the improvement of healthy food access and food security. At the individual or household level, studies found that urban agriculture helped increase fresh food access (Armstrong, 2000) and save food expenses (Wakefield et al., 2007); at the community level, food donation practices alleviated food desert problems (Corrigan, 2011). Given that most of these studies relied on qualitative data or case studies, more quantitative and generalizable analysis has been called for (Draper & Freedman, 2010).

So far, a few studies have been conducted to quantify the capability of urban agriculture in food provision. At the global scale, Clinton et al. (2018) estimated that urban agriculture has the potential to achieve 1.5%–3% of worldwide crop production. Martellozzo, Landry, Seufert, Rowhani, and Ramankutty (2014) showed that urban agriculture has limited potential in many developing countries due to large population densities and unavailability of urban land. Among all the urban areas, they noted the importance of promoting urban agriculture in small to medium-sized urban areas given that these areas account for a large portion of the world population and available urban land.

Several studies have also examined the food production capacity of urban agriculture at the region or city scale. Based on the available land of New York City, Plunz et al. (2012) showed that community gardens could help address healthy food access in some neighborhoods although they were not feasible to meet the entire city's food provision. In Oakland, McClintock, Cooper, and Khandeshi (2013) found that under a conservative land use scenario vacant and underutilized public land could produce 2.9% to 7.3% of the vegetables consumed in the city. By considering three scenarios of food production sites, including vacant lots, residential lots and industrial and commercial rooftops, Grewal and Grewal (2012)'s case study of Cleveland suggested the possibility of achieving a high level of food self-sufficiency in a city.

While these quantitative studies provide important insights into the capacity of urban agriculture for food provision, they mainly examine the globe or a city/region as a whole. These results might be misleading because depending on the distribution of the available land, low-income or food desert residents may have no or limited access to these food production spaces (Parece, Serrano, & Campbell, 2017). Meanwhile, none of these studies considered the substantial variation in the growing seasons of different crops. Challenges associated with land availability variation within a city/region along with crop differences are also noted by MacRae et al. (2010). As a result, a more realistic urban agriculture capacity assessment is needed to address these challenges.

Additionally, all the existing quantitative studies have primarily focused on land availability as the main constraint for urban food production. In these studies, little attention has been paid to water despite its important role for growing food. In fact, agriculture is the largest water user worldwide accounting for more than 70% of the global water use (OECD, 2010). While demand for water increases globally, limited water availability and climate change have brought about water stress in many regions. About 30–48% of the world's population is estimated to live under the severe water scarcity condition for at least 4–6 months a year (Mekonnen & Hoekstra, 2016), and many regions will experience a higher risk of water shortage in the coming century (Seager et al., 2007). As a result, water access imposes another critical constraint on urban agriculture (de Fraiture, Molden, & Wichelns, 2010). To address the water access issue, rather than relying on municipal potable water, efforts have sought alternative water resources for urban agriculture (Pedrero, Kalavrouziotis, Alarcon, Koukoulakis, & Asano, 2010), including rainwater harvesting (Lupia, Baiocchi, Lelo, & Pulighe, 2017; Parece & Lumpkin, 2016) and reclaimed wastewater (van Lier & Huibers, 2010; Norton-Brandão, Scherrenberg, & van Lier, 2013; Parsons, Sheikh, Holden, & York, 2010).

Rainwater harvesting (RWH) includes the use of passive and active systems. Passive systems are designed to retain water until it can be naturally absorbed into the land (swales and pervious pavers are common passive strategies). Active systems, by comparison, collect, clean, and store rainwater for later use (tanks and cisterns are prevalent elements of active harvesting). Active and passive RWH systems have been increasingly implemented in areas that face growing water constraints under climatic, environmental, and social changes (Amos, Rahman, & Gathenya, 2016, Hamel & Fletcher, 2014). Lupia et al. (2017) conducted a RWH study in Rome and found that about 19% and 33% of the existing food production gardens could achieve water self-sufficiency for the low and high irrigation efficiency scenarios, respectively. Some areas such as the Southern U.S. and Mediterranean countries have started to use reclaimed/recycled urban wastewater to irrigate agricultural crops (Pedrero et al., 2010). In the U.S., Florida and California are among the largest producers and users of reclaimed wastewater (Parsons, 2018). It is highlighted that harvested rainwater and reclaimed water can provide a sustainable, ecologically responsible, water supply for increasing food production and nutritional access (Molina, 2010).

This research provides a study to assess the capability of urban agriculture to address food deserts. An integrated system of available urban land, RWH, and reclaimed water access is developed to examine optimal urban food production. Unlike existing quantitative studies that examine a city/region as a whole, this study considers the variation of resource availability in different neighborhoods and introduces three food production scenarios to account for different levels of community collaboration. Temporal variation in precipitation and crop growing seasons are also considered.

3. Maximizing food production in food deserts

This study aims to identify the optimal use of vacant land and alternative water resources to address healthy food access in food deserts. The United States Department of Agriculture (USDA) defines food deserts based on low-income neighborhoods that have low-level access to health food stores. In many studies, the low-level access was evaluated based on whether an urban neighborhood has a supermarket or large grocery store within 1 mile. Currently, most studies use census tracts to delineate "food deserts". The resulting food deserts can be too coarse for many regions (Bao & Tong, 2017). In this study, we adopted the USDA food desert criteria and delineated food deserts at the block group scale (indexed as b), the smallest units with socioeconomic data available. Using finer spatial units also helps capture the local food production nature of many urban agriculture practices.

We consider two alternative water resources, weekly passive and active RWH potential and reclaimed water access. Crops chosen at different sites during different seasons are based on their output and the resources (e.g., land and water) available locally. In particular, we developed a new spatial optimization model so that limited resources in different neighborhoods can be best allocated for maximal food production. Recently, Mack et al. (2017) developed a spatial optimization model for siting community gardens to provide healthy food access to food deserts. In their model, food production resource constraints are not considered, including vacant land size, crop variety, and water access. In this research, we propose a novel spatial optimization model that focuses on food production capacity by integrating the spatial variations of vacant land and alternative water resources to best address urban healthy food access.

Fig. 1 illustrates a food production site with access to both RWH and reclaimed water. The availability of a reclaimed water pipeline at the site ensures reclaimed water access for appropriate crops at all times. As for rainwater, while passively harvested rainwater is mainly available during the precipitation period, actively harvested rainwater can be stored in a rainwater tank/cistern for future use. As a result, the availability of actively harvested rainwater for crop irrigation at time t depends on the amount of rainwater remaining in the rainwater tank, which is a function of precipitation, catchment type and area, and the amount that has already been drawn from the tank previously. In achieving the maximum food production, the model determines the crops to be grown at different sites during different times of year given the availability of land and water.

In this study, we use a month (t) as the time unit to track the planting and harvesting periods of vegetables. However, irrigation needs and rainwater availability are evaluated on a weekly basis (q) to ensure sufficient temporal resolution in the model. If irrigation needs were evaluated at the monthly level, passive rainwater collected in the beginning of a month would be counted as available for the entire month although in reality passive rainwater often does not last for a month.

We introduce three scenarios to account for different levels of community collaboration involved in urban agriculture. In particular, Scenario A corresponds to a situation where urban food production and distribution are highly coordinated and food produced in areas with access to abundant land and water can be distributed and shared with residents in other areas. In some cases, urban agriculture involves localized food production and consumption where residents grow and consume vegetables in their neighborhoods or neighboring areas. Scenario B represents such a case where residents produce and consume food either in their own neighborhood or nearby areas considering accessibility. For example, Blaine, Grewal, Dawes, and Snider (2010) conducted a study in Cleveland, Ohio and found that most community gardeners traveled less than 10 min to their gardens with more than half by walk. Scenario C refers to a much more localized system where food production and consumption only occur in the same neighborhood.

Consider the following notation,

b: index of block groups

c: index of vegetable categories

h: index of alternative water resources (1: reclaimed water; 2: rainwater)

q: index of weeks

t: index of months (entire set T)

v: index of vegetable types (entire set V)

U: set of vegetable types that cannot be irrigated using reclaimed water

a_v: factor used to convert food production of vegetable v to cups (USDA, 2018)

A_v: minimum cups to be grown if vegetable v is selected

Cap: capacity of rainwater tanks

$f_{v,t,b}^{h}$: amount of vegetable v planted in month t in block group b with h as the irrigation water

F_c^{min}: yearly minimum production of vegetables in category c

F_c^{max}: yearly maximum production of vegetables in category c

g_v: time needed for vegetable v to grow before harvesting (in months)

L_b^h: vacant land in block group b that has access to alternative water resource h

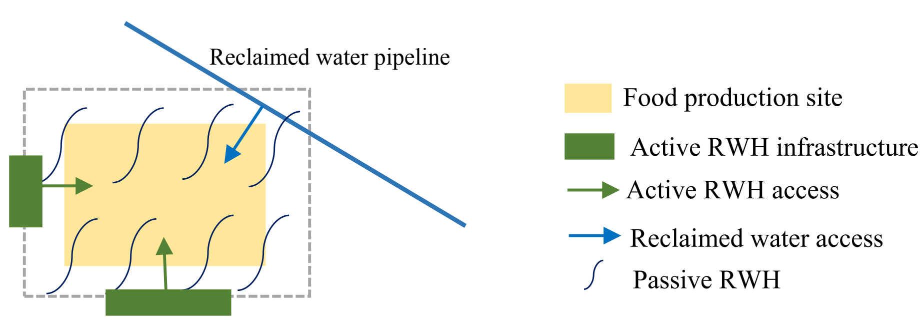


Fig. 1. Illustration of alternative water resources for food crop irrigation.

L_b^T: total vacant land in block group b

l_v: land needed to grow one cup of vegetable v

M: a large number

N_c: a set defining the types of vegetables in vegetable category c

N_t: a set defining the weeks in month t

$w_{v,t,q}$: irrigation water needed in month t and week q for producing a cup of vegetable v

$W_{t,q,b}^r$: rainwater left in the tank(s) in month t and week q in block group b

$W_{t,q,b}^a$: active rainwater collection in month t and week $q$in block group b

$W_{t,q,b}^p$: passive rainwater collection in month t and week q in block group b

$\varphi_{t,q,b}$: water drawn from rainwater tanks during week q in block group b

$$y_{v,t,b}^h = \begin{cases} 1 & \text{if vegetable } v \text{ is planted in month } t \text{ in block group } b \text{ and uses } h \text{ as the irrigiation water} \\ 0 & \text{otherwise} \end{cases}$$

Three maximal urban food production (MUFP) models are constructed for the three scenarios. We introduce the general model structure first and then discuss the community collaboration constraints formulated for the different scenarios.

Maximize

$$\sum_b \sum_t \sum_v \sum_h a_v f_{v,t-g_v,b}^h \tag{1}$$

Subject to

$$\sum_h \sum_v \sum_{j=0}^{g_v-1} l_v f_{v,t-j,b}^h \le L_b^T \qquad \forall\ t,\ b \tag{2}$$

$$\sum_v \sum_{j=0}^{g_v-1} l_v f_{v,t-j,b}^1 \le L_b^1 \qquad \forall\ t,\ b,\ v \tag{3}$$

$$f_{v,t,b}^1 = 0 \qquad \forall\ t,\ b,\ v \in U \tag{4}$$

$$f_{v,t,b}^h \ge A_v y_{v,t,b}^h \qquad \forall\ v,\ t,\ b,\ h \tag{5}$$

$$f_{v,t,b}^h \le M y_{v,t,b}^h \qquad \forall\ v,\ t,\ b,\ h \tag{6}$$

$$\varphi_{t,q,b} \ge \sum_v \sum_{j=0}^{g_v-1} f_{v,t-j,b}^2 w_{v,t,q} - W_{t,q,b}^p \qquad \forall\ t,\ b,\ q \in N_t \tag{7}$$

$$\varphi_{t,q,b} \ge 0 \qquad \forall\ t,\ b,\ q \in N_t \tag{8}$$

$$W_{t,q,b}^r \le W_{t,q-1,b}^r + W_{t,q,b}^a - \varphi_{t,q,b} \qquad \forall\ t,\ b,\ q \in N_t \tag{9}$$

$$W_{t,q,b}^r \ge 0 \qquad \forall\ t,\ b,\ q \in N_t \tag{10}$$

$$W_{t,q,b}^r \le Cap \qquad \forall\ t,\ b,\ q \in N_t \tag{11}$$

Objective (1) aims to maximize the total amount of vegetables to be produced. Constraints (2) specify the amount of land available in each block group for food production taking into account the growth period of each type of vegetable. Constraints (3) specify the land that has access to reclaimed water for growing vegetables eligible for reclaimed water irrigation. Constraints (4) prevent vegetables ineligible for reclaimed water irrigation from being irrigated using reclaimed water. Constraints (5) to (6) are constructed to ensure that if vegetable v is chosen in block group b ($y_{v,t,b}^h$=1)at least a meaningful amount (A) will be grown. These constraints are imposed mainly based on a practical consideration, as growing a minimal amount of food (0.1 cups) is not realistic although the model may allow such a solution in achieving the maximal production.

Constraints (7) state that during week q when there is no passive rainwater collection or the passive rainwater collection cannot meet the irrigation needs, irrigation water will be drawn from RWH tanks with$\varphi_{t,q,b} \ge 0$. Here we assume that vegetables that are eligible for reclaimed water irrigation and have access to reclaimed water will rely on reclaimed water only. Constraints (8) ensure a non-negative amount of water drawn from a RWH tank. Constraints (9) are used to update the status of each RWH tank on a weekly basis. They establish that the water remaining in a tank is the amount left from the previous week subtracted from the water drawn to meet the current week's irrigation needs. Constraints (10) and (11) ensure no overdrawing from a RWH tank and water in a RWH tank does not exceed the capacity of the tank, respectively.

For Scenario A, we construct the following additional constraints, (12) and (13), to specify the highest level of community collaboration by assuming that food production and distribution occur across the entire study area. In particular, Constraints (12) ensure the minimum food production in each vegetable category, and Constraints (13) state that food production does not exceed the overall food consumption to avoid waste.

$$\sum_t \sum_{v \in N_c} \sum_b \sum_h f_{v,t-g_v,b}^h \ge F_c^{min} \qquad \forall\ c \tag{12}$$

$$\sum_t \sum_{v \in N_c} \sum_b \sum_h f_{v,t-g_v,b}^h \le F_c^{max} \qquad \forall\ c \tag{13}$$

For Scenario B, where residents collaborate on food production and distribution with nearby neighborhoods, we use constraints (14)-(16) to characterize the neighborhood level collaboration. More specifically, Constraints (14) to (15) allow food production and sharing in neighboring areas to help address the minimum and maximum food consumption in a neighborhood. Constraints (16) ensure that the overall food allocated from block group b to its neighboring areas does not exceed the overall food production in b.

$$\sum_{k \in \Phi_b} \sum_t \sum_{v \in N_c} z_{v,t,k,b} \ge \eta_b \Pi_{b,c}^{min} \qquad \forall\ b,\ c \tag{14}$$

$$\sum_{k \in \Phi_b} \sum_t \sum_{v \in N_c} z_{v,t,k,b} \le \eta_b \Pi_{b,c}^{max} \qquad \forall\ b,\ c \tag{15}$$

$$\sum_{k \in \Psi_b} z_{v,t,b,k} \le \sum_h f_{v,t-g_v,b}^h \qquad \forall\ b,\ v,\ t \tag{16}$$

Where

$\Pi_{b,c}^{min}$: yearly minimum vegetables needed in category c in block group b

$\Pi_{b,c}^{max}$: yearly maximum vegetables needed in category c in block group b

Φ_b: set of neighboring block groups in which residents from block group b participate in urban agriculture

Ψ_b: set of block neighboring groups from which residents participate in urban agriculture in block group b

$z_{v,t,k,b}$: amount of vegetable v allocated from block group $k$to block group b in month$t$

$$\eta_b = \begin{cases} 1 & \text{if block group } b \text{ can produce the minimum amount of vegetables required} \\ 0 & \text{otherwise} \end{cases}$$

For Scenario C, where residents practice urban agriculture only in their own neighborhoods with no food sharing among different neighborhoods, we formulate constraints (17) and (18) to reflect such a practice. These constraints specify that vegetables produced within each neighborhood meet the minimum food production requirement but do not exceed the amount that can be consumed in the neighborhood.

$$\sum_t \sum_{v \in N_c} \sum_h f_{v,t-g_v,b}^h \ge \eta_b \Pi_{b,c}^{min} \qquad \forall\ b,\ c \tag{17}$$

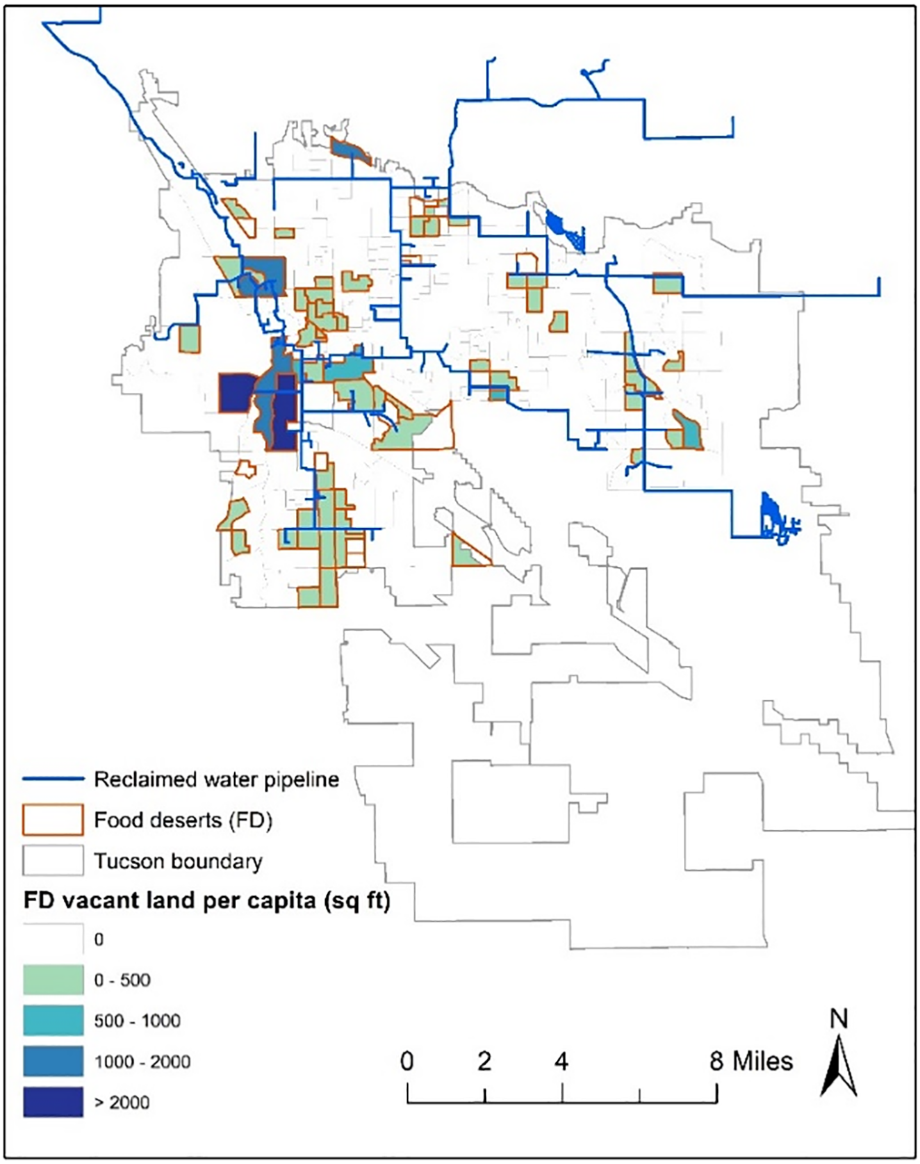


Fig. 2. The study area.

$$\sum_{t}\sum_{v\in N_c}\sum_{h} f^h_{v,t-g_v,b} \le \eta_b \Pi^{max}_{b,c} \qquad \forall\, b, c \tag{18}$$

Similar to many spatial optimization models (Tong & Murray, 2012), the MUFP involves locational decisions and spatial relationships. First, the critical decision variables, $f^h_{v,t,b}$ and $y^h_{v,t,b}$, are concerned with the spatial distribution of food items to be produced. Also, whether and how alternative water resources can be used for food production at a site requires a proximity assessment of the relevant infrastructures, such as rooftops and reclaimed water pipelines (also see Fig. 1). Furthermore, the community collaboration specification in the model involves an evaluation of the spatial relationships among different neighborhoods. For example, in Scenario B the food production/sharing collaboration is mathematically formulated through an introduction of the nearby neighborhoods and a specification of the food production/distribution among them.

4. Study area and data collection

Our empirical study was conducted in the City of Tucson, Arizona (see Fig. 2). The region has been a historic passageway and home to a rich overlay of settlement patterns for over 4000 years. In 2000, archaeologists discovered layers of irrigation trenches in the region, distinguishing the area of the U.S. Southwest as the longest continuously farmed landscape in North America (Mabry, Carpenter, & Sanchez, 2008). However, agricultural production in the region has become a challenge due to the persistent drought. In traditional urban agriculture installations, the potable/drinking water system is the source of irrigation. In water stressed cities, like Tucson, this potable water infrastructure faces a gap between available water and water demand. The Arizona Department of Water Resources (ADWR) projects that in 25 years Arizona will need to come up with an additional 900 k acre feet of water to meet the demand from its growing population (Arizona Department of Water Resources, 2014). To address this gap, alternative water supplies (e.g. RWH and reclaimed water) provide irrigation water without taxing the already stressed potable/drinking water system. Thus, supporting urban agriculture through RWH and/or reclaimed water is a sustainable model for food production through locally renewable water supplies which do not add additional burden to the water stressed urban environment.

The region also faces economic changes, with its metropolitan area ranked sixth poorest in the U.S. (City of Tucson, 2012). Food insecurity is one of the pressing issues in the region (Bao & Tong, 2017).

Table 1
Planting profile for different types of vegetables.

Category	Time to Harvest (days)	Month												Eligibility for Reclaimed Water Irrigation
		1	2	3	4	5	6	7	8	9	10	11	12	
Dark green														
Broccoli	S = 120-130	S							S	S	S	S	S	N
Spinach	40-90	S	S							S	S	S	S	N
Lettuce (leaf)	50-90	S	S						S	S	S	S	S	N
Turnip greens	90-120	S	S						S	S	S	S	S	N
Red and orange														
Tomatoes	50-120			T					T					N
Carrots	60-100	S	S	S	S				S	S	S	S	S	N
Red pepper	90-120			T				T						N
Winter squash	90-120			S				S	S					Y
Pumpkin	90-120			S				S	S					Y
Legumes														
Blackeyed pea	90-120				S	S	S	S	S					Y
Yardlong bean	60-90			S	S	S	S	S						Y
Pinto bean	60-90							S						Y
Lima bean	60-100			S	S									Y
Peas	60-120 (Sept); 120-150 (Nov)	S	S							S	S	S	S	Y
Starchy														
Potatoes	90-120	S	S											N
Corn	70-90		S	S	S			S	S					Y
Other														
Lettuce (head)	50-100	S	S						S	S	S	S	S	N
Onions (Shallots)	80-100							X						N
Bean (Green/Snap)	60-90			S	S			S	S	S				Y
Cucumber	60-90		S	S	S				S	S				N
Green pepper	90-120		T	T				T						N
Cabbage	T=80-90; S=120-130								S	S	S	S	S	N
Summer squash	60-90		S	S	S				S	S				N
Cauliflower	T=90-100; S=120-130	S							S	S	S	S	S	N
Beets	60-80	S	S	S						S	S	S	S	N

S: grow by seed; T: grow by transplant; X: set of cloves.

Currently, at the county level an initiative has been proposed to expand the local food system to help achieve optimal food production in the Sonoran Desert (Nabhan, 2013). Along with many cities in the region, Tucson is confronted with a challenge: how to devise a cost effective, equitable and sustainable water supply while addressing healthy food access? As part of the efforts to help the county to expand the food production network, we apply the MUFP to assess the capability of relocalized food production using sustainable water resources to address healthy food access in food deserts.

As mentioned previously, we used the two USDA criteria, low-access and low-income, to evaluate the food desert status at the block group level. We collected supermarket and large grocery store information from Reference USA and evaluated the low-access status based on whether a block group had a food store within one-mile travel distance. We obtained the low-income status from the 2016 American Community Survey (ACS). Combining the low-access and low-income criteria resulted in a total of 93,752 people (17.8% of the city population) living in food deserts. Parcel data were obtained from Pima Association of Governments (PAG) to identify the public vacant land. Analysis gave an overall 711 acres of vacant land in food deserts (also see Fig. 2). When areas within 1 mile of a food desert were also considered, additional vacant land of 1562 acres were identified. These vacant parcels were then used as the candidate food production sites in the MUFP.

Rainwater has drawn increasing attention as a possible solution to Tucson's water and food access deficits as, in sheer volume, annual precipitation would more than account for all of Tucson's annual water need. However, rainwater is a resource that must be gathered in decentralized interventions, rather than one large public works construction. In the study area, rooftops were assumed to be the infrastructure for active rainwater collection. LiDAR data with a resolution of 1 foot were collected from PAG to extract rooftops. Rainwater that could be harvested from a rooftop was estimated based on the size and type of the roof. Remote sensing data were also obtained from PAG to identify impervious surface and bare land in the study area. For a candidate food production site, rainwater availability was estimated based on both active and passive rainwater collection. Active RWH was estimated using non-residential rooftops within 200 m of the site, and passive RWH was computed based on the ground level impervious surface within a catchment area of 100 m of the site. Daily rainfall information from 2007 to 2016 was obtained from National Oceanic and Atmospheric Administration (NOAA) to analyze the precipitation patterns in the region. Tucson experiences two seasons of rain: short winter rains and long summer deluges during the North American Monsoon season. The most recent ten years (2007–2016) of daily rainfall was examined for a wet year and dry year to set best and worst case bounds. This ten-year time span is representative of the future megadrought scenarios that are projected to occur in the region by recent climate models (Ault, Mankin, Cook, & Smerdon, 2016). The wet year was defined by the year with the highest aggregate amount of rainfall in the ten-year time span. Similarly, the dry year was selected as the lowest aggregate amount of rainfall in the ten-year time span.

Reclaimed water is another option for providing the water needed to expand Tucson's urban food production system. Tucson began constructing its reclaimed water network in 1984. The current reclaimed water pipeline system connects the city's three largest irrigation land uses: golf courses, cemeteries, and parks (including university campuses). Annually, Tucson has approximately 1–3 billion gallons of unsubscribed reclaimed water available (Tucson Water, 2015) that can be used to expand the current irrigation network. In the U.S., to address the environment and public health concerns, a number of states, including Arizona, California and Florida, have developed comprehensive regulations and/or guidelines governing reclaimed water quality (EPA, 2012). As for food crop production, the Arizona Department of Environmental Quality (ADEQ) regulates that reclaimed water irrigation must not come into direct contact with the food product (Code, 2016). We obtained the reclaimed water network from Tucson Water and, for each candidate food production site evaluated, the reclaimed water access based on a threshold of 200 feet, the maximum distance at which Tucson Water will connect parcels to the existing network (Tucson Water, 2018).

As for food crops, we considered five categories of vegetables following the USDA's Vegetable Group classification, including dark green, red and orange, legumes, starchy and other. In each category, vegetables are selected based on how common they appear on family meals and suitability for cultivation in the region (Umeda, 2018). Table 1 provides the planting profile for the vegetables included in this study with green cells highlighting the harvest time. For each type of vegetable, Table 1 also describes its eligibility for reclaimed water irrigation. The irrigation needs for each type of vegetable is estimated using formula (19): crop coefficients were adopted from Allen et al. (1998); ET_0 was evaluated for each month based on the 2007–2016 weather data (AZMET, 2018).

$$ET_c = ET_0 * K_c \tag{19}$$

Where
ET_c: crop evapotranspiration (mm);
ET_0: reference crop evapotranspiration (mm);
K_c: crop coefficient

5. Results

We applied the MUFP to assess the food production capacity in Tucson's food desert neighborhoods considering the three levels of community collaboration: (A) full collaboration among all food deserts; (B) collaboration between a food desert and neighboring areas; and (C) no collaboration. As we mentioned earlier, Scenario A corresponds to a situation where urban food production and distribution is highly coordinated and food produced in areas with access to abundant land and water can be distributed and shared with residents in other areas. Scenario B represents a case where residents produce and consume food either in their own neighborhoods or nearby areas, considering accessibility. Scenario C refers to a much more localized system where food production and consumption only occur in the same neighborhood.

We also considered temporal variations in precipitation. Based on the 10-year precipitation data (2007–2016), we assessed the food production capacity for two weather conditions: a dry year and a wet year (also see Fig. 3). We used three rainwater tank sizes, 1600 gallons, 3200 gallons and 10,000 gallons, to examine their impacts on food production. These tank sizes were based on the existing RWH rebate program offered through Tucson Water that funds an 800 gallon threshold. These sizes also correspond to typical prefabricated tank sizes available in the region. The spread between these sizes was at increments large enough for significant comparative results. To ensure sufficient food crop varieties across different categories, for each vegetable category we specified a minimum production (F_c^{min}) to meet the nutritional needs of 5% of the food desert population.

Fig. 4 plots the maximal food production considering the varying levels of community collaboration, weather conditions and rainwater tank sizes. Following the recommendation of USDA (USDA, 2018), a daily vegetable intake of 2.5 cups per person leads to an annual 85,548,700 cups of vegetables needed by all food desert residents. Results show that under Scenario A the resources (land and water) are sufficient for addressing the vegetable needs in all Tucson's food deserts. We note that in this case the food production does not exhaust all the resources available. In fact, if we remove constraints (13) to allow a maximal usage of the resources, the MUFP model gives a production 15–35 times the amount of vegetables needed by all food desert residents, depending on the rainwater tank sizes and weather conditions. Under Scenario B with a medium level of community collaboration, the food production drops to 87%-97% of the total vegetable needs in all food deserts. The minimal food production (35%–49%) is observed under Scenario C when food production and consumption are maximally localized.

As for the impacts of rainwater tank sizes (T), Fig. 4 shows that except for Scenario A where resources are not completely used, the adoption of larger tanks increases food production. The impacts are higher for Scenario C than Scenario B: a larger tank leads to a production increase of 5%-14% under Scenario C compared to that of 3%-7% under Scenario B. As for weather conditions, production under Scenario C is more affected with a decrease of 7% during the dry year compared with a decrease of 3% under Scenario B.

Fig. 5 shows that reclaimed water access can significantly contribute to the overall food production. In the study area, although the vacant land with access to reclaimed water only accounts for 21% of the total vacant land, food production using reclaimed water achieves a higher rate of 33%. Fig. 5 plots the proportion of food produced using reclaimed water under the three scenarios. In general, a higher level of community collaboration leads to more reclaimed water food production: the average food production by reclaimed water is 42% for Scenario A, 27% for Scenario B and 29% for Scenario C. Given that reclaimed water access is limited to areas around the reclaimed water pipeline network (Fig. 2), a higher level of community collaboration makes it possible to distribute the food produced using reclaimed water to meet demand in areas where food production is insufficient. As discussed previously (also see Fig. 4), adoption of larger rainwater tanks results in more food production in general. This leads to a decrease in the proportion of food produced using reclaimed water under Scenarios B and C.

Depending on precipitation, food production is not evenly distributed across all seasons. Fig. 6 shows the monthly food production based on the tank size of 3200 gallons and a wet year weather condition. Considering the low precipitation in late spring (see Fig. 3) and limited vegetables that can be harvested in summer (see Table 1), it is not surprising to observe the minimal food production in summer. With the summer monsoon and rainwater tanks to store rainwater, we notice a high food production in the following months from October to December. Winter rain contributes to the food production in early spring. While the rainwater food production has a high variation due to the seasonable precipitation, reclaimed water access helps decrease the monthly food production variation by 17% under Scenarios B and 7% under Scenario C. We note that under Scenario A, the monthly food production given by the model is one of the many possible ways as neither land nor water available has been completely exhausted.

Model results highlight the importance of both land and water for urban agriculture. Fig. 7 plots the amount of land and rainwater used for food production in two food desert block groups, block group 1 and block group 2, assuming T = 3200 gallons, no community collaboration (Scenario C), and a wet year weather condition. In this case, block

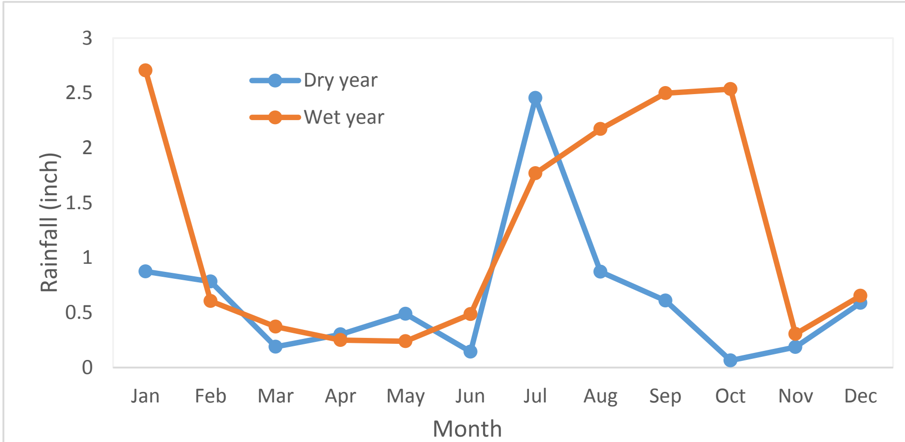


Fig. 3. Monthly rainfall distribution in the study area (North American monsoon season runs on average from mid-July to mid-October).

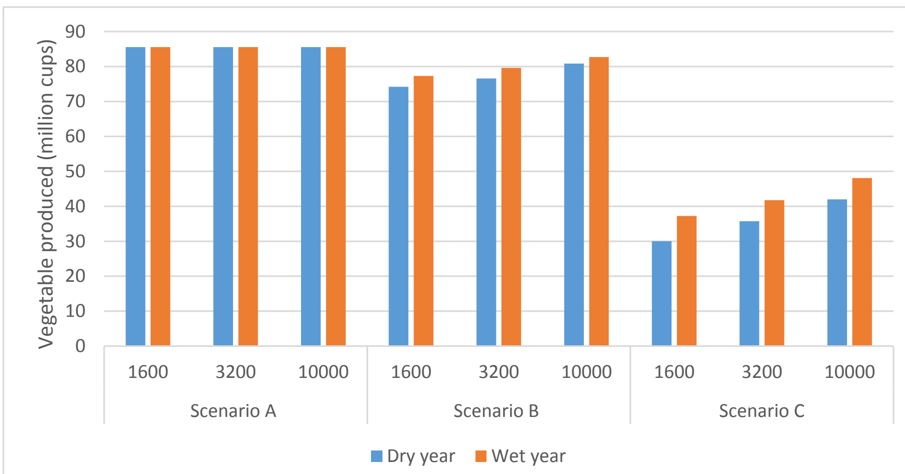


Fig. 4. Urban food production by scenario.

group 1 has access to more vacant land (115.8 square feet per capita) compared to block group 2 (4.3 square feet per capita); block group 2 has access to more water resources given that it is located in close proximity to the reclaimed water pipeline network whereas block group 1 is not. In both block groups, the overall food production can only partially meet the vegetable needs of the local residents. Fig. 7(a) shows an insufficient water case where water availability limits the food production: on average 88% of the vacant land in the block group is left unused whereas rainwater is maximally used with water being continuously drawn from the rainwater tank. Fig. 7(b) shows an

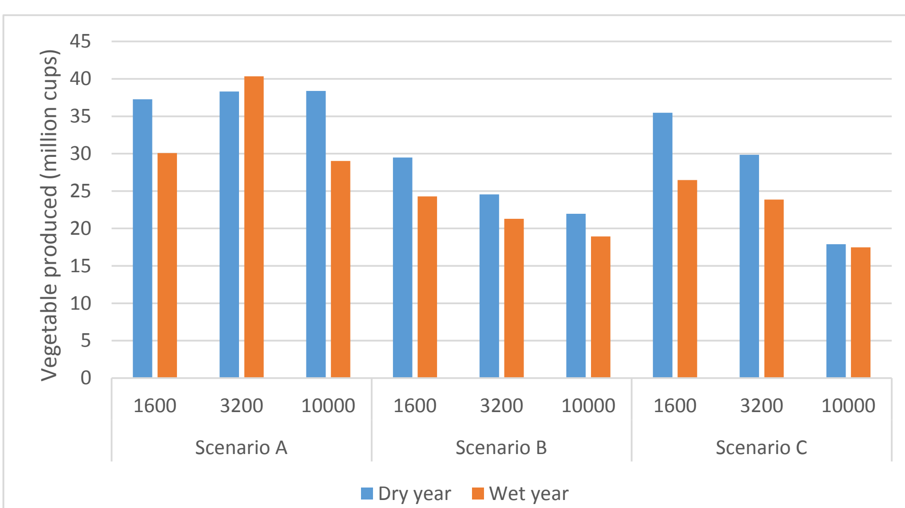


Fig. 5. Urban food production using reclaimed water.

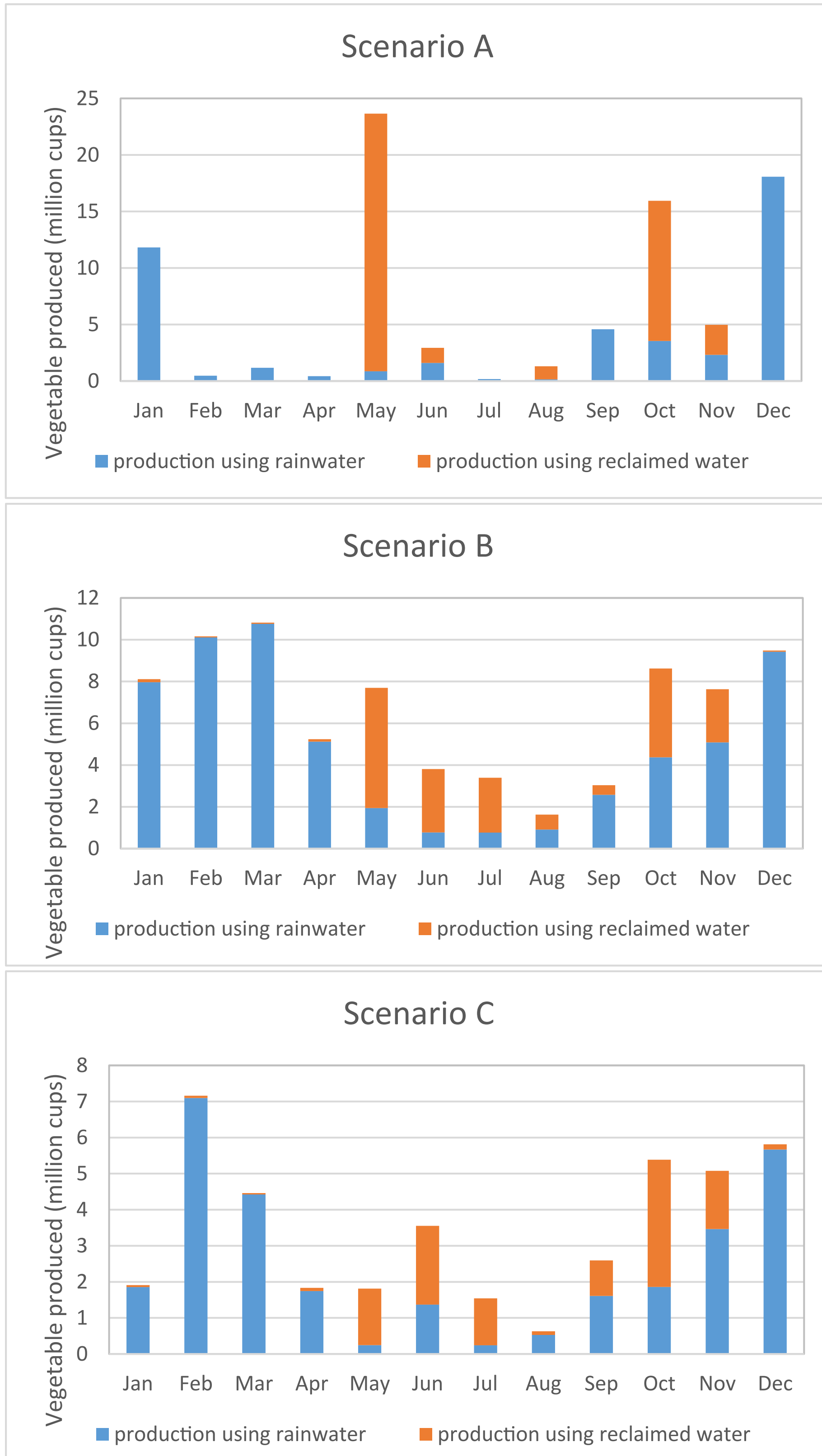
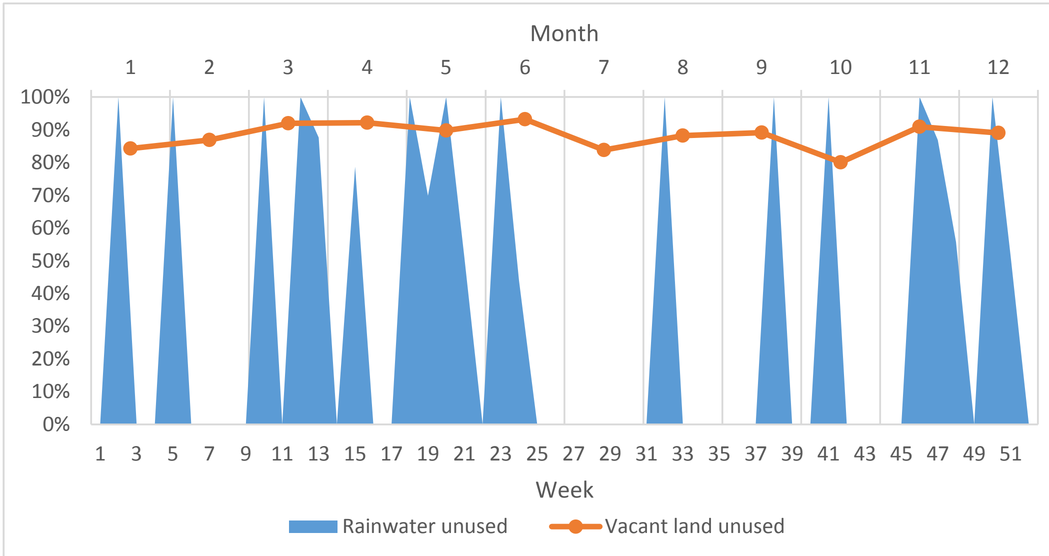


Fig. 6. Monthly food production assuming $T = 3200$ gallons and a wet year weather condition.

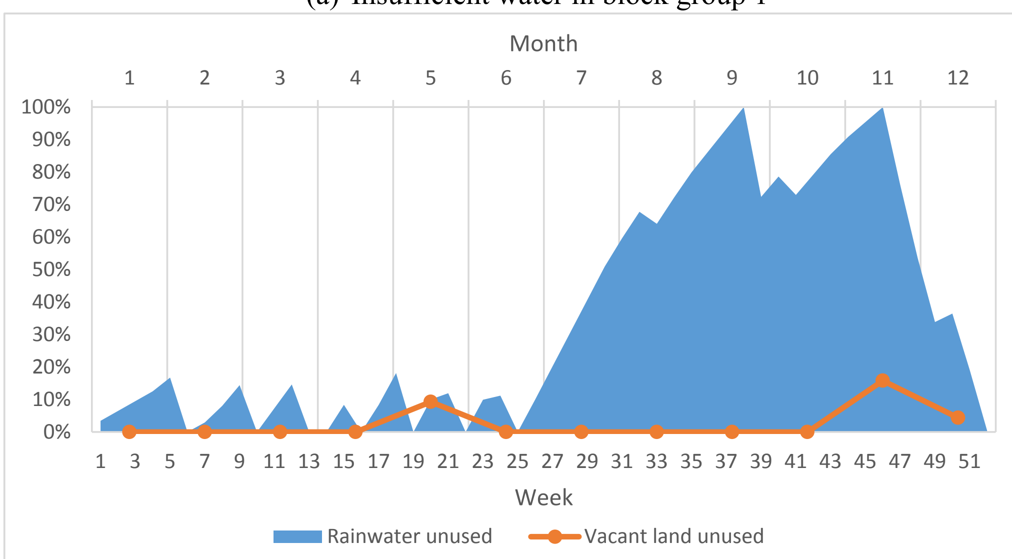
insufficient land situation where land availability restricts the food production: minimum vacant land is left unused throughout the year despite the reclaimed water access and substantial rainwater left in the tank starting in June.

6. Discussion

Traditionally, at the municipality level there is no functional division dedicated to food. Only in the past few years, city planners,



(a) Insufficient water in block group 1



(b) Insufficient land in block group 2

Fig. 7. Importance of land and water access for urban food production.

researchers and professionals have started to engage food on their urban planning agendas. In the U.S. and Canada, a number of food-related initiatives have been proposed (e.g., *People's Food Policy*, *The People's Garden*, *Let's Move*) to promote urban agriculture and local food production (Mok et al., 2014). Along with the national efforts, similar initiatives have been established in Tucson to help improve healthy food access. As part of the effort to support urban agriculture, this study provides important insights into the sustainable capacity of urban food production for addressing food deserts.

The research contributes to the urban food system studies by providing a quantitative analysis of urban agriculture in areas that face imminent water shortage. Although many studies have qualitatively reported various benefits of urban agriculture, limited research has examined the capability of urban agriculture to address the food security issue, especially in water stressed regions. By integrating urban vacant land with alternative water resources, the case study in Tucson indicates the feasibility of urban agriculture to address local food deserts. Model results show that food production is found to vary substantially with levels of community collaboration. With a full level of community collaboration, the resources available in Tucson can produce significantly more vegetables than the amount needed by all food desert residents. A partial community collaboration with neighboring areas achieves an overall food production meeting 80% of the vegetable needs in food deserts. A food production practice with no community collaboration reduces the overall production to 35% to 56%.

In this study, we assume that vacant land in food deserts or neighboring areas can be converted and used as food production sites. Currently, efforts have been made in many cities to encourage residents to convert vacant land to urban agriculture sites such as community gardens, including the "Adopt-a-Lot" program in Baltimore, Pittsburgh, and Los Angeles, and the GrowNYC's Garden Program in New York City. However, in many cases using vacant land for food production is considered as interim, and land tenure remains a critical barrier to urban agriculture (Saldivar-tanaka & Krasny, 2004; Guitart et al., 2012; Horst et al., 2017). When opportunities are available, urban agriculture sites are often at a risk of being used for housing and commercial developments. In the late 1990s and early 2000s, hundreds of community gardens built on public vacant land in New York City were demolished for retail and housing development (Schmelzkopf, 2002). The South Central Farm of the Los Angeles Regional Food Bank was closed after a private owner purchased the land back despite community resistances including campaigns, protests and site occupation (Lawson, 2007). Studies have also shown that community gardens have positive impacts on neighborhood property values, especially in poor neighborhoods (Voicu & Been, 2008). However, increased commercial potential due to neighborhood gentrification and rising property values may result in displacement of low-income people (Markham, 2014). Therefore, solutions to ensure land tenure for urban agriculture and minimize gentrification impacts are needed. Some examples include nonprofit land trust, transfer of land to city park departments, and integration of community gardens into city plan (Kirschbaum, 2000). These models can be coupled with urban food production for long term tenure of agricultural land use in urban areas.

We consider both rainwater and reclaimed wastewater as alternative resources for food crop irrigation. Unlike rainwater, reclaimed water is climate independent and therefore presents a supplement, complement, or alternative to rainwater. In the study area, model results indicate that the reclaimed rainwater consumption across all the three scenarios is well below the existing surplus in the system. For areas where RWH potential is low compared to the demand (e.g. Fig. 7(a)), an extension of the existing reclaimed water pipeline network might be beneficial. As for rainwater collection, our analysis suggests that larger tank sizes help increase food production. This is as expected because more rainwater can be stored in larger tanks to provide continuous irrigation for more food crops when there is no precipitation. Further, RWH systems are designed based on an interrelationship between catchment area, profile of rain variability, and profile of usage. Although larger cistern sizes did result in greater food production, this increase was constrained by the fact that the catchment area (aggregate area of adjacent rooftops to the vacant land) remained fixed for each block group. Future studies could conduct a cost-benefit analysis of different infrastructure enhancement scenarios, such as an expansion of the reclaimed water pipeline network and an increase of rainwater catchment areas and tank sizes. In addition, in this study we focused on vegetables commonly available at grocery stores and supermarkets. These vegetables may not be necessary, efficient or culturally best for all regions. Considering the long history of farming in Tucson, an incorporation of native, drought resilient crops points to another future research direction.

The study has a few limitations. First, as rainwater availability and crop planting vary with seasons, there exists substantial temporal variation in food production. In this study, we examined land and water as the major constraints for urban food production, and labor and coordination efforts during peak seasons were not considered. Also, costs were not addressed in this study. As an example, while reclaimed water rates are much lower than those of municipal potable water, the infrastructure investments can be nontrivial for RWH. Since 2012, Tucson has offered a passive and active RWH Rebate Program at a $2000 maximum rebate for the installation of residential systems (passive systems are capped at $500). Rebate adopters match the rebate amount given for each installation. In some urban areas, soil may be contaminated or too hard (e.g. caliche soil) to grow food crops. In these cases, additional costs will be needed for constructing raised garden beds. In addition to issues related to land availability and water resources, ensuring successful community gardens can be challenging due to lack of participation and leadership within gardens (Rateike, 2015). Future studies could evaluate impacts of these additional constraints on urban food production. Also, this research mainly focused on public vacant land for potential urban food production. The inclusion of other forms of urban agriculture, such as rooftop gardens and backyard gardens, may significantly add to the urban agriculture capacity. For example, in the study area there is a great potential for backyard gardening with a total of 543 acres of land available. An assessment of the urban food production capacity by incorporating these additional forms of urban agriculture remains an important topic for future research.

7. Conclusion

Currently the profit driven food industries identify the most profitable markets for their service provision, leaving many low-income and disadvantaged neighborhoods unserved or underserved by supermarkets and large grocery stores. These neighborhoods have been widely found to be food deserts, where access to healthy food is limited. This study provides an assessment of the capacity of urban food production for addressing food deserts. Integrating the interactions between land, water and nutritional deficits, a spatial optimization model has been developed to allocate limited resources for maximal food production. Three levels of community collaboration are considered in food production and distribution. Three sustainable water sources are incorporated into the model with corresponding limitations: reclaimed water (with limited adjacencies to existing pipelines), active RWH (with limited precipitation, roof catchment areas, and storage capacity), and passive RWH (with limited adjacencies to impervious catchment). Our study in a U.S. medium-sized city highlights that urban areas with restricted water access can substantially enhance their local food production capacity in an ecologically responsible manner using available municipal land.

CRediT authorship contribution statement

Daoqin Tong: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Courtney Crosson:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing - review & editing. **Qing Zhong:** Data curation, Formal analysis, Methodology, Visualization, Writing - review & editing. **Yinan Zhang:** Data curation, Writing - review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2020.103859.

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