LETTER

Shifting landscapes: decoupled urban irrigation and greenness patterns during severe drought

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Abstract

Urban outdoor water conservation and efficiency offer high potential for demand-side management, but irrigation, greenness, and climate interlinks must be better understood to design optimal policies. To identify paired transitions during drought, we matched parcel-level water use data from smart, dedicated irrigation meters with high-spatial resolution, multispectral aerial imagery. We examined changes across 72 non-residential parcels using potable or recycled water for large landscape irrigation over four biennial summers (2010, 2012, 2014, and 2016) that encompassed a historic drought in California. We found that despite little change in irrigation levels during the first few years of the drought, parcel greenness deteriorated. Between summers 2010 and 2014, average parcel greenness decreased $-61\%$ for potable water irrigators and $-56\%$ for recycled water irrigators, providing evidence that vegetation could not reach its vigor from wetter, cooler years as the drought intensified with abnormally high temperatures. Between summers 2014–2016 as drought severity lessened, irrigation rates decreased significantly in line with high drought saliency, but greenness rebounded ubiquitously, on average $+110\%$ for potable water irrigators and $+62\%$ for recycled water irrigators, demonstrating climate-driven vegetation recovery as evaporation and plant evapotranspiration rates decreased. Transitions were similar for customers with both potable and recycled water; vegetation changes were dominated by the overarching climatic regime. As irrigation cannot always overcome drought conditions, which will become more severe under climate change, to maintain vegetation health, utilities and urban planners should consider the tradeoffs between providing green spaces and water scarcity. This includes evaluating the roles of climate-appropriate landscaping and adaptive reallocation of potable and recycled water resources to enhance water security. By addressing emerging themes in urban water management through analysis of data from forthcoming water metering and aerial imagery technologies, this research provides a unique perspective on water use, greenness, and drought linkages.

Introduction

Demand-side management via conservation and efficiency plays a key role in increasing urban water system resiliency (Gleick 2003, Gonzales and Ajami 2017a). In particular, outdoor water use is often recognized as the urban water subsector with the highest capacity for conservation during droughts and beyond (Gober et al 2015, Hogue and Pincetl 2015). Researchers have estimated that 1.9% of land cover in the continental US is turfgrass, which classifies it as the single largest irrigated crop in the country (Milesi et al 2005). As a result of this widespread preference for irrigated landscapes and lawns (Robbins and Birkenholtz 2003), outdoor water use can account for over half of urban water demand, including high levels of...
overwatering (Gregg et al. 2007, Haley et al. 2007, Endter-Wada et al. 2008, Mini et al. 2014, Litvak and Pataki 2016).

Designing optimal outdoor water conservation and efficiency strategies requires not only understanding water use patterns, trends, and behavior, but also how vegetation and vegetative health respond to irrigation changes and climate stress. Irrigation is used to maintain urban landscapes such as lawns and non-native trees, so policies like outdoor watering restrictions and turf conversion programs can transform landscapes and vegetation both temporarily and permanently (Kenney et al. 2004, Mini et al. 2015, Brelsford and Abbott 2017, Breyer et al. 2018). Cultural norms, perceptions, and other social factors influence landscaping practices and outdoor water use, including receptiveness to conservation policies and programs (Nassauer et al. 2009, Zhou et al. 2009, Larson and Brumand 2014, Sisser et al. 2016, Dilling et al. 2019). Simultaneously, climatic conditions alter vegetation health (Kaplan et al. 2014, Chen et al. 2015, Liang et al. 2017). However, limited spatially and temporally detailed data in the water sector has led to uncertainties about distinct relationships between outdoor water conservation and greenness (Hogue and Pincett 2015).

Pairing water use and remote sensing data can be limited by the scales at which water use is reported and landcover imagery is captured. Spatially, most research has been done at aggregated levels. Obtaining account-level water use data is difficult and most remote sensing imagery is taken at pixel sizes greater than the area of a single parcel, prompting researchers to aggregate customers to geographic levels like census tracts and zip codes (Turner and Ibes 2011, Mini et al. 2014, Chen et al. 2015, Breyer et al. 2018) or municipal scales (Zipper et al. 2017). Temporally, water use is recorded monthly or bimonthly (and sometimes only accessible to researchers at annual scales) while remote sensing imagery is captured at time scales ranging from one snapshot in time to weekly or every few years. Additionally, previous studies linking outdoor water use and greenness have mostly been done by approximating the portion of water used indoors versus outdoors from billing data, but these methods can leave uncertainty about actual values (Mini et al. 2014, Romero and Dukes 2016).

Our research aims to develop a more tightly-coupled, parcel-level understanding of how irrigation behavior and vegetation vigor evolve during severe drought through high-resolution data gathering, integration, and analysis. We evaluated water use from dedicated irrigation meters that are also ‘smart meters’, known as advanced metering infrastructure (AMI), which provide more accurate and higher temporal resolution water use measurements and are emerging in the water sector (Boyle et al. 2013, Cominola et al. 2015). We coupled these water use observations with aerial imagery from the National Agricultural Imagery Program (NAIP) where we binarily classified image pixels as photosynthetically active vegetation (green) or not photosynthetically active (other) (California Data Collaborative 2017). We focused specifically on non-residential large landscape properties, which represent a unique and understudied sector and allowed us to compare matched water use and greenness trends by customers with different water types (potable or recycled) subject to different local policy regimes.

Importantly, our study takes place before and during a historic drought that was marked by unusually high temperatures (Lund et al. 2018), providing information about the response of vegetation to hot and dry conditions, which are more likely to occur during future droughts in the face of climate change (Cayan et al. 2010, Diffenbaugh et al. 2015) and can lead to high irrigation evaporation and plant evapotranspiration (St Hilaire et al. 2008). Understanding how landscapes evolve under varying climatic and watering regimes can help utilities optimize conservation strategies and enhance irrigation efficiency in existing and future developments. Additionally, the results of this research can help urban planners better design public and private non-residential green spaces, like the properties evaluated in this study, by offering insights into the tradeoffs between water use and vegetation health under a warming climate.

Methods

Study location and drought setting
We evaluated water use and greenness patterns in a case study of the City of Redwood City (Redwood City), located in the San Francisco Bay Area, California. We analyzed outdoor water use by non-residential large landscape irrigation customers in the service area to address three emerging themes in urban water use. First, these customers have dedicated irrigation meters that eliminate assumptions about how much water is used indoors versus outdoors. In addition, these dedicated meters are also outfitted with AMI technology that measures and reports water use at high temporal resolutions. Finally, within the service area, customers are connected to different water types—some large landscape customers use potable water while others use recycled water, an emerging and increasingly important drought-resilient water supply source.

Customers with different water types are subject to different pricing schemes and policies. Those using potable water are subject to budget-based rates where each customer has a customized monthly water use budget, calculated using dynamic climate variables and their property characteristics, and are charged differentially based on how much they use compared to that budget (City of Redwood City 2015). Recycled water users are not subject to budget-based rates and are charged the same amount for every unit of water (City of Redwood City 2015). Recycled water
produced by Redwood City’s treatment plant meets California’s ‘unrestricted use’ Title 22 standards but is not used for irrigating lawns where children play, such as schools or parks, because of public resistance (Ingram et al 2006).

In line with aerial imagery availability, our analysis takes place during summers 2010, 2012, 2014, and 2016, a period encompassing changing climatic conditions including the 2012–2016 historic California drought (figure 1). The monthly palmer drought severity index (PDSI) for California’s Central Coast Region where Redwood City is located classifies summer 2010 as hydrologically wet, with dry conditions beginning in summer 2012, becoming most severe in summer 2014, and lessening in summer 2016.

The 2012–2016 California drought was one of the most extreme in the state’s history (US Geological Survey; California Water Science Center 2018) and resulted in widespread water supply challenges. These conditions were accompanied by unprecedented state-level political actions, considerable news media coverage, and elevated public awareness, which in turn led to high levels of drought saliency, or societal prominence, and which has been linked to water conservation (Quesnel and Ajami 2017, Gonzales and Ajami 2017b). There are currently no standard metrics for quantifying drought saliency; researchers have used a variety of proxies such as news media coverage or internet search frequency, both which provide insights into peak events and periods of heightened awareness (Quesnel and Ajami 2017, Treuer et al 2017, Gonzales and Ajami 2017b, Roby et al 2018, Kam et al 2019).

Here, we focus on cumulative drought awareness by providing the hydrologic drought saliency index developed by Gonzales and Ajami (2017b). The hydrologic drought saliency index is calculated using the PDSI and takes into account both drought severity and duration (Gonzales and Ajami 2017b). Coming off of a wet period in 2010 and 2011, there was low drought prominence in summer 2012, with saliency starting in 2013, building in 2014 coinciding with California’s Governor’s declaration of drought state of emergency, increasing in 2015 in line with statewide mandatory water use restrictions, and growing into 2016 until the wet winter of 2016–2017.

Redwood City implemented local conservation measures during the drought to achieve savings required by statewide mandates, including those specifically aimed at large landscapers. Following the State Water Resources Control Board outdoor water restriction mandate in July 2014 (California State Water Resources Control Board 2014), Redwood City large landscape irrigation customers using potable water were subject to fines if they exceeded 70% of their water use budgets. This percentage was reduced to 90% budget exceedance in spring 2016 matching the state-led switch from mandatory to voluntary water use reductions through ‘self-certified’ conservation goals. Throughout the drought, recycled water irrigators did not face any conservation programming or watering restrictions due to a higher recycled water supply availability than demand but still conserved in parallel to customers irrigating with potable water due to high drought saliency and awareness (Quesnel and Ajami 2019).
Data

Water use
Daily, customer-level water use observations from AMI were obtained from Redwood City for all large landscape irrigation customers in the service area from 2008 to 2016 which resulted in 1.65 million observations. There are two types of large landscape customers with dedicated irrigation meters in Redwood City: commercial, industrial, and institutional (CII) customers and multi-family residential customers. In this study, we focus on the larger of the two groups, CII customers, which includes lawns in front of commercial properties, ofﬁce parks, hospital and school landscaping, public parks, and other non-residential properties. From 2008 to 2016 there were 499 CII large landscape accounts in the service area resulting in 1.11 million daily observations.

The high-temporal resolution daily data required pre-processing (Figure 2). We permanently removed 1427 negative observations (0.1% of the database) and 6704 observations flagged as leaks (0.6% of the database). The database contained 516 365 zero observations (46.5% of the database); unlike most single-family residential households which use water daily, large landscape irrigation customers might not use water or irrigate every day, thus we retained these zero values as true. We did, however, temporarily remove zero observations during outlier analysis to prevent ﬁltering from being skewed to non-watering days. We removed outliers using Tukey’s Fence method where \( \text{outliers} \geq \text{upper quartile} + 1.5 \times \text{interquartile range} \) based on each customer’s water use distribution (Tukey 1977). This removed 13,684 observations (2.3% of the database without negative numbers, leaks, or zeros). With zeros added back in, the final database contained 1.09 million observations (97.7% of the original database). Ten accounts were removed because they contained only zero observations, and eight accounts were removed when we constrained the database to years 2010–2016, leaving 481 accounts.

Temporally, we examined water use at a weekly scale. Some accounts did not have observations for every single day in our 7 year period either due to reporting errors or removal during outlier analysis. To get average weekly water use for each account, we calculated average daily water use each week and multiplied by 7. Over the entire time period, we calculated aggregated weekly averages across customers with (1) potable and (2) recycled water connections to get two weekly water use time series. We calculated weekly water use deviations from these two time series by finding average water use for each water type for each week number (1–52) and then calculating the difference between that average and water use during each week number during each year. We added locally estimated scatterplot smoothing (loess) lines of best ﬁt to these deviation time series to identify long term trends. Since aerial imagery was taken in late July or August, we consider summer water use as May–August, and we calculated average weekly water use per customer during each summer.

Aerial imagery
We extracted multispectral, aerial remote sensing data from NAIP as one snapshot in time for four summers: 2010, 2012, 2014, 2016. Pixel resolution was 1 m for 2010, 2012, and 2014 and 0.6 m for 2016. The imagery included red, green, blue and near-infrared bands taken in late July or August of corresponding years. Pixels within each parcel were categorized using a

![Figure 2. Data processing and integration flowchart.](image-url)
binary classification method as either photosynthetically active vegetation (green) or other as defined by the California Irrigable Landscape Algorithm (CILA) (California Data Collaborative 2017). In this case, other does not necessarily indicate an impervious surface—a pixel with this classification could also signify dead vegetation that is no longer photosynthetically active. Artificial turf would also be classified as other in our algorithm. The CILA has been evaluated by the California Department of Water Resources and found to have an 89% accuracy rate for error—adjusted landscape estimates (Olofsson et al. 2013). A shapefile was provided by Redwood City which contained the locations of irrigation meters throughout the service area (provided in latitude and longitude coordinates). ArcGIS was then used to geospatially match accounts to parcel polygons identified by Assessor’s Parcel Numbers (APNs). After geocoding constraints, NAIP observations were extracted for 296 parcels linked to 209 large landscape accounts. Additionally, parcel sizes were calculated using ArcGIS.

Data integration
The final step in our data processing was to match the water use and remote sensing observations. In some cases, multiple account meters were associated with one parcel and were aggregated if all accounts on that parcel had the same water type. We excluded from our analysis parcels with multiple connections irrigating with different water types at the same time in order to separate and distinguish between behavior by customers using potable versus recycled water. Conversely, some accounts were associated with multiple parcels, in which case we aggregated all parcel areas for that account. We eliminated parcels with 0% greenness in 2010, our baseline year, in order to have a value for comparison.

Accounts in Redwood City are continually opening and closing. We accounted for this by only keeping parcels with water use observations during each summer, even if the observations were from different accounts, including a non-zero observation in 2010. With these account matching and filtering constraints, the final analysis was undertaken for 72 parcels—49 with potable water connections and 23 with recycled water connections, which represented 106 accounts total. The distribution of 2010–2016 weekly water use observations for the final subset of 106 accounts was not significantly different than the distribution of 2010–2016 weekly water use observations for the preprocessed database with 481 accounts (Kolmogorov–Smirnov test, $p < 0.001$). The 72 parcels were spatially distributed throughout the service area (figure 3).

Comparative analyses
We examined 2010–2016 average weekly water use and water use deviations from average in the context of precipitation and temperature, temperature anomalies from 30-year monthly averages, policy events, and drought saliency to better understand changes in water use throughout the service area for customers with potable and recycled water. Using the results of our remote sensing analysis, we analyzed changes in parcel greenness during our four biennial summers of interest. We compared summer-to-summer changes in parcel greenness and customer-level average summer weekly water use distributions. Finally, we evaluated coupled water use and greenness transitions between biennial summers to evaluate how the two changed together or divergently. We calculated average irrigation efficiencies (average weekly water use per green area) each summer, demonstrating how much water was needed to maintain green urban vegetation during different climatic conditions.

Results
With higher temperatures and little to no precipitation during the summers (figure 4(a)), customers using potable and recycled water followed seasonal irrigation patterns (figure 4(c)). Shifting water use trends and patterns shadowed policy regimes and drought saliency. Visually examining the two average weekly water use time series (figure 4(c)) shows that potable customers used less water in summers 2015 and 2016 than previous summers, a trend seen across the state and matching conservation policies for potable users and high drought saliency. Recycled water customers also conserved in summers 2015 and 2016, although to a lesser extent, despite the absence of conservation-encouraging regulations like those imposed on customers with potable water.

Weekly water use deviations from average show relative water use change points during the 7 year period. In the beginning of the drought in late 2012 through early 2014, potable customers had higher than average weekly water use (figure 4(d)), signaling that irrigators were likely trying to increase their water use to maintain turf during abnormally hot and low precipitation conditions (figures 4(a), (b)) and in the absence of conservation regulations. Then, in August 2014 following the first local conservation regulation for potable irrigators, there was a switch from customers using more than average to using less than average (figure 4(d)). The most dramatic switch for customers using potable water occurred in spring 2015 when California’s governor announced a mandatory urban water conservation regulation, after which customers irrigating with potable water used less than average for the remainder of the time period. This same 2015 switch can be seen in the time series of recycled water use deviations from average, with a general, although not absolute, decrease from May 2015 onwards.

The spring 2015 announcement, however, did not lead to any changes in local policy for large landscape
customers—ininstead, building drought saliency and high public awareness likely prompted irrigators of both water use types to use less water in 2014, 2015, and 2016 than earlier phases of the drought (Quesnel and Ajami 2019). These monotonically decreasing trends, which started in 2013, can be seen in both loess lines of best fit (figure 4(d)). Looking specifically at weekly water use deviations from average during our four summers of interest (figure 4(e)), customers with both water types exhibited above average weekly water use during summers 2010, 2012, and 2014 and below average water use in 2016 compared to the other summers in the 7 year period.

From our remote sensing algorithm, we measured green area (figure 5(a)) and parcel size, which varied dramatically among the 72 parcels in our analysis from 0.1 acres to 35 acres. Because the median size of parcels with potable water connections (1.76 acres) was significantly smaller than those with recycled water connections (5.10 acres) (Wilcoxon Rank Sum Test, p < 0.01), we normalized green area (which changed each summer) by parcel area (which remained constant over time) to get a metric termed ‘greenness’. We compared changes in greenness for each summer of interest for both potable and recycled water customers. By examining greenness transitions in the context of drought conditions (figure 5(c)) and temperature anomalies (figure 4(b)), we found that greenness patterns followed climatic trends.

The distributions of greenness across the 72 parcels in our sample were significantly different between each of the four summers of interest (Wilcoxon Signed Rank Test, all 6 comparisons p < 0.01). A heatmap visually displays these changes by showing parcel greenness where each row represents one parcel, and the parcels are ordered from summer 2010 highest to lowest greenness (figure 5(c)). Overall, parcel greenness was highest in summer 2010 (average greenness = 33%) which was hydrologically wet and cool, decreased in summer 2012 with the beginning of the dry period (average greenness = 21%), was lowest in summer 2014 during severe, hot drought conditions (average greenness = 14%), and rebounded in summer 2016 as drought severity decreased (average greenness = 26%) (figure 5(d)). Parcel greenness was lowest in summer 2014 for 63 out of the 72 parcels (87.5% of the parcels) and was lower in summer 2014 than summer 2016 for every parcel.

We compared customer-level greenness (figure 5(f)) and average weekly water use (figure 5(g)) distributions across each summer for each water type through density plots. Like the aggregated distributions, greenness distributions were significantly different each year for both potable water users (Wilcoxon Signed Rank Test, all 6 comparisons p < 0.01), and recycled water users (Wilcoxon Signed Rank Test, all 6 comparisons p < 0.01). Parcel greenness trended together for both customer types (figure 5(f)) despite differing irrigation policy regimes, with both transitions following climate conditions.

Customer average weekly water use distributions showed a different pattern. For potable customers, distributions were statistically similar for summers 2010, 2012, and 2014 (Wilcoxon Signed Rank Test, all 3 comparisons p > 0.05), with significantly lower use in 2016 than the other 3 summers (Wilcoxon Signed Rank Test, all 3 comparisons p < 0.01). Recycled water users also had similar average weekly water use distributions between 2010, 2012, and 2014 (Wilcoxon Signed Rank Test, all 3 comparisons p > 0.05) and between 2010 and 2016 (Wilcoxon Signed Rank Test, p > 0.05). Recycled water irrigators used significantly less water in 2016.
than in 2012 (Wilcoxon Signed Rank Test, p < 0.01) and 2014 (Wilcoxon Signed Rank Test, p = 0.03).

Examining transitions between the biennial summers highlights the decoupled relationship between irrigation and greenness (figures 6(a), (b)). For customers with potable water, average parcel greenness decreased from 30% in summer 2010 to 18% in summer 2012 (−39% change from 2010) to 12% in summer 2014 (−36% change from 2012, −61% change from 2010). A similar pattern is seen for recycled water customers as average parcel greenness decreased from 39% in summer 2010 to 25% in summer 2012 (−35% change from 2010) to 17% in summer 2014 (−32% change from 2012, −56% change from 2010). Yet during those same summers, as greenness decreased dramatically, average weekly water use changed marginally. Average weekly water use by customers with potable water went from 33.4 CCF/week in summer 2010 to 32.2 CCF/week in summer 2012 (−4% change from 2010) to 34.1 CCF/week in summer 2014 (+6% change from 2012, +2% change from 2010). Recycled water customers used 82.7 CCF/week in summer 2010, 91.1 CCF/week in summer 2012 (+10% change from 2010), and 86.3 CCF/week in summer 2014 (−5% change from 2012, +4% change from 2010). Irrigators could not maintain the vegetation health of their landscapes as the drought progressed.

Figure 4. Climate and water use trends 2010–2016 (a) average monthly temperature and cumulative monthly precipitation (US National Climate Data Center 2016); (b) monthly temperature anomalies from 30 year (1981–2010) averages (US National Climate Data Center 2016); (c) time series of average weekly water use by customers irrigating with potable and recycled water; (d) weekly deviations from average weekly water use with locally estimated scatterplot smoothing (loess) lines of best fit; (e) average summer weekly water use deviations from average with boxplots showing deviations for each week May–August. Water use was reported in hundreds of cubic feet (CCF), a common unit of measurement for water utilities which is equivalent to 748 gallons, and we retained these units throughout our analysis to facilitate communication with Redwood City.
The paired transition from 2014 to 2016 shows a complementary story. Average greenness on parcels irrigated with potable water increased in summer 2016 to 25% (+110% from summer 2014) while average weekly water use decreased dramatically to 18.6 CCF/week (−45% from summer 2014). Similarly, average greenness for recycled water customers rebounded to 28% in summer 2016 (+62% from 2014) and average weekly water use dropped, although not as drastically as for potable users, to 76.7 CCF/week (−11% from 2014). During this transition, decreased water use due to customer conservation did not lead to decreased greenness. Instead, ubiquitous greenness increases across every single parcel can likely be attributed to lessening drought severity, cooler temperatures, winter rainfall, and lower plant evapotranspiration that helped vegetation rebound (table 1).

Because vegetation largely recovered in summer 2016, we can deduce that decreases in greenness during summer 2014 were likely due to temporary changes, like the occurrence of poor vegetation health despite irrigation efforts or customers letting their lawns go brown, instead of permanent changes like turf removal or complete landscape conversion to artificial turf or other non-photosynthetically active landscapes. This hypothesis is confirmed by the fact that greenness changed in the same pattern for recycled and potable customers, who were subject to different pricing and policy schemes and conserved at different rates, but experienced the same climatic conditions within the service area. While greenness did not fully rebound in summer 2016 to summer 2010 levels for 58 of the 72 parcels (81.7% of the parcels), our study confirms findings from previous research that urban vegetation can at least partially survive drought periods and thus urban irrigation can serve as a flexible water resource (Zipper et al. 2017).

Finally, we calculated average water use per vegetated area each summer (figure 6(c)), one of the most relevant ways to measure urban irrigation efficiency (Gage and Cooper 2015). As parcel greenness decreased from summers 2010 to 2012 and 2012 to 2014 but water use did not change substantially, water use per green area increased. In other words,
customers sustained similar irrigation rates, but vegetation vigor could not be maintained, leading to higher irrigation rates per healthy vegetation area and lower irrigation efficiency. Customers with potable water applied on average 0.75 in/week of water in summer 2010, which increased to 1.70 in/week in summer 2012 and 1.97 in/week in summer 2014. While recycled water customers used more water per green area each summer—they are not subject to budget-based rates, faced no conservation programming during the drought, and are encouraged to use water more liberally than their potable counterparts—their irrigation efficiencies followed the same pattern. In summer 2010, average irrigation efficiency for customers with recycled water was 0.87 in/week, and this number increased to 1.48 in/week in summer 2012 and 2.18 in/week in summer 2014.

The transition from summer 2014–2016 with increased greenness but decreased water use led to lower water use per green area. Customers with potable water connections used 0.54 in/week in summer 2016 while recycled water customers used 1.15 in/week. The cooler climate during summer 2016 compared to 2014 resulted in lower plant and lawn evapotranspiration rates and thus higher irrigation efficiency. Additionally, during hot summers, if customers irrigated with traditional sprinkler systems and/or during the heat of the day, high evaporation rates could have impeded irrigation efficiency. Some irrigators may have installed more efficient irrigation systems during the drought, leading them to use less water while still keeping their plants healthy in summer 2016.

Discussion

This research highlights the interlinks between urban outdoor water use, vegetation greenness, and climate. We examined changes in customer-level irrigation and parcel greenness before and during a historic, abnormally hot drought in California. Our study was novel in that we coupled high-resolution data from emerging water metering and remote sensing technologies in our investigation, which allowed us to develop a multi-year, parcel-level study. Data gathering, cleaning, processing, aggregation, and integration efforts were a central part of our study, and those procedures alone can serve as guidance for future researchers working with those types of forthcoming datasets.

We found that despite differing local policy and pricing regimes, potable and recycled water users changed their water use behavior in parallel. Summer to summer changes in parcel greenness also followed similar trends for customers with both water types, but these trends did not match irrigation patterns. Greenness transitions followed climatic conditions as vegetation greenness decreased from summer 2010, which was hydrologically wet, to summer 2012, which signified the beginning of the drought. Parcel greenness was lowest for 87.5% of parcels in summer 2014 under severe, hot drought conditions despite minimal changes in irrigation. Greenness increased from summer 2014 levels across every parcel in summer 2016 as drought conditions lessened, even as water use decreased, which led to more efficient irrigation. These results emphasize that even with continued irrigation, vegetative vigor may not always be maintained.
Table 1. Greenness and irrigation transitions.

| Drought conditions | Summer 2010 | Summer 2012 | Summer 2014 | Summer 2016 |
|--------------------|-------------|-------------|-------------|-------------|
| Drought saliency   | Hydrologically wet | Beginning of drought | Severe, hot drought conditions | Decreasing drought severity |
|                    | No drought  | Low saliency | Increasing saliency             | Peak saliency               |
| Average values for customers irrigating with potable water | Local conservation policies | None | None | Fines for >73% of budget in July/August | Fines for >73% of budget in May; Fines for >90% of budget in June/July/August |
|                   | Weekly water use (CCF/week) | 33.4 | 32.2 | 34.1 | 18.6 |
|                   | Parcel green area (acres) | 1.23 | 0.74 | 0.48 | 0.94 |
|                   | Parcel greenness (% of parcel) | 30.1 | 18.4 | 11.7 | 24.6 |
|                   | Irrigation efficiency (in/week) | 0.75 | 1.20 | 1.97 | 0.54 |
| Average values for customers irrigating with recycled water | Local conservation policies | None | None | None | None |
|                   | Weekly water use (CCF/week) | 82.7 | 91.1 | 86.3 | 76.7 |
|                   | Parcel green area (acres) | 2.61 | 1.70 | 1.09 | 1.84 |
|                   | Parcel greenness (% of parcel) | 39.4 | 25.4 | 17.3 | 27.9 |
|                   | Irrigation efficiency (in/week) | 0.87 | 1.48 | 2.18 | 1.15 |
during droughts as hot, dry weather leads to high evapotranspiration rates, vegetative health deterioration, and browning. Rebounding greenness in 2016 also indicated that landscaping changes were likely temporary instead of permanent and that vegetation can at least partly survive drought conditions.

These connections bring up important decision-making challenges when simultaneously considering water scarcity and urban landscaping. In our 72-parcel sample, average green area for large landscape customers irrigating with potable water ranged from 0.48 acres in summer 2014 to 1.23 acres in summer 2010 while average parcel green area ranged from 1.09 acres in summer 2014 to 2.6 acres in summer 2010 for customers irrigating with recycled water. These large landscape areas require ample water to maintain vegetative health, but simultaneously, lawns provide important ecosystem services (Monteiro 2017), and public parks, like some of the properties examined in this study, can substitute for individual landscaping and irrigation on private properties (Halper et al. 2015). Considering these types of tradeoffs is important for water utilities and city planners designing and planning urban spaces for increasing urban populations under future intensified drought scenarios.

Irrigating with recycled water is one step towards more sustainable water resources management and may allow for more water to be applied to landscapes during drought if recycled water supply availability exceeds demands. However, if lawn greenness cannot be maintained during hot and severe droughts even with increased irrigation rates and higher irrigation efficiencies, even using recycled water may not be the best solution. If recycled water for irrigation is curtailed during water supply shortages, having flexible, decentralized infrastructure could allow that water to be reallocated to other uses. Planners should also consider drought-resilient and climate-appropriate landscaping. For example, trees can provide shade and serve as water-saving measures by decreasing lawn evapotranspiration (Litvak et al. 2014). And, as vegetation can at least partly bounce back after droughts, watering restrictions that prevent futile watering efforts should be considered, especially for landscapes irrigated with scarce potable supplies.

While specific to our analysis, the conditions of our study (i.e. severe droughts, elevated drought saliency, conservation measures, etc.) are not unique and thus the results of our research have widespread implications and lessons beyond our particular area of interest. One important outcome is that this study highlights the need for continually updated high spatial and temporal resolution data that can capture land cover changes. For example, one limitation of our study is the absence of aerial imagery for summer 2015, the peak of severe droughts conditions but also water conservation for large landscape irrigators in Redwood City and across California. There are, however, promising new remote sensing technologies like drones and smallsats that daily image all of the Earth (i.e. Planet.com) and provide extensions to this work, including improving the temporal levels of analysis. These findings also warrant the discussion of smart irrigation systems, which can be connected to AMI as part of a smart grid for water. While these automated technologies have high water savings potential, it is important to adjust settings during drought. If irrigation cannot overcome high evapotranspiration rates, low soil moisture and precipitation deficits, over-irrigating during drought could result in waste.

Landscapes are frequently changing in response to climate and policy conditions, and it is important to understand irrigation and vegetation dynamics for future effective water resources management. Rethinking our urban landscapes to account for climate change will become increasingly important: How can we provide green spaces while taking into account water scarcity challenges?

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