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Spatial Optimization of Residential Green Spaces for Water Conservation and Heat Mitigation: A Case of Phoenix Metropolitan Area, Arizona

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Introduction

- Urban green infrastructure offers many environmental, ecological, and social benefits:
  - Improves water quality and reduces surface runoff.
  - Contributes to building thermoregulation (e.g., green roofs and green walls).
  - Provides shade as well as a greater sense of well-being for urban residents.
  - Increases biodiversity and maintains a healthy urban ecosystem.
  - Fixation of CO_2 and remediation of air pollution.
  - Increases urban resilience to climate change and reduces the urban heat island (UHI) effect.






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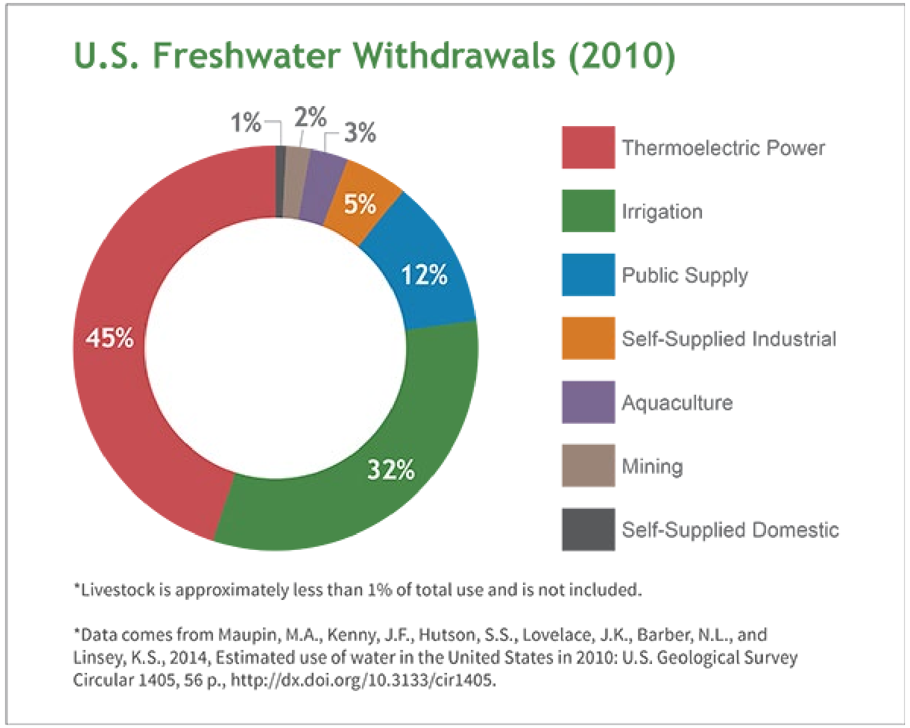
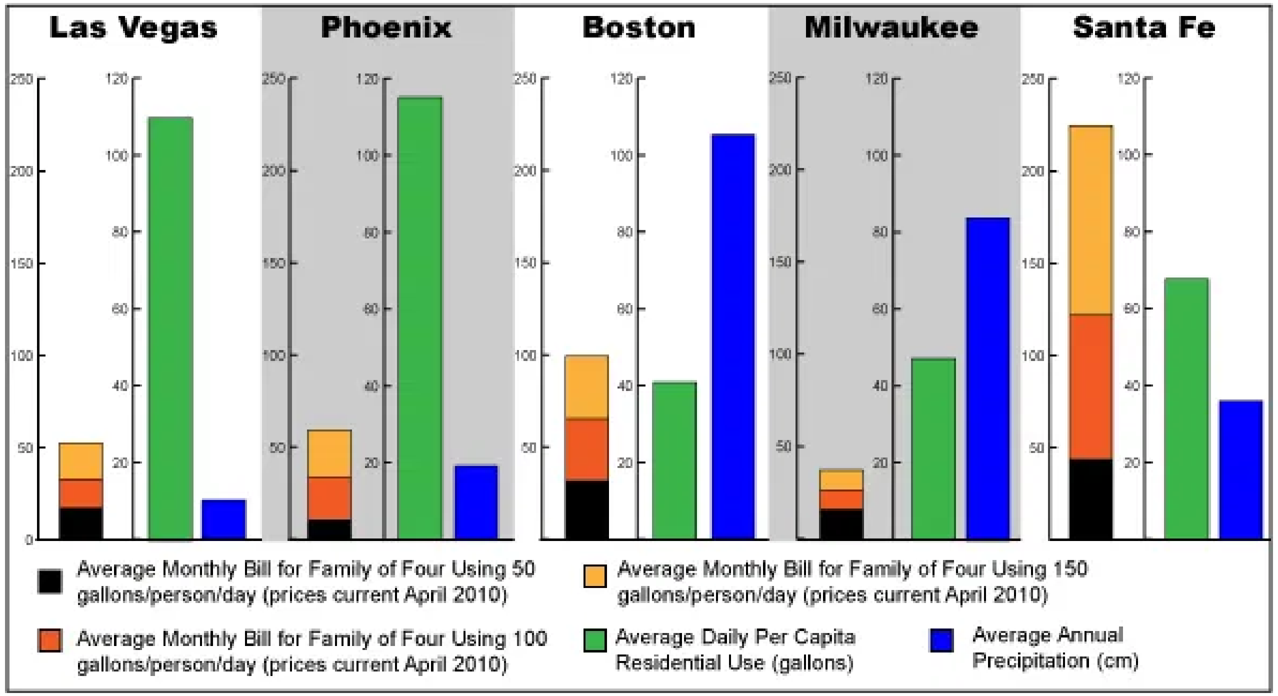
Introduction

- Despite all the benefits, for desert cities, increasing green spaces would lead to higher water use for irrigation. which may put more pressure on water resources and urban sustainability.

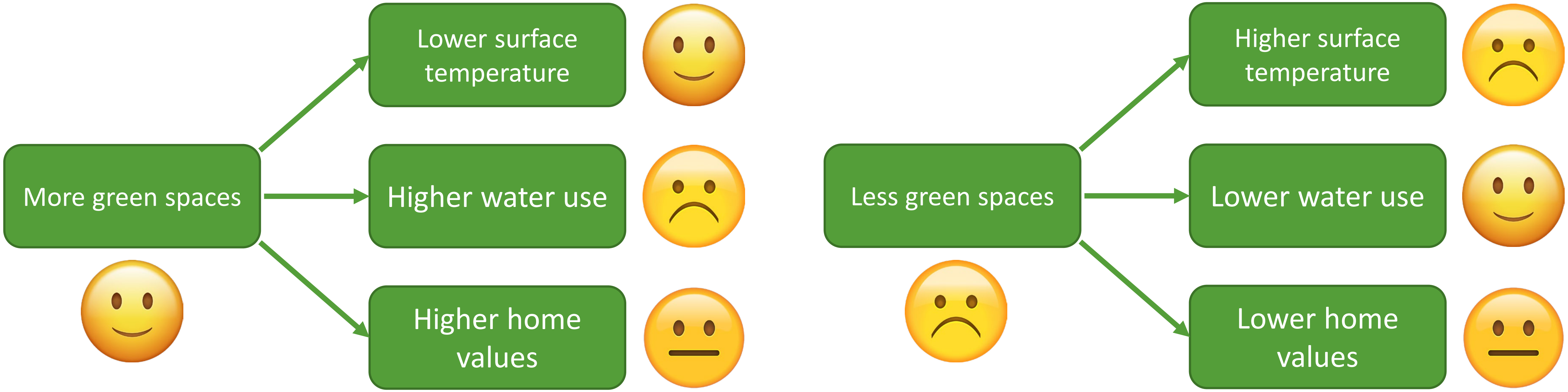




Source: Circle of Blue, 2010

Introduction

- For residential areas in a desert city:



How to optimize the spatial composition of residential green spaces to balance the trade-offs between surface temperature, water use, and property values for a desert city?

Introduction

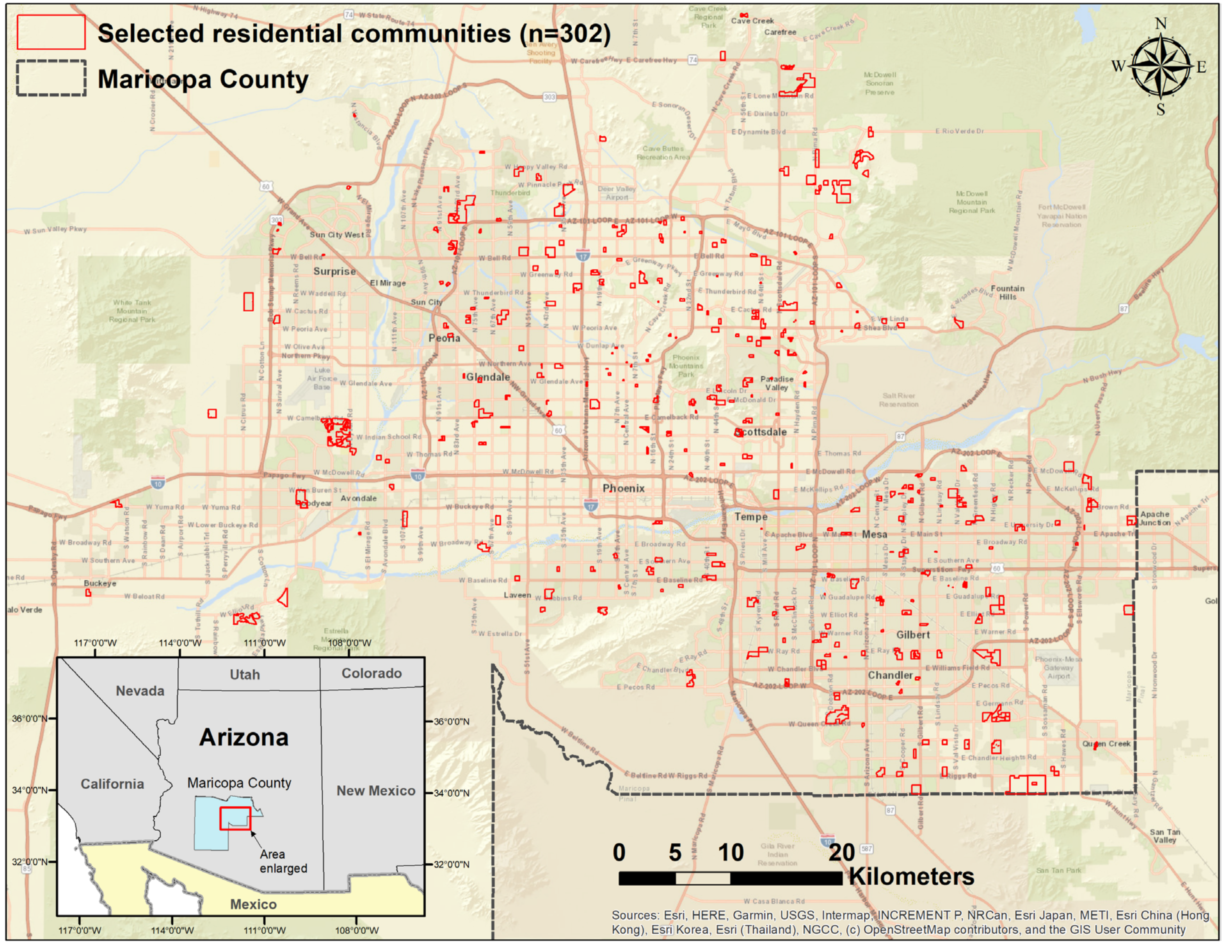
- Research Objectives:

1. To examine the impacts of spatial composition of different vegetation land cover types on land surface temperature (LST), outdoor water use (OWU), and property sales value (PSV) in residential areas of a desert city.

2. To optimize the spatial composition of residential green spaces to achieve a relatively lower LST and OWU and to maintain PSV at the same time.

3. To propose residential landscaping strategies for urban sustainability of desert cities based on the optimization results.

Study Area



Phoenix metropolitan area (PMA), Arizona, USA

- Population (2021):
  - 4.95 million (10th in the U.S.)
- Area:
  - 14,600 mi^2 (5th in the U.S.)
- Gross GDP (2021):
  - $310 billion (14th in the U.S.)

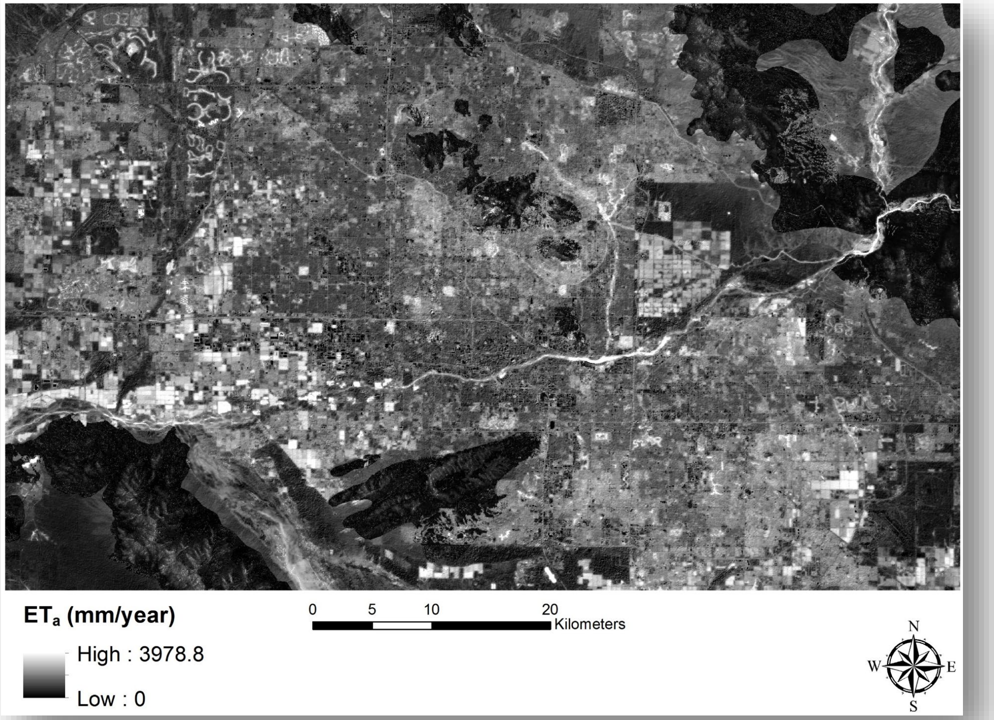
Data and Methods

- LST Data
  - 16 daytime LST images from Landsat 5 TM
  - 7 daytime LST images from Terra ASTER
  - Images were acquired for the summer months (June through September) in 2010.
  - A mean summer LST image was calculated by averaging all the 23 LST images.

Satellite/Sensor	LST Product	Spatial Resolution	Relative Accuracy	#Images Used
Landsat 5 TM	Collection-2 Level-2 LST	120 m (resampled to 30 m)	0.19 Kelvin	16
Terra ASTER	Surface Kinetic Temperature (AST_08)	90 m (resampled to 30 m)	0.3 Kelvin	7

Data and Methods

- OWU Data
  - OWU was estimated using actual evapotranspiration (ET_a) as a proxy (Singh *et al.*, 2014).
  - ET_a was modeled using the METRIC (**M**apping **E**vapo**t**ranspiration at high spatial **R**esolution with **I**nternalized **C**alibration) model (Allen *et al.*, 2007).
    - 22 cloud-free Landsat 5 TM images in 2010
    - Weather data from AZMET weather stations in PMA
    - Annual water use data collected from 49 city parks
  - 365 layers of estimated daily ET_a were created using the METRIC model. Total summer ET_a was then calculated by adding up all the daily ET_a images in the summer months.
  - Total summer ET_a was then used to estimate OWU.



Data and Methods

- PSV Data
  - Property sales records between 2009 and 2011 at parcel level were obtained from the Maricopa County Assessor's Office https://www.maricopa.gov/3942/GIS-Mapping-Applications .
  - We calculated mean PSV (U.S. Dollars in thousands, $k) using all the sales records within each selected residential community.
  - Using three-year data can reduce the variation due to the economic recession in 2008–2009.

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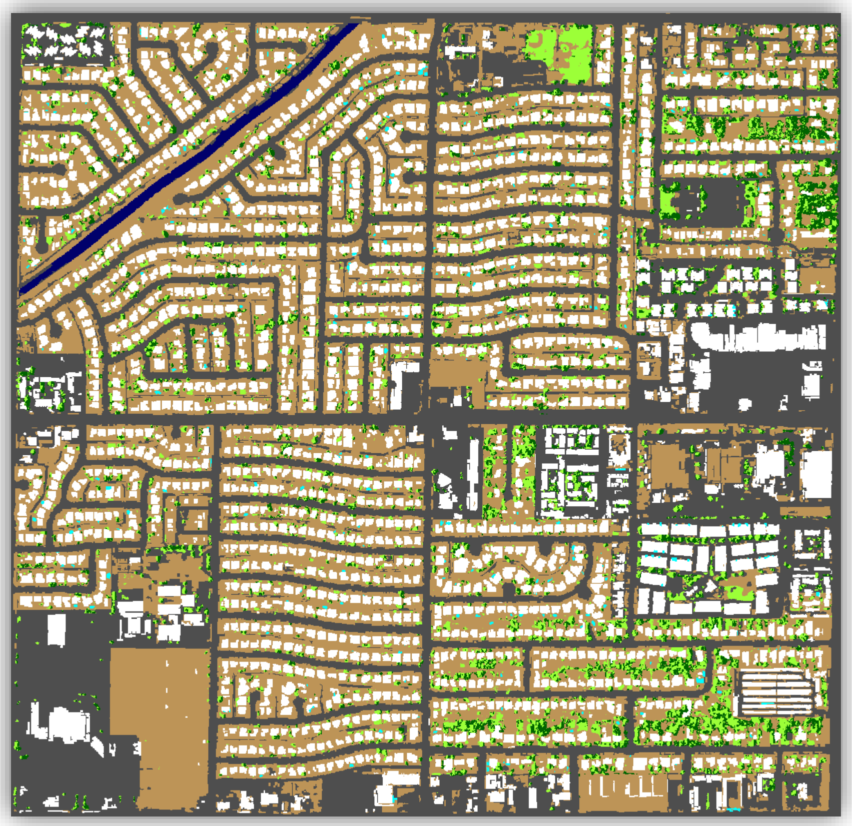
Data and Methods

- Land Cover Data
  - Land cover classification was performed by the Central Arizona – Phoenix Long-Term Ecological Research (CAP-LTER) at Arizona State University using 2010 National Agriculture Imagery Program (NAIP) imagery and an object-based image classification technique.
  - This land cover map has 1-m spatial resolution and 12 classes with an overall accuracy of ~92%.
  - Four classes were used: grass, shrub, trees, and open soils.
    - We calculated grass%, shrub%, tree%, and soil% within each residential community.



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Data and Methods

- OLS Regression

$$y_j = \beta_{oj} + \sum \beta_{ij} x_i + \varepsilon_j$$

where:

i = index of 4 independent variables (grass%, shrub%, tree%, and soil%);

j = index of 3 dependent variables (LST, OWU, and PSV);

x_i = area percentage of vegetation type i;

β_{0j} = intercept term of the regression model for dependent variable j;

β_{ij} = coefficient estimate for land cover type i in relation to dependent variable j; and

ε_j = error term of the regression model for dependent variable j.

Data and Methods

- Optimization
  - Based on the regression results, we formulated the optimization question as an integer programming problem with an objective function to minimize the summation of model-predicted LST and OWU.

$$\boldsymbol{Minimize} \sum (\boldsymbol{y_{LST}} + \boldsymbol{y_{OWU}})$$

  - We then selected top 100 sub-optimal solutions to this objective function that generated the smallest possible summation of LST and OWU, and then searched for the highest predicted PSV values within these 100 solutions.
  - The top 5 best scenarios were finally selected as the optimal solutions.

Results

- Relative ranking of cooling efficiency: **Trees** > **Grass** > **Shrubs** (Soil% is insignificant).
- Relative ranking of water use efficiency: **Soils** > **Trees** > **Grass** (Shrub% is insignificant).
- Relative contribution to PSV: **Grass** > **Shrubs** > **Trees** > **Soils**.

Model (Dependent variable)	**A** (LST[a])				**B** (OWU[b])				**C** (PSV[c])			
R^2	0.616				0.517				0.264			
Adj. R^2	0.598				0.495				0.228			
p	< 0.01				< 0.01				< 0.01			
RMSE[d]	1.626				77.113				429.540			
Independent variable	B[e]	SE[f]	p	β[g]	B	SE	p	β	B	SE	p	β
Grass%	−0.135*	0.042	0.002	−0.242	10.172*	1.997	0.000	0.432	52.638*	13.595	0.000	0.442
Shrub%	−0.118*	0.046	0.012	−0.206	−1.588	2.175	0.467	−0.065	27.657*	12.881	0.035	0.247
Tree%	−0.243*	0.029	0.000	−0.689	3.680*	1.390	0.010	0.247	19.698*	7.926	0.015	0.300
Soil%	−0.009	0.020	0.646	−0.042	−2.114*	0.942	0.027	−0.229	12.297*	5.491	0.028	0.293
Cons.	54.183*	1.121	0.000	–	410.5*	53.139	0.000	–	−615.858	317.402	0.056	–

[a] Land surface temperature
[b] Outdoor water use
[c] Property sales value
[d] Root mean square error
[e] Unstandardized coefficients
[f] Standard error
[g] Standardized coefficients
* Statistically significant at the 0.05 level

Results

- Optimization results suggest that:
  - Grass coverage should be minimized to the lowest.
  - Shrub coverage should be given the largest weight among all the three vegetation types.
- A residential landscape composed of 1-2% grass, 11-13% shrubs, 7-9% trees, and 62-64% soils can lead to the lowest possible LST and OWU, and meanwhile maintain a relatively high PSV.

Optimization results with top 5 scenarios.

Scenario	Grass	Shrub	Tree	Soil	Predicted LST[a] (°C)	Predicted OWU[b] (mm)	Predicted PSV[c] ($k)
a	2%	13%	7%	63%	50.1	331.3	761.6
b	2%	13%	7%	62%	50.1	333.2	749.3
c	2%	11%	8%	64%	50.2	334.4	738.2
d	1%	13%	9%	62%	49.8	334.2	736.0
e	1%	13%	8%	63%	50.0	327.5	728.6

Summary statistics of all the independent and dependent variables. These values were calculated based on all the selected single-family residential communities ($n = 302$).

Variable	Independent variables				Dependent variables		
	Grass %	Shrub %	Tree %	Soil %	LST[a] (°C)	OWU[b] (mm)	PSV[c] ($k)
Min.	0.0	0.0	0.0	7.3	41.5	104.9	32.0
Max.	34.6	17.8	42.7	97.0	55.6	800.0	4700.0
Mean (μ)	8.0	3.2	12.1	38.8	50.3	452.8	341.4
Std. Dev. (σ)	4.8	4.5	8.1	12.8	2.5	123.0	429.2
$\mu + \sigma$	12.8	7.7	20.2	51.6	52.8	575.8	770.6
$\mu + 2\sigma$	17.6	12.1	28.3	64.4	55.3	698.8	1199.8
$\mu - \sigma$	3.15	–	4.06	26.02	47.7	329.7	–
$\mu - 2\sigma$	–	–	–	–	45.2	206.7	–

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Recommendations

- Minimizing grass% but increasing shrubs% could significantly lower OWU but won't increase LST, while PSV maintains relatively high.
- Although trees are the most efficient to lower LST, they consume the highest amount of water.
- Replacing turf grass with desert-adapted shrubs or trees could become a sustainable development practice for residential communities in desert cities to mitigate heat and conserve water.
- We recommend widely adopting a xeric landscape style that mostly include individually watered and low water-use exotic and native plants as a sustainable landscaping strategy.
- **Xeriscape** is a water-efficient landscaping method which can save an average of 55.8 gal/sq. ft. (or 2.27 m^3/m^2) per year resulting from replacing turf grass with xeric landscape (Sovocool *et al.*, 2006).

Summary

- Minimizing the use of turf grass in a desert city is crucial because it is the least water use efficient, although it lowers LST and contributes to PSV.
- Desert-adapted shrubs and trees should be widely adopted because they have higher water use efficiency, can significantly lower LST, and contribute to PSV at the same time.
- A slight tradeoff between the most environmentally efficient landscape type (e.g., xeriscaping) and property value maximization (e.g., grass) can be considered in some existing residential neighborhoods.
- This study provides evidence and a theoretical basis for the environmental benefits of turf removal programs and xeric style landscaping design, which can be used as a guideline by desert cities for a better design of residential landscaping and for urban sustainability.

Thank you!

Questions?

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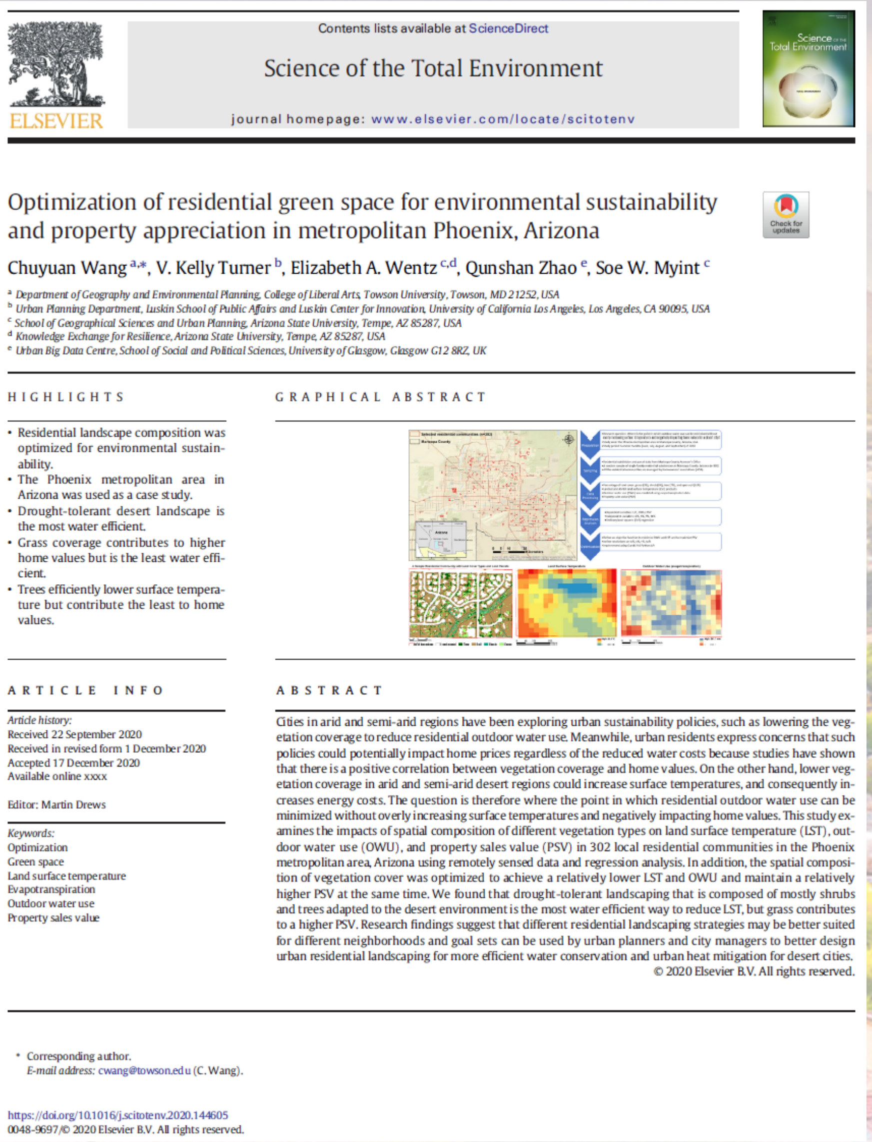

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Optimization of residential green space for environmental sustainability and property appreciation in metropolitan Phoenix, Arizona

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HIGHLIGHTS

- Residential landscape composition was optimized for environmental sustainability.
- The Phoenix metropolitan area in Arizona was used as a case study.
- Drought-tolerant desert landscape is the most water efficient.
- Grass coverage contributes to higher home values but is the least water efficient.
- Trees efficiently lower surface temperature but contribute the least to home values.

GRAPHICAL ABSTRACT

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ABSTRACT

Cities in arid and semi-arid regions have been exploring urban sustainability policies, such as lowering the vegetation coverage to reduce residential outdoor water use. Meanwhile, urban residents express concerns that such policies could potentially impact home prices regardless of the reduced water costs because studies have shown that there is a positive correlation between vegetation coverage and home values. On the other hand, lower vegetation coverage in arid and semi-arid desert regions could increase surface temperatures, and consequently increases energy costs. The question is therefore where the point in which residential outdoor water use can be minimized without overly increasing surface temperatures and negatively impacting home values. This study examines the impacts of spatial composition of different vegetation types on land surface temperature (LST), outdoor water use (OWU), and property sales value (PSV) in 302 local residential communities in the Phoenix metropolitan area, Arizona using remotely sensed data and regression analysis. In addition, the spatial composition of vegetation cover was optimized to achieve a relatively lower LST and OWU and maintain a relatively higher PSV at the same time. We found that drought-tolerant landscaping that is composed of mostly shrubs and trees adapted to the desert environment is the most water efficient way to reduce LST, but grass contributes to a higher PSV. Research findings suggest that different residential landscaping strategies may be better suited for different neighborhoods and goal sets can be used by urban planners and city managers to better design urban residential landscaping for more efficient water conservation and urban heat mitigation for desert cities.

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