How Smart Are 'Water Smart Landscapes'?*

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1 ABSTRACT

Understanding the effectiveness of alternative approaches to water conservation is imperative for ensuring the security and reliability of water services for urban residents. We analyze data from one of the longest-running "cash for grass" policies – the Southern Nevada Water Authority's Water Smart Landscapes program – where homeowners are paid to replace grass with desert landscaping. We use a sixteen year long panel dataset of monthly water consumption records for 300,000 households in Las Vegas, Nevada. Utilizing an event study and a panel difference-in-differences approach, we estimate the average water savings per square meter of turf removed. We find that participation in this program reduced the average treated household's consumption by 24 percent. We find no evidence that water savings degrade as the landscape ages. Depending on the assumed time horizon of benefits from turf removal, we find that the WSL program cost the water authority about \$1.62 per thousand gallons of water saved, which compares favorably to alternative means of water conservation or supply augmentation.

2 INTRODUCTION

Policymakers in many municipalities are increasingly faced with the harsh reality of water scarcity. Drought declarations have become commonplace, with the 2014 Drought State of Emergency in California serving as but one high-profile example. This scarcity has been primarily driven by a combination of reduced rainfall and increased demand due to rapid population growth in arid regions such as the U.S. Southwest. Gaps between water supply and demand were historically addressed by augmenting supply through large scale water infrastructure projects, but now these projects are largely regarded as excessively costly. As a result, water utilities increasingly focus on encouraging water conservation among their customers. Economists have frequently advocated raising water delivery prices as a way to allocate the burden of water rationing efficiently across users while encouraging customers to direct their water conservation efforts toward low-valued uses first. However, raising prices, particularly of sufficient magnitude to cause a conservation effect, can create undesirable distributional consequences and may be politically unpopular (Wichman, Taylor, & von Haefen, 2016). As a result, water utilities often adopt a range of non-price policies such as watering restrictions, marketing campaigns, norm-based messaging, and subsidies for modifications to indoor and outdoor water infrastructure (Olmstead & Stavins, 2009; Brent, Cook, & Olsen, 2015).

Policies targeting outdoor landscaping are especially popular, and are often justified on the basis that outdoor water use has constituted 60 to 65% of residential demand in arid areas over a long time period (Mayer & DeOreo, 1999; Mayer, 2016). Consumers are often poorly educated about their outdoor water use (Attari, 2014), suggesting that there may be low-hanging fruit for water conservation with even small incentives and changes in customer awareness. California recently devoted millions of dollars to replace turf with drought friendly landscapes (Goldenstein, 2015). While the difference in watering requirements of mesic (i.e. high water use, often with sprinkler or flood irrigation) vs. xeric (i.e. low water use, with individual drip irrigation) landscaping are well established (Mayer, Lander, & Glenn, 2015) and short-run savings have been demonstrated in a few cases (Sovocool, Morgan, & Bennett, 2006; Medina & Gumper, 2004), questions remain unanswered about landscaping subsidy programs. Do these programs produce long-term savings, or do they suffer from the offsetting behaviors of the rebound effect exhibited for energy efficiency investments (Sorrell, Dimitropoulos, & Sommerville, 2009; Gillingham, Kotchen, Rapson, & Wagner, 2013), low-flow plumbing (Campbell, Johnson, & Larson, 2004), and day-of-week watering restrictions (Castledine, Moeltner, Price, & Stoddard, 2014)?[1] Do they conserve water in a cost-effective manner relative to other forms of conservation or supply augmentation?

To address these questions, we analyze data from one of the longest-running "cash for

[1] Reduced effectiveness may also occur from leaks from aging drip irrigation and increased water demands from vegetation due to the micro-climatic effects of widespread xeric landscaping (Klaiber, Abbott, & Smith, 2017; Gober et al., 2012).

grass" policies – the Southern Nevada Water Authority's (SNWA) Water Smart Landscapes program (WSL). This program pays homeowners to replace their lawns with xeric landscapes. Utilizing a panel difference-in-differences (DID) approach, we use sixteen years of monthly water customer billing data provided by the Las Vegas Valley Water District combined with geocoded spatiotemporal data on program enrollment to estimate the average water savings per area of turf removed. To measure the temporal impacts of the program, we estimate water savings separately for four seasons of the year. We exploit the long-running nature of the WSL program and the staggered enrollment of homes over time to investigate the long-run durability of conservation gains. We investigate the private gains to homeowners from WSL due to lower water bills and reduced landscape maintenance and weigh these gains against the unsubsidized cost of landscape transformation under WSL to better understand to what extent the investments under WSL might have occurred without the rebates. Finally, we estimate annualized water savings per dollar of subsidy spent and compare these costs to the costs of other means of conservation or supply augmentation in order to assess WSL's cost-effectiveness.

We find that the savings generated by the WSL program were significant in all four seasons, albeit 20% less overall than previous engineering estimates. The water gains from turf removal were also highly durable – we find no evidence of declines in water savings up to a decade after the initial landscape change. Finally, given reasonable inferences on the additionality of subsidized landscape changes, we find that WSL was a relatively cost-effective means for the SNWA to effectively augment its water supply in the face of severe water scarcity.

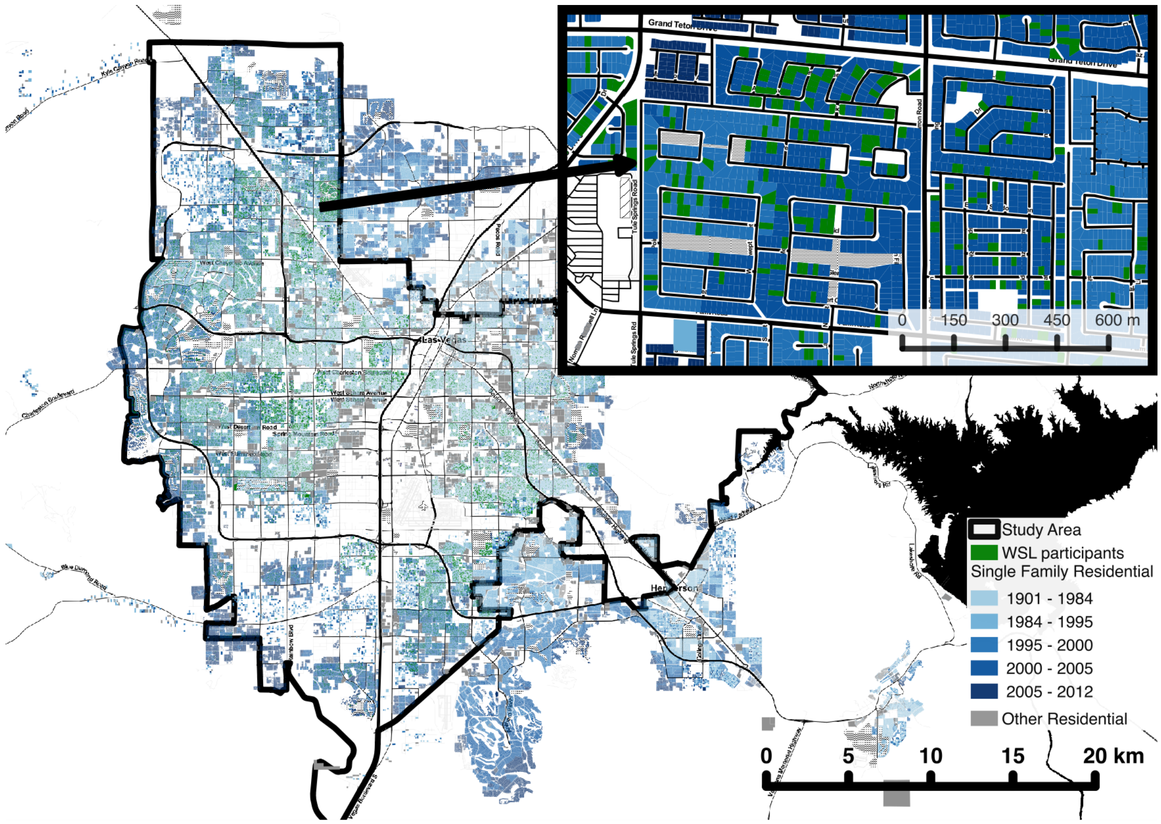

Figure 1: Residential Parcels in the Las Vegas metro area. The study area consists of the urbanized parts of the Las Vegas Valley Water District service area. Single-family residential parcels are colored by the year in which they were constructed. WSL participating homes are colored in green.

3 BACKGROUND

3.1 Las Vegas Water Policy

Las Vegas, located within Clark County Nevada, has long been at the forefront of U.S. "Sun Belt" development, with its MSA growing from approximately 850,000 residents in 1990 to nearly 2 million in 2010. Most of this growth occurred outside of the historical core of the city, with residential land area more than doubling (Brelsford & Abbott, 2017). Over 90% of Clark County's water supply comes from Lake Mead on the Colorado River (SNWA, 2009). This dependence on a river whose waters are fully allocated and in a multi-decadal drought (Castle et al., 2014), combined with Nevada's status as a junior rights-holder under the Colorado River Compact, have heavily shaped the development of Las Vegas' water policy. The Southern Nevada Water Authority (SNWA) was created in 1991 as a water "super agency" comprising five water districts, including the Las Vegas Valley Water District (LVVWD) (which serves approximately three-quarters of Clark County, including all unincorporated areas and the city of Las Vegas) and two sanitation districts (Harrison, 2014). The SNWA was designed to cooperatively manage water allocations across its members as well as to coordinate supply augmentation and demand management efforts. It also manages water conservation programs and provides strategic planning to the whole metro region. LVVWD and the other regional water agencies still manage the day-to-day infrastructure, operations, and billing within their service areas.

Starting in the late 1990s, Las Vegas began a number of initiatives aimed at curbing water use (Brelsford & Abbott, 2017). These efforts accelerated with the declaration of a severe drought in the early 2000's. In this period, managers outlined a broad range of incentives, legislative, and educational strategies aimed at curbing water use – particularly outdoor water use (SNWA, 2009, 2014; Jensen & Rockey, 2003). Incentive programs to conserve water included coupons for up to \$200 off a pool cover, up to \$40 off an irrigation clock, and \$25 off a rain sensor. However, the centerpiece of the changes in the incentive programs was a substantial increase in the scope of the WSL program. Las Vegas also instituted landscaping and building code changes that changed the water intensity of new development. These include measures constraining the use of turf in new construction, limits on pools and water features, and strict standards on plumbing fixtures and methods in order to reduce leaks and encourage the use of low flow fixtures. A number of measures were also passed which restricted watering by time of day and day of week and allow streamlined enforcement of provisions against water waste. Finally, the SNWA initiated multiple informational campaigns on drought awareness and water conservation targeting both commercial and residential sectors, including a series of award-winning TV commercials (SNWA, 2009, 2014; Shine, 2013).

While water policy in Las Vegas has generally leaned toward non-price instruments, the LVVWD did implement a number of increases in prices and changes of price structure since the early 2000s. In September 2003, in conjunction with a new drought management plan, LVVWD implemented the first water price increase since 1996, an increase of 26% for the average consumer. The marginal (nominal) price for residential water above 20,000 gallons increased from \$1.92 to \$3.02 per 1,000 gallons (kgal), while the service charge and price for a household's first 5,000 gallons remained unchanged. In 2007, there was another upward adjustment in prices. Along with a nominal increase in the fixed service charge, the block structure was steepened slightly. The price for the first step increased by \$0.05/kgal, while the price for the highest step increased by \$0.46/kgal – with the result that the average bill increased by approximately 8% for a typical customer.

Las Vegas' entire economy was heavily affected by the 2008 recession. Housing prices fell precipitously to their 1995 levels – only regaining their pre-recession levels in 2018 (U.S. Federal Housing Finance Agency, 2018). New housing starts collapsed (Federal Reserve Bank of St. Louis, 2018) and vacancies rose as foreclosure rates reached some of the highest levels in the nation, with 32,000 in 2009 alone (Hogan, 2016). A substantial share of SNWA's pre-2008 budget came from connection charges: a one-time fee of several hundred dollars paid by the builder of a new property to tie into city water. Therefore, when the housing market crashed, SNWA needed alternative revenue sources to fund its operations, including its conservation programs. As a result, water prices were increased once again. The price for the first block increased by \$0.06/kgal, while the price for the highest block increased by \$1.10/kgal. The service charge was also increased by \$2, yielding a 17% increase in the average water bill. In January 2010 and again in January 2011, the service charge was increased by \$2 without changing the marginal prices. The 2008, 2010 and 2011 rate changes were all aimed at addressing concerns about budget shortfalls in response to the great recession.

Table 1: Summary Statistics for the WSL program by program cohort. The tier 2 threshold is the converted area defining the boundary between tier 1 and tier 2 pricing per additional m^2. The subsidy cap is the maximum rebate SNWA provided per conversion. All dollar values are nominal.

	Cohort 1	Cohort 2	Cohort 3	Cohort 4
Active Date	Jan 03 to Dec 06	2007	Jan - Nov 2008	Nov 2008 +
Rebate Tier 1 ($/$m^2$)	10.76	21.53	16.15	16.15
Tier 2 Threshold (m^2)	-	139	-	465
Rebate Tier 2 ($/$m^2$)	-	10.76	-	10.76
Subsidy Cap ($)	25,000	-	-	300,000
No. Participants	6,318	3,150	3,496	11,163
Avg Lot Area (m^2)	824.3	782.6	822.7	830.8
Avg WSL Area (m^2)	133.9	114.4	120.3	109.3
Pre Treatment Consumption (kgal)				
Spring	16.8	15.4	17.2	17.3
Summer	30.7	28.2	31.2	30.1
Fall	22.2	21.0	22.3	22.4
Winter	10.9	11.1	11.5	11.4
Annual	222.2	207.5	227.2	222.6

3.2 The Water Smart Landscapes Program

SNWA has long focused its conservation efforts on reducing outdoor water use. This is driven in large part by the fact that Las Vegas receives return flow credits for any water that is withdrawn and subsequently returned to Lake Mead. As a result, most water used indoors does not count against SNWA's allocation since it is ultimately treated and returned to the reservoir. Since a substantial portion of outdoor water use cannot be recaptured, reductions in outdoor water use provide a much larger increase in effective supply than an equivalent amount of indoor conservation. Perhaps the best known of SNWA's efforts at curbing outdoor water use is the Water Smart Landscapes program.

SNWA instituted WSL in 1996 as a small pilot program, and expanded it to all customers in 1998. They initially offered bill credits for water conserved, rather than credits in terms of the landscape area converted, but this was difficult to measure and confusing to customers. In July 2000, SNWA began issuing water bill credits to customers who converted their lawns to desert landscaping based upon the size of the converted area, crediting homeowners \$4.30/m^2, with a cap of \$1,000. In a period of mounting concern about drought, in early 2003 SNWA substantially increased the rebate to \$10.76/m^2, increased the subsidy cap to \$25,000, and began issuing checks to participants rather than rebates on subsequent water bills. The process of WSL conversion consisted of an application followed by a site visit verifying that the property met minimum conversion requirements and that the turf was in fact alive and irrigated. Upon approval the owner may replace their lawn with xeric landscaping or artificial turf. Replacing turf with impermeable surfaces is not permitted, and there is a requirement that converted areas must have at least 50% estimated living plant cover at maturity. After a final site visit verifying the extent of the conversion and the suitability of the post-conversion landscape, the owner receives their payment. On average 163 days passed between application and completion, while 4.3% of conversions took more than a year to complete.

Table 1 shows how the program design changed over our sample period – creating four distinct cohorts. Between January 2003 and December 2006 all turf removal was subsidized at a constant rate of \$10.76/m^2 up to a cap of \$25,000 per single property.[2] This subsidy cap was removed during Cohort 2 (January to December 2007), and a two-tiered rebate structure was created whereby the first 139 m^2 of turf removed were subsidized at twice the rate of any additional conversions (which were compensated at the old rate of \$10.76/m^2). In January 2008, this structure was replaced by a flat \$16.15/m^2 rebate with no cap. This design was short-lived, however; in November 2008, a tiered structure was re-introduced, with the first 465 m^2 earning the \$16.15/m^2 rebate and with additional conversions receiving \$10.76/m^2, subject to a subsidy cap of \$300,000.

SNWA notes that landscape conversions typically cost about \$15 per m^2 (\$1.40 per ft^2 in 2000 dollars), approximately \$1600 to \$2000 per home depending on the cohort (Sovocool et

[2] Some homeowners chose to convert more landscape than was necessary to earn the maximum rebate allowance. In these cases, both their total rebate, and the as-measured turf conversion area are included in SNWA records.

al., 2006; SNWA, 2014). However, higher-end landscapes may cost substantially more. This suggests that WSL rebates covered approximately 2/3 the out-of-pocket cost of conversion prior to 2007 and most if not all of the costs thereafter.

Aside from changes in the subsidy rates over time, the other major change in the WSL program related to restrictions on the length of time owners were required to maintain the conversion. At first there was no restriction; however, in February 2003 property owners were required to maintain the converted landscape for 5 years. In March 2004, this restrictive covenant was extended to the shorter of 10 years or until the property was sold. Finally, in June 2009, the program required that the xeric landscape must be maintained in perpetuity, even after the property is sold. Despite these requirements, SNWA staff members have no recollection of any efforts to ensure long-term compliance for converted landscapes.[3]

Altogether, about 29,000 homeowners in single-family residential properties in the study area had converted about 3.4 km^2 of turf by the end of 2015, in comparison to about 143.8 km^2 of total outdoor residential land. Enrollment in the program was rapid between 2003 and 2008 and responded in intuitive ways to changes in subsidy values at the cohort boundaries (Fig. A.1, Fig. A.2). After a rapid decline in enrollments after the 2008 housing crisis, enrollments stabilized around 2003 levels in recent years – driven in part by the fact that much of Las Vegas' newer housing stock has limited eligibility for the WSL program due to building restrictions limiting the use of turf in new construction. WSL adoption was spread unevenly across the study area, with greater uptake in more established neighborhoods closer to the city center (Fig. 1). While there is at least one participating home in each census tract in the study area, measures of spatial autocorrelation, such as Moran's I, show significant spatial clustering of WSL participants, and there is evidence of social contagion effects in adoption across participants in the same neighborhood (Brelsford & De Bacco, 2018).

Table 2 shows some differences in characteristics between WSL-participating homes and the non-participating population as a whole. WSL participating households have substan-

[3]Conference call with SNWA staff members Kent Sovocool, Morgan Mitchell and Toby Bickmore, April 22nd, 2014

tially higher pre-treatment consumption, and typically reside in larger, higher-valued homes, with larger lots and higher rates of pool ownership. Participating homes also tend to be somewhat older. This is likely driven by the fact that the 2004 building code constrained the installation of turf in new homes, making these homes less likely to be eligible. Indeed, we find that homes built before 2004 have about a 1.0% per year probability of participating vs an 0.11% probability per year for homes built after. A latent factor which may contribute to the differences in home characteristics between participants and non-participants is home ownership. When a home is owner-occupied, the benefits and costs of WSL participation all accrue to the same decision maker, whereas incentives might not be so well-aligned for rental properties if market failures, information asymmetries, or differences in landscaping preferences between renters and owners prevent the owner from recovering the full water savings benefits of xeriscaping in the rental price of the home.

Table 2: Average water consumption and structural characteristics for homes with a WSL conversion and homes without. For WSL-participating homes the first rows show consumption for the year prior to the WSL conversion. For All Non-WSL homes, average consumption is shown for 2006; the most common final pre-treatment year.

	WSL Participants	All Non-Participants
Pre Treatment Consumption (kgal)		
Spring	16.9	11.9
Summer	30.2	18.9
Fall	22.1	15.3
Winter	11.3	9.8
Indoor Area (m^2)	199.9	185.9
Lot Area (m^2)	823.3	638.0
Pool Ownership (%)	34.1	22.0
2012 Value ($)	58,009	51,182
Median Vintage	1993	1997
N	24,127	270,029

4 DATA

The base dataset used in this analysis is a sixteen year long panel of individual monthly household water consumption records in urban parts of the Las Vegas Valley Water District (LVVWD) Service Area between January 2000 and December 2015. Datasets from three different sources are merged together: Clark County Tax Assessors rolls for the physical characteristics of the homes, LVVWD records on water consumption, and SNWA records on WSL application and completion dates. The intersection of all three datasets includes records on 299,921 households, 29,892 of which are WSL participants. These households are contained in the study area outlined in black in Fig. 1, which is the urbanized part of the LVVWD service area, containing about 75% of the population of the Las Vegas metro area.

After the spatial merge, an additional 5,765 WSL participating households are excluded for two reasons. First, we excluded 5,620 conversions because they occurred before SNWA began recording WSL application dates in October 2003. Second, we excluded 145 additional participating households because they have multiple WSL conversions recorded. These 5,765 households are also excluded from the list of potential control group homes. This leaves 270,029 potential control group households and 24,127 WSL participating homes in the dataset.

Thus, each complete record includes 1) the home's structural characteristics as defined by the Clark County Assessors office in 2012, such as indoor area, lot size, number of rooms, bathrooms, bedrooms, and plumbing fixtures, as well as the presence or absence of a pool; 2) the application date, completion date, WSL conversion area, and WSL rebate value for any WSL conversion that occurred; and 3) monthly recorded water consumption for each month between January 2000 and December 2015.

This list of parcels is then converted into an unbalanced panel dataset of household by month observations of water consumption and WSL participation status, with 50,730,071 raw observations. Not all houses have consumption records for all months between January 2000 and December 2015; nearly forty percent of the 299,921 homes in the dataset were constructed after 2000, and other homes have had periods of vacancy or missing data for other reasons. There are 175,855 geolocated households with valid consumption data in 2000. This increases to 292,181 households in 2015 due to Las Vegas' significant population growth and new construction over the intervening years.

Consumption records are further checked for consistency and validity in three different ways. First, the first month of non-zero water use recorded for each home is excluded as these months often show unusually high consumption. This excludes 299,921 observations. Second, observations with negative consumption recorded are clearly physically impossible and are excluded. Additionally, the two months prior to a negative record are excluded. This excludes 4,424 observations based on negative values alone (some consecutive), and an additional 6,254 based on the two months prior to a negative observation. We exclude these observations since they are likely indicative of a leak or an overcharge and the subsequent correction process.[4] Finally, as a guard against extreme outliers, an additional 84,219 observations are excluded because the within-panel z score is greater than five.

Although there were sometimes caps on the maximum conversion area that could be rebated or the maximum rebate allowed as described in Table 1, we use both the actual area of landscape that was converted rather than the landscape area that was eligible for rebate, and the actual rebate received. Unless otherwise noted, the nominal dollar values for water bills, water prices, rebate amounts, and any other payments have been deflated to year 2000 dollars.

4.1 Seasonality

Outdoor water use in Las Vegas is heavily influenced by the distinct seasonality of its arid, Sunbelt climate. The dominant features of this climate are a long, hot, and dry "Summer"

[4]LVVWD describes a "leak adjustment process" on their website (https://www.lvvwd.com/customer-service/pay-bill/high-bill.html), in which customers who meet certain criteria and show documentation that they fixed a major leak can have subsequent water bills adjusted to correct for the exceptionally high consumption. The average within-household z score for these leak affected months is 3.4, substantially higher than the dataset as a whole.

season between May to August and a cool, relatively wet "Winter" season from November to February, connected by brief transitional "Spring" and "Fall" regimes in March and April and September and October.[5] Household water consumption patterns are affected by this seasonality, especially for homes with significant water-intensive landscaping. While the water demands of landscaping differ over the year, inconsistent rainfall in the "cool season" combined with automated landscape watering equipment leads many households to water their landscapes year-round to some extent.[6]

To provide insight into the temporal footprint of water savings from WSL, we avoid pooling water consumption across distinct seasons of the year into a single regression in favor of estimating distinct regressions for each of the aforementioned seasons (March-April, May-August, September-October, November-February), where household water use within each season is averaged across all months within that season. This approach has the advantage of allowing for more flexibility of seasonal control than is typically observed in pooled analyses. Since our winter season straddles calendar years, we define the *water year* as running from March to February, where January and February of a given calendar year are included in the previous water year. That is, the winter 2004 season's consumption is composed of average consumption from November and December 2004, and January and February 2005. Fig. 2 shows average consumption by season and by month for our complete dataset.

Our seasonally-averaged panel dataset consists of about 4.5 million observations across 299,921 households, where 388,597 observations are excluded based on the criteria described above. A season's record is excluded for a household if any one of the monthly records within a season contain suspect data.

[5]Between November and February Las Vegas has high temperatures around 15°C and lows around the 5°C with monthly rainfall of 1.3 to 1.8 cm. March and April have typical high temperatures from 20 to 30°C and low temperatures between from 5 and 15°C., with monthly rainfall tapering from about 2 cm to about 0.5 cm. May and June are hot and very dry, with monthly accumulated rainfall less than 0.25 cm, and average high temperatures in the around 35°C. July and August are very hot and a little less dry. Average high temperatures are around 40°C, and monthly accumulated rainfall can be up to 1.3 cm. In September and October, rainfall accumulations are about 0.75 cm per month, and the typical high temperature gradually tapers from about 40 to 25°C.

[6]Another factor that encourages year-round outdoor water use is the practice of overseeding annual rye grass to establish a winter lawn. This can create large water demands in the early months of the cool season.

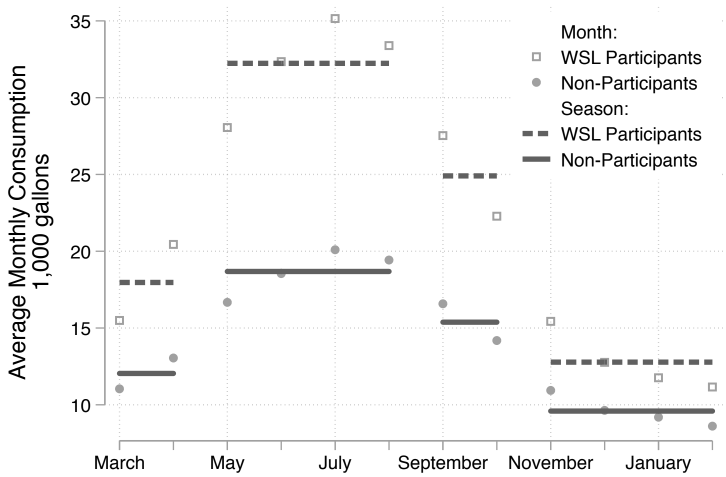

Figure 2: Average Water Consumption by Month and Season, for WSL participating households and non-participating households. Note that WSL participating households consume significantly more water before treatment than non-participating households, especially in the summer. WSL participant data is shown for pre-conversion consumption only.

4.2 Defining Treatment and Control Groups

The "treatment" group in our sample consists of all homes that completed a single WSL landscape conversion between October 2003 and December 2015. Our panel difference-in-differences approach relies upon comparisons of *changes* in the water consumption of WSL participants before and after conversion relative to changes in a "control" group that is not changing their enrollment status at the same time. The validity of this design rests upon the assumption that the treatment and control groups are sufficiently similar that it is plausible that the trend in the control group serves as a good surrogate for the trend in the treatment group in the absence of treatment (Angrist & Pischke, 2009). The validity of this parallel trends assumption is more plausible to the extent that WSL participating households appear representative of typical Las Vegas households. As noted above, this is not the case. In addition to the aforementioned differences in structural characteristics (Table 2), Fig. 2 shows that pre-treatment water consumption for WSL households is significantly higher than for non-participating households, especially in the summer.

In an effort to address this challenge we follow Ferraro and Miranda (2014, 2017) by pre-processing our sample to match each treated household with a non-participating household that has a similar location, infrastructure characteristics, and/or pre-treatment water consumption patterns. Given the lack of agreement in the literature concerning the best matching approach, we consider four different matching strategies, in addition to not matching at all:

1. **Random**: Randomly select an untreated household from the same Census block group as the treated household.

2. **Consumption**: Conditional on an exact match on Census block group, match with replacement using the Mahalanobis distance for all four seasons' average consumption in the calendar year prior to treatment for the treated home.

3. **Assessor**: Conditional on an exact match on Census block group and the binned construction year, match with replacement using the Mahalanobis distance for indoor area and lot size.

4. **Assessor + Gap**: Add the average pre-treatment winter/summer consumption gap to the characteristics described for Assessor matching. This variable proxies for (unmeasured) outdoor vegetation area and water consumption.

Matching relies upon a "selection on observables" justification for any differential trends in water consumption across treatment and control groups over time. It has substantial empirical support in traditional DID designs where the policy treatment occurs at a single point in time (Ferraro & Miranda, 2017). The fact that households enrolled in WSL over different years in our study provides an alternative panel identification approach without a separate control group – using only the sample of homes that eventually participate in WSL. In this case the implicit control group at any time is the group of homes that already have or eventually will select into WSL but are not currently changing treatment status. Satisfying the parallel trends assumption requires that the timing of WSL enrollment is uncorrelated with homes' counterfactual water use trend. This approach slightly relaxes the selection on observables assumptions of the DID approach by implicitly selecting homes into the control group on the basis of both observable and unobservable characteristics that are correlated with WSL participation (including latent adoption of other water-saving technologies or behaviors) and that may influence counterfactual trends in water use. We examine the sensitivity of our estimates to the choice of the control group in the following results.

5 ESTIMATION APPROACH

5.1 Average Treatment Effect

The WSL policy made subsidies available to all homeowners with eligible landscapes. We observe whether homeowners successfully complete a WSL landscape conversion and the amount of turf removed; we also observe the water consumption of both WSL participants and non-participants. However, we do not observe the other ways in which participants or non-participants might be altering their landscapes, homes, or behaviors to change their water use. Given these data, our goal is to estimate the average treatment effect on the treated (ATT) on water use for the "treatment" of voluntarily accepting the WSL subsidies and completing the required landscape conversion, vs. the alternative of not participating in WSL, ATT^{WSL}. We measure this effect in areal terms – gallons saved per m^2 of turf removed under the subsidy.

This measure of effectiveness differs conceptually from an alternative ATT measure that is frequently estimated by engineers: the ATT of a m^2 of turf removal and landscape replacement (i.e. landscape transformation), $ATT^{INSTALL}$. This is the expected difference in water use between a treatment group that is randomly assigned their landscape outcome under WSL vs. a control group that holds their landscape constant (Bennear, Lee, & Taylor, 2013). The treatment in this case is the landscape change itself, not participation in the WSL program. In principle ATT^{WSL} is bounded from above (in absolute terms) by $ATT^{INSTALL}$ since the control group for the latter holds the landscape constant, whereas some individuals in the control group for ATT^{WSL} may have adopted water saving landscaping without subsidization (Bennear et al., 2013). However, in Las Vegas' case, we expect that ATT^{WSL} closely approximates $ATT^{INSTALL}$ because the WSL program was aggressively marketed over much of its history and the subsidies under WSL were substantial, covering a substantial portion of the cost of conversion. These factors suggest that households that did not take advantage of the WSL subsidy should consist primarily of households that chose not to engage in large-scale turf replacement.

5.2 Event Study

To examine the plausibility of the identifying assumptions that underlie our use of the difference-in-differences estimator, we follow Grooms (2015), but using only the sample of WSL treated homes.

$$c_{it} = a + \sum_{k=-15}^{k=11} \beta_k [\tau_{it} = k]_{it} + \gamma_t + \zeta_b + \epsilon_{it} \tag{1}$$

where c_{it} is average monthly water consumption for household i in water year t over the focal season. We define the timing of treatment using the application date to minimize the potential for misleading pre-treatment trends in water use associated with the landscape replacement process. For treated homes, *event year* $\tau_{it} = 0$ begins with the first consumption season in which the homeowner files an application to participate in the WSL program and continues for each of the three subsequent seasons (i.e. the first full year of treatment). k is used as an index over all possible event years. We label households as *in-transition* during the period between WSL program application and completion. We exclude data for treated homes during the transition period unless otherwise noted in order to avoid confounding estimates of the short-run treatment effects of WSL completion with the water use patterns of homes still in transition.

It is necessary to omit one relative time period as the base category that is absorbed into the model intercept. We omit period $\tau_{it} = -1$. The result is that the β_k coefficients are interpreted as changes in seasonal water consumption relative to the year prior to WSL application. The model is estimated using fixed effects ζ_b denominated at the Census block-group b to control for omitted heterogeneity across space and calendar year fixed effects γ_t to control for shared temporal trends.[7] Cluster-robust standard errors are used with clusters defined at the block-group level.

While we ultimately rely upon a more parsimonious panel DID specification for our estimates of WSL's physical and cost- effectiveness, the event study estimates are useful in two important ways. First, the β_k reveal the temporal profile of impacts to the treatment group in the time periods immediately before WSL conversion. This allows us to examine whether the timing and magnitude of estimated impacts is sensible in light of what is known about the WSL program. If the β_k coefficients in the years before homes apply to WSL are negative, this may speak to evidence of omitted time-varying factors for the treatment group that lowered water use in the pre-treatment period. For example, households may pursue WSL after engaging in other water-saving investments or behavioral changes. If the control group does not engage in these same investments, the DID estimate may make WSL appear less effective than it actually was. Second, the event study provides estimates of the longer-run patterns of water savings after WSL conversion, providing a basis for examining the permanence of water savings under the program.

5.3 Baseline Models of WSL Effectiveness

To develop a baseline estimate of the ATT of WSL participation, ATT^{WSL}, we estimate the following regression separately for each of the four seasons, using the matched control groups specified in Section 4.2:

[7] It is not possible to estimate Eq. (1) using parcel fixed effects due to the inability to simultaneously identify relative time fixed effects (i.e. to distinguish them from a linear time trend) in the presence of a full set of absolute time fixed effects using within variation alone (Borusyak & Jaravel, 2016).

$$c_{it} = \zeta_i + \gamma_t + \beta_0 a_{it} + \beta_1 \kappa_{it} + \epsilon_{it} \tag{2}$$

where c_{it} is average monthly water consumption (in gallons) over the focal season in year t, and a_{it} is the WSL conversion area (in m^2) for each home/year combination. ζ_i is a parcel-level fixed effect reflecting time-invariant unobserved heterogeneity in water use across households which may be correlated with an individual's decision to enroll in WSL. κ_{it} is a dummy variable which is equal to 1 if $\tau_{it} < -1$ for WSL-treated homes and 0 otherwise. We consider including this variable since it sets the baseline year of the DID specification to the year prior to WSL – a choice that provides a conservative estimate of water savings in the event of any evidence of anticipatory effects in the event study. The WSL area, a_{it}, estimate is proportionally adjusted in any season in which a WSL conversion occurs mid-season. For example, if a WSL conversion was in place for only two of the four months in a given season, the WSL area in that season is adjusted to half of it's true value. As with the event study, we exclude homes during the period when a WSL conversion is in progress.[8]

We estimate Eq. 2 using the fixed effects (within) estimator. In order to address problems of serial autocorrelation in individual water consumption (Bertrand, Duflo, & Mullainathan, 2004), we report cluster-robust standard errors (Cameron & Miller, 2015), with clusters defined at the household level.

5.4 Economic Analysis

We explore the economic case for the WSL program from both public and private perspectives. From the public perspective, we consider the cost-effectiveness of WSL in terms of the water savings per dollar of subsidy. We focus on cost-effectiveness rather than employing a full-fledged benefit cost analysis due to the difficulties of estimating the social cost of water for Las Vegas. Furthermore, for much of the period of our analysis Las Vegas has been com-

[8]We tested alternative approaches to coping with mid-season conversions and seasons in which a conversion is in progress and found that the estimates were very similar.

pelled by drought-induced scarcity to find immediate means to reduce consumptive water use. Therefore, cost-effectiveness seems appropriate for the decision context.

From a private perspective, we estimate the annualized benefits to residents from WSL in terms of lower water bills and reduced yard maintenance and compare the stream of these benefits to the costs associated with the landscape conversion. We use this comparison to examine the strength of private incentives for turf removal in the absence of subsidization – considering whether WSL primarily rewarded landscape conversions that would have occurred even without the incentive vs. inducing new conversions (i.e., additionality).

5.4.1 Public Cost-effectiveness

Providing a consistent and interpretable estimate of the water savings generated by WSL rebate payments requires defining a projected lifespan for the associated water savings and and a temporally consistent method of comparing the water savings to the rebate payments. WSL rebates are given as an upfront payment for water savings that accrue over a long period of time. In order to resolve these temporal scales, we calculate the annuitized cost of providing the subsidy – effectively the ongoing monthly cost of the debt associated with raising the one-time rebate payment, hereafter referred to as the annuitized subsidy payment, P_{it}.[9]

We must also consider that the water savings from WSL should not be attributed to a parcel indefinitely; eventually many homeowners may have converted to water-saving landscaping without subsidization. Furthermore, in the absence of incentive-based programs like WSL, more draconian emergency policy measures may have been necessary to achieve water conservation goals, inducing otherwise hesitant homeowners to install a xeric landscape. Therefore, the water savings of WSL (and hence the annuitized costs of securing them) should be calculated over the expected term until the landscape would have transitioned to

[9]While SNWA paid WSL rebates out of its regular operating budget, they did issue bonds over our study period and therefore we consider the opportunity cost of budgetary resources to be defined by the cost of capital.

xeric cover in the absence of the subsidy. There is no defensible single estimate of this term, and so we consider durations of 5, 10, 20, and 40 years. To calculate the annuitized cost we utilize the real cost of capital for the SNWA as reflected in the coupon rates of municipal bonds issued by SNWA and Las Vegas in the mid-2000s.[10]

Using the annuitized subsidy payment, we estimate panel DID models analogous to Eq. 2:

$$c_{it} = \zeta_i + \gamma_t + \beta_0 P_{it} + +\beta_1 \kappa_{it} + \epsilon_{it} \tag{3}$$

β_0 is the monthly water savings associated with an additional monthly dollar spent on WSL rebates.

5.4.2 Private Benefits

In order to estimate the private benefits households receive from participating in the WSL program in the form of reduced water bills, we estimate seasonal regressions of the form shown in Eq. 2, where the dependent variable, mean seasonal consumption, is replaced with the average monthly water bill within that season, B_{it}.

$$B_{it} = \zeta_i + \gamma_t + \beta_0 a_{it} + +\beta_1 \kappa_{it} + \epsilon_{it} \tag{4}$$

β_0 estimates the average monthly reduction in the water bill in each season per m^2 of turf removed. By comparing these estimated water savings to the typical average cost per m^2 of removing turf and re-landscaping, we assess whether investing in WSL-style landscapes is economically sensible from a private perspective in the absence of subsidies and for reasonable discount rates.[11]

[10]Nominal rates on municipal bonds issues by SNWA and Las Vegas averaged approximately 5% in the mid-2000s. The annual real cost of capital is 2.36% after adjusting for a mean inflation rate of 2.58%. The equation used to calculate the annuitized subsidy payment is $P_{it} = \frac{r \cdot L_i}{1-(1+r)^{-12n}}$, where r is the monthly real cost of capital, n is the term length (in years), and L_i is the lump sum subsidy payment.

[11]We do not consider whether there is any differential positive or negative amenity value to homeowners from the landscape itself. This could be assessed using hedonic price models; however, this amenity value

6 RESULTS

6.1 Event Study

Fig. 3 shows the β_k coefficients from Eq. 1 for the treatment group in each season. The event study results demonstrate that there is a large and persistent reduction in water use after a household applies for WSL (between $\tau = -1$ and $\tau = 0$). While water consumption is quite stable up until two years before WSL application ($\tau = -2$), we do observe an anticipatory decline of between 10 and 20 percent of the overall decline in consumption at $\tau = -1$ – the last datapoint before the decision to participate in WSL has been registered.

One explanation for this small anticipatory decline in water use could be reductions in outdoor water use in anticipation of turf removal, or selecting into the program after a period of low investment in their turf landscape, when it needs substantial effort to recover. While homeowners could partially reduce the watering of their turf, WSL subsidy eligibility requires that a lawn be alive at the time of its removal, so withholding water from a landscape entirely is not likely. Alternatively, as homeowners approach the decision to convert their landscaping they may also be more likely to make other investments in water efficient infrastructure or to adopt water-conserving behaviors.

If most of the early reductions in water use represent anticipatory reductions in water use ultimately tied to WSL, then the DID estimation strategy presented in Eq. 2 may understate the effects of WSL due to some reductions in water use occurring before the measured treatment date. However, if imminent WSL-adopters are more likely to adopt additional water conservation measures immediately prior to a WSL-subsidized landscape change than the counterpart control group, this may be a source of upward bias in estimated water savings from WSL. We are unable to differentiate these alternative hypotheses from our data, but provide estimates that bound the potential biases below.

must be considered apart from any capitalized water savings (or potential increases in energy bills) from the xeric landscaping. Klaiber et al. (2017) find evidence in Phoenix, AZ that mesic landscapes have a higher value to homeowners than xeric landscapes, even after controlling for neighborhood micro-climate. However, much of the value of green landscape occurs through spillovers to neighboring properties.

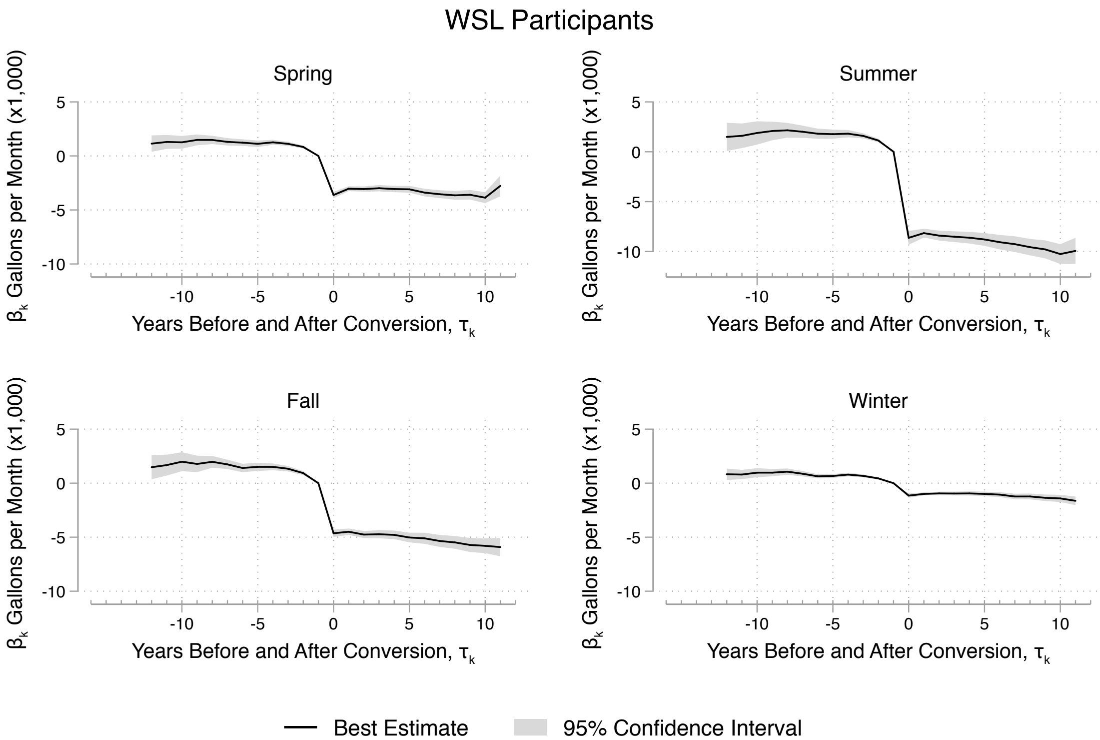

Figure 3: Event Study Results by season for WSL Participants.

Broadly speaking, the magnitude of the estimated WSL-induced reductions in water use across seasons is consistent with expectations from seasonal differences in water consumption and vegetative water needs. In the spring, we observe a drop in consumption of about 3,860 gallons/month, summer 9,380, fall 5,420, and in the winter, a decline of 1,430 gallons/month. Given that the average size of a WSL conversion is 118 m^2, this suggests a reduction in consumption of 33, 79, 46, and 12 gallons/month per converted m^2 in the four seasons. The event studies also suggest that the water savings from WSL were persistent up to a decade after conversion, with small continued downward trends in Summer/Fall and stable reductions in water use in Spring/Winter.

6.2 WSL Effectiveness

In order to evaluate whether any of the matched groups selected in Section 4.2 are a sufficiently good match to the WSL population, we perform t-tests of differences in means, Kolomogorov-Smirnov tests of differences in distributions, and additionally show differences in trends for each of the potential matched control groups. These results are presented in Appendix A.2. We find that despite reasonable correspondence in means between key characteristics for some matching strategies, the Kolmogorov-Smirnov tests easily reject the null hypothesis of equivalent treatment and control distributions in almost all cases. Most concerning, figures A.3-A.7 demonstrate a consistent differential trend in consumption between the two populations, with the control group showing a stronger declining time trend in water use than the treated population, regardless of the match strategy. This differential trend violates the parallel trends assumption underling DID models, and suggests that eq. 2 will likely *underestimate* the water savings from WSL.[12]

This prediction is strongly confirmed by the estimates of the baseline DID model (Eq. 2) in Table 3. Model 1 presents the results estimated with no external control group while the remaining models (2-5) are estimated using the four alternative matched controls described in Section 4.2. The matched control groups all yield lower estimated savings than model 1, with consumption matching providing the lowest estimates of savings. However, the differences are modest, less than 9%, and statistically insignificant.

In an effort to eliminate the biasing effects of the differential trend, we augmented our most closely matched specification, the Assessor+Gap model, by allowing the control group to have its own separate linear trend. The resulting estimates of water savings per m^2 (Appendix Table A.5, Model 6) are both statistically and practically indistinguishable from the estimates without a control group (Model 1). The total difference between these two models is less than 2 gal/m^2 per year, and is never more than 0.2 gal/m^2 in any month. This pattern occurs whenever a time trend is included for the control group regardless of the underlying control group.

[12]Beyond the four matching strategies outlined in Section 4.2, we tried a range of characteristics- and consumption-based matching approaches. These included the addition of pools, home value, number of rooms or bathrooms to the characteristic set and the use of multiple lags of pre-treatment consumption and various combinations of seasonal consumption and the winter/summer consumption gap. None of these approaches helped to mitigate the problem of differential trends.

These results suggest that the use of a separate matched control group, while advocated in recent literature (Ferraro & Miranda, 2017, 2014), contributes little to reliable identification compared to panel DID using only the past and future WSL participants as controls when a differential trend is present.

In order to address the problem of differential trends, we hypothesize that homes which eventually select into the WSL program may be more similar along a variety of unmeasured dimensions than any group matched on observable characteristic. In figure A.8, we show that there are no strong time trends in the distribution of observable home characteristics among WSL-participating homes, suggesting that the quality of matching on observables between WSL-treated homes and the time-varying control group of past and future treated homes is consistent over time (Ferraro & Price, 2013; Ferraro & Miranda, 2017). Additionally, Fig. A.9 shows that the pre-treatment trend in consumption for homes that are treated by WSL in any given year and the trend for the implicit 'control' group in the unmatched regression of past and future WSL participants track one another and show none of the evidence of differential trends noted in the models with a matched control group. Thus, allowing the WSL population which is not currently changing their landscape to serve as a control group for households that are actively changing successfully identifies a control group without systematic differential trends. Given this evidence, and the fact that Model 1 implicitly captures aspects of selection into treatment by comparing homes being treated with homes that have already or will eventually select into WSL, we use Model 1 as our preferred specification for the remainder of the paper.

In order to further demonstrate the robustness of our results to specification changes, Appendix Table A.5 shows three additional variations on the specification used for Model 1. Model 7 includes homes during the transitional period between WSL application and completion, which results in an approximately 9% decline in the estimate of WSL-driven water savings. This demonstrates that excluding data when we are uncertain if a new xeric landscape has been installed or not is important, since failing to do so likely falsely classifies some homes as treated when this is not the case. Model 8 drops the dummy variable κ_{it} in Eq. 2 which was included to address the anticipatory decline observed in the event study, thereby increasing the estimated savings by a relatively modest 3%. Since we cannot distinguish between pre-WSL reductions in water use as a result of anticipatory changes in watering patterns vs. other non-WSL water savings (i.e. new household appliances), we maintain Model 1 as a conservative estimate of WSL's effect. Finally, Model 9 restricts the sample to the 19,050 homes in a fully balanced panel. Again, the results do not meaningfully change. In Appendix A.5, we also demonstrate that there is no evidence of heterogeneity in the areal effect of WSL. The conversion size for any given household does not appear to influence the water saved per meter converted.

Utilizing Model 1, we find that the seasonal pattern of monthly WSL savings is 27, 68, 43, and 12 gal/m^2 in spring, summer, fall and winter, respectively. Cumulative annual savings are 457 gal/m^2 (SE=9.08). Note that while summertime water savings are dominant, even winter savings are substantial at roughly 17% of summer conservation levels. Indeed, over 40% of estimated water savings occur outside of the summer months. This reflects the relatively warm and arid conditions in Las Vegas year-round as well as the common landscaping practice of overseeding Bermuda grass, a heat-tolerant species that goes dormant in the winter, with annual ryegrass in the fall and winter months. The much larger water savings in fall compared to spring (Table 3) may reflect avoiding the multiple daily waterings required to germinate and establish a winter ryegrass lawn.

The long-running nature of the WSL program coupled with our long panel dataset allows us to investigate the durability of the water savings from the program. The event study results in Fig. 3 provide evidence that the water savings from WSL are persistent for up to 10 years after adoption. In Appendix A.6, we develop an extension of the baseline panel DID results allowing both heterogeneous areal treatment effects across WSL cohorts (where cohorts are defined by changes in program design) and an interaction effect between time since WSL adoption and the areal treatment effect validates these findings. The water

Table 3: Estimates of WSL effectiveness. In models 1-5, the model specification is held constant while the control group is varied. All models exclude homes during their transition period and include a dummy variable for $\tau < -1$.

		1	2	3	4	5
WSL Area	Spring	-26.21***	-25.89***	-25.73***	-25.61***	-25.13***
		(1.54)	(1.51)	(1.51)	(1.50)	(1.51)
	Summer	-67.70***	-66.87***	-66.21***	-66.36***	-64.87***
		(4.03)	(3.88)	(3.89)	(3.90)	(3.92)
	Fall	-43.03***	-42.67***	-42.17***	-42.18***	-41.24***
		(2.18)	(2.09)	(2.10)	(2.12)	(2.13)
	Winter	-11.94***	-11.93***	-11.84***	-11.58***	-11.45***
		(0.90)	(0.87)	(0.87)	(0.87)	(0.88)
Match Strategy		None	Random	Consump	Assessor	Assr + Gap
R^2	Spring	0.150	0.098	0.103	0.103	0.107
	Summer	0.348	0.227	0.235	0.238	0.242
	Fall	0.236	0.155	0.163	0.163	0.169
	Winter	0.092	0.064	0.067	0.067	0.070
Households		24,127	48,372	48,218	48,254	48,254
Observations	Spring	355,954	718,291	725,393	726,386	726,759
	Summer	350,419	711,067	718,751	719,120	720,444
	Fall	358,372	722,769	729,739	730,718	731,252
	Winter	357,011	722,680	729,486	730,459	730,939

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

conserving effects of WSL participation show no signs of attenuation over time, indeed there is some evidence that WSL's water conserving effects increase over time.

6.3 Economic Performance

6.3.1 Public Cost-effectiveness

Season-specific estimates of the monthly gallons of water conserved per year-2000 dollar, β_0 from Eq. 3, are shown in Table 4.[13] These estimates measure the average monthly water

[13] Aside from the obvious difference in exogenous variable, the specification is equivalent to that of Model 1 for the physical effectiveness regressions.

Table 4: Estimates of β_0 from Eq. 3: average gallons saved per dollar spent on WSL rebates assuming rebate expenses are annuitized monthly over a period of 5, 10, 20 or 40 years and WSL-induced water savings last the same number of years. The Annual row shows the the year-round average monthly water savings for each monthly dollar spent on rebates, computed as the weighted average of the four seasonal estimates.

		Repayment Period			
		5 years	10 years	20 years	40 years
Payment ($)	Spring	-127.86***	-241.65***	-433.05***	-704.70***
		(7.11)	(13.43)	(24.07)	(39.17)
	Summer	-328.41***	-620.68***	-1,112.26***	-1,809.97***
		(18.52)	(35.00)	(62.72)	(102.06)
	Fall	-207.21***	-391.61***	-701.77***	-1,141.99***
		(10.20)	(19.28)	(34.54)	(56.21)
	Winter	-56.90***	-107.53***	-192.70***	-313.58***
		(3.98)	(7.53)	(13.49)	(21.95)
	Annual	-184.28***	-348.28***	-624.12***	-1,015.63***
		(6.65)	(12.56)	(22.51)	(36.62)
R^2	Spring	0.148	0.148	0.148	0.148
	Summer	0.342	0.342	0.342	0.342
	Fall	0.232	0.232	0.232	0.232
	Winter	0.091	0.091	0.091	0.091
Households		24,127	24,127	24,127	24,127
Observations	Spring	355,954	355,954	355,954	355,954
	Summer	350,419	350,419	350,419	350,419
	Fall	358,372	358,372	358,372	358,372
	Winter	357,011	357,011	357,011	357,011

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

savings procured by the annuitized subsidy payment implied by the lump-sum subsidies to homeowners – the monthly water savings associated with an additional monthly dollar spent on WSL rebates. The estimates in different columns reflect alternative assumptions about the number of years of additional water savings provided by WSL, where the horizon for calculating the annuitized subsidy payment is matched to this interval.

The water savings per dollar vary significantly depending on assumptions about the horizon of the public investment. Under the relatively conservative assumption that WSL secured 10 years of water savings on a typical property, we find that for every dollar spent on the WSL program, about 348 gallons of water are saved at a cost of \$2.87/kgal. In comparison, if WSL secured 20 years of additional water savings, then the water savings increases to 624 gal./\$ (\$1.60/kgal.). These values straddle the retail pricing of water of about \$2.23/kgal.[14]

6.3.2 Private Benefits

The estimated monthly savings on customers' water bills, β_0 from Eq. 4, are shown in Table 5. We find an annual water bill savings of 79¢ per m^2 of turf converted under WSL. Median (average) WSL conversion areas are approximately 90 m^2 (118 m^2), so the median (average) annual reductions to the water bill are about \$72 (\$93). This is about 24% of the annual water bill for the typical WSL participant. Given a typical conversion cost under WSL of \$15/m^2 (Sovocool et al., 2006; SNWA, 2014), the undiscounted repayment period is nineteen years – insufficient without other offsetting benefits or cost reductions to induce landscape conversions in the absence of the subsidy.

Aside from its water consumption, the maintenance of turf is costly in terms of time or money for mowing, fertilization, and winter overseeding. An informal canvas of Las Vegas landscaping companies[15] suggest they would reduce their number of visits by about one half for xeric lawns relative to turf landscapes, resulting in an approximate savings of \$500/year for a typical yard. Considering both maintenance and water savings, we find that a WSL-style landscape conversion passes a private benefit-cost test for private discount rates of less than .30 or .23 for the median and mean size conversions, respectively.[16] These internal rates of return are high relative to market discount rates, perhaps suggesting homeowners would

[14]This is the average price per thousand gallons paid by all consumers in the sample across all years.

[15]In January 2018 we contacted eight full service landscaping maintenance companies in the Las Vegas area, and three were willing to discuss their charges for a hypothetical property with turf vs. xeric landscaping. Two of the three companies quoted a similar percent change in their typical annual charges for turf vs xeric landscaping (\$1,500 vs \$700 from one company, and \$960 vs \$480 from the other) while the third company said that they would charge the same overall rate, but only come half as often.

[16]This calculation follows from first deflating \$500 to its year-2000 value and considering the investment over a 20-year horizon.

invest in transforming landscapes without subsidization. However, the extensive literature on similar investments in energy conservation demonstrates that homeowners often forgo far more attractive investments – routinely declining projects with apparent rates of return of 20 to 100% (Jaffe, Newell, & Stavins, 2004). While there are many candidate explanations for this efficiency gap (Gillingham & Palmer, 2014), most of the same market and information failures, behavioral anomalies, and principal-agent problems arising in energy conservation investments are relevant to water conservation as well – casting doubt on whether the rates of return for xeriscaping are sufficiently high to induce significant investment from homeowners without WSL.

This assessment does not consider any utility lost or gained from the landscape change itself. However, evidence from the similar Phoenix real estate market (Klaiber et al., 2017) shows that homes with green landscapes command a premium of 0.7% relative to xeric yards, where this premium is net of any capitalized water or maintenance savings. This suggests that the decision to transform one's landscaping comes at the cost of reduced wealth of the same order of magnitude as the direct costs of the landscape change, regardless of the preferences of the homeowner for water conservation or landscape features. This further reduces the attractiveness of WSL-style landscape change in the absence of subsidies or other incentives.

Table 5: Estimates of β_0 from Eq. 4: private monthly savings (in year 2000 cents) for each square meter of turf converted to xeric landscaping under the WSL program. The Annual column shows the estimated total annual savings from a weighted sum of the four seasonal estimates.

	Spring	Summer	Fall	Winter	Annual
WSL Area (m^2)	-3.98***	-12.5***	-7.55***	-1.60***	-79.46
	(0.41)	(0.49)	(0.57)	(0.18)	(0.41)
R^2	0.034	0.134	0.070	0.014	
Households	24,127	24,127	24,127	24,127	
Observations	355,954	350,419	358,372	357,011	

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

7 DISCUSSION & CONCLUSIONS

Our DID analysis provides robust evidence that households who accepted WSL subsidies to modify their water-intensive landscaping saw substantial reductions in water use compared to households that did not take advantage of the subsidies in that year. As noted in Section 5.3 there are ample reasons to expect that this estimate is approximately the same as a DID comparison between households taking on WSL-style landscape transformations and those that do not ($ATT^{WSL} \approx ATT^{INSTALL}$). WSL subsidies were substantial and the WSL program was aggressively promoted such that awareness of the program was widespread by the mid-2000s. These factors, combined with the finding in Section 6.3.2 that the landscaping changes mandated under WSL were likely unattractive as private investments to most homeowners, suggests that few households in the control group of eventual adopters of WSL engaged in significant turf removal prior to utilizing the subsidy.

A critical concern for policy is the *additionality* of the WSL subsidy. If all WSL conversions were driven by the policy itself then the entire estimated average water savings of the program can be attributed to the subsidy. While we lack external data to allow us to estimate additionality (Boomhower & Davis, 2014; Bennear et al., 2013), there are solid arguments that suggest it was likely high. First, we've argued in Section 6.3.2 that the private economic case for turf removal was likely unattractive for homeowners without strong aesthetic or environmental preferences for xeric landscaping. Second, unlike many other durable goods such as refrigerators, air conditioners, or toilets (Davis, Fuchs, & Gertler, 2014; Bennear et al., 2013) there is no clear physical depreciation rate or replacement horizon for turf landscaping, and we have every reason to expect that the typical turf is quite long-lived. Therefore, compared to many other more short-lived durable goods, there is little reason to suspect that homeowners would have been been compelled to replace or tear out their turf in the absence of the subsidy.[17]

[17] It is possible that some households that had already planned to undertake a major renovation of their landscaping were induced by the WSL subsidy to install a more water-conserving landscape than they would have otherwise chosen. Our DID estimates may overstate the additionality of WSL for these households;

The estimated water savings from WSL were significant at 457 gallons/m^2 per year – yielding reductions in annual water use of about 24% (53,900 gallons, based on a 118 m^2 average conversion). Nevertheless, these estimates are 24% less than those of Sovocool et al. (2006) of approximately 600 gallons/m^2 annually. There are many potential causes for this gap. The Sovocool et al. study utilizes data from a pilot study that completely predates our sample, during a period when the rebate price was roughly 1/3 of what was offered during our study period. A combination of selection toward water-conscious early adopters and potentially more attentive calibration of irrigation equipment in the pilot period may have lead to optimistic estimates of water savings compared to under full-scale implementation.[18] The Sovocool et al. study also directly measured water application for outdoor irrigation through use of sub-meters. While ideal for estimating changes in outdoor water consumption, this approach misses potential indoor "rebound effects," (Gillingham et al., 2013) (e.g., from taking longer showers, responding less urgently to leaks and running toilets, or running dishwashers or washing machines more often). Our analysis considers the net effect of WSL on household water use, and therefore accounts for these offsetting effects.

Finally, it is possible that WSL indirectly induced complementary water-hungry landscape investments on the part of homeowners. For example, some homeowners may bundle turf removal and xeric landscaping with a new pool or water feature. The availability of WSL subsidies may have induced (or shifted forward) such bundled conversions by lowering the overall cost of the remodel. Unfortunately, the assessor data does not provide longitudinal information on pool and water feature installation, and so we are unable to assess the magnitude of these effects.[19]

The durability of WSL water savings may be attributable to the fact that most xeriscaped

however, we have no data on the potential size of this segment.

[18] Landscape installers and maintenance companies may have incentives to set irrigation timers to water more heavily than necessary in the long run to ensure the establishment and rapid growth of the new landscape.

[19] To the extent that these complementary investments would not have occurred in the absence of WSL (i.e. were "caused" by WSL) then our estimates are appropriate net measures of WSL's net effect on water use.

landscapes are watered using automated timers; once these systems are calibrated (in many cases by hired landscapers) many homeowners may have a tendency to ignore outdoor watering until a major event (e.g., a broken irrigation pipe, an excessively high water bill, or dying plants) occurs. Furthermore, unlike many household appliances, where greater energy or water efficiency may directly induce more intensive use of the appliance over time due to the lower cost of its services (i.e., turning down the thermostat on a more efficient air conditioner), there may be fewer incentives to exploit this intensive margin with respect to the landscape watering since watering more intensively is unlikely to provide additional landscape services. While there may have been rebound effects from WSL, our estimates suggest these developed shortly after the new landscape was installed so that the initial water savings of WSL were maintained in the long run.

The cost-effectiveness of WSL turns upon the assumed horizon of the public investment – the average length of time until water conserving landscaping would have occurred on treated parcels in the absence of the program. This assumption is difficult to substantiate given the lack of a natural replacement horizon for landscaping. However, an investment horizon of at least 20 years seems reasonable given the durability of landscape features. In this case 1000 gallons can be conserved for $1.62 ($0.98 if water savings are accrued over 40 years).

By comparison, the average annual water bill for a Las Vegas residential customer was $293 during the study period, giving an overall average retail price of $2.23/kgal.[20] To the extent that the average retail price approximates the marginal cost of pumping, treating and delivering water from existing supplies (primarily from Lake Mead), it suggests that the cost of reducing water use through WSL is less than the costs of supplying that same amount of water to customers.[21]

Given the scarcity and insecurity of Las Vegas' Colorado River allocation and the drought

[20]The lowest marginal price charged for water, which is likely substantially below the marginal cost of supply, has declined from $0.98 and $0.89 during the study period, while the highest has increased from $2.27 to $3.56 over the same period.

[21]This comparison does not account for any marginal administrative costs associated with WSL.

that strongly shaped its water policy in the 2000s, the marginal cost of augmenting supplies may be the most appropriate comparison to the costs of water savings through WSL. Yet, for the short to medium-term horizon for which WSL was designed, Las Vegas had (and continues to have) few means to augment its supply aside from water conservation. While some western cities have been able to expand their water supplies through purchasing agricultural water rights, Las Vegas has not been able to do so in recent decades due to a combination of limited surface-watered agriculture in southern Nevada, political and infrastructure barriers to transfers within-state, and institutional barriers to interstate transfers. With very limited surface water availability, Las Vegas has looked to regional groundwater sources to augment supply. In 1989, Las Vegas began applying for water permits to access groundwater from more northern parts of the state, especially the Snake Valley Aquifer underlying both Nevada and Utah. A multi-billion dollar pipeline was planned to convey water to Las Vegas. These efforts have faced substantial opposition from ranchers and rural residents of the areas in both Nevada and Utah, and despite nearly three decades of effort and litigation, construction has not begun (Hall & Cavataro, 2013; Gehrke, 2013; Longson, 2011; Jenkins, 2009; Green, 2008). Indeed, a widely-used database of water transfers in the western US from 1987 to 2009 reports *no* purchases of water rights by the City of Las Vegas or the Las Vegas Valley Water District in the period of our study (Donohew & Libecap, 2017). Therefore, while we lack a concrete estimate of the cost of augmenting supply to Las Vegas, it seems clear that options for obtaining water at any price are highly uncertain, and would certainly be substantially larger than the prices charged to retail customers.

Given the prohibitive cost of augmenting supply in the near-term, the relevant economic context for a budget-constrained Las Vegas policy maker was how the publicly borne cost of a quantity of water conservation through WSL compared to other means of saving water.[22] Throughout the 2000's Las Vegas pursued a multi-pronged policy of water conservation.

[22]A full social benefit-cost analysis would need to include the direct costs of landscape conversion borne by homeowners, potentially offset by lower maintenance costs, as a cost of the program. Furthermore, the costs of the subsidy, while relevant to the utility, represents a transfer from the water utility to homeowners and is therefore not a social cost.

In addition to stringent restrictions on turf in new construction and other construction incentives and regulations, programs targeted at existing residents including the enhanced enforcement of outdoor water waste, coupons for pool covers, rain sensors, and other irrigation systems, restrictions on the use of water features, retrofit packages for indoor fixtures in single-family homes, and an award-winning publicity campaign to promote outdoor water conservation (SNWA, 2009, 2014).

In a recent analysis of water policies in Albuquerque, NM Price, Chermak, and Felardo (2014) estimate that cost-effectiveness of utility rebates ranged from \$0.39/kgal for low-flow showerheads, \$1/kgal for dishwashers and washing machines, and over \$8.00/kgal for the replacement of low-flow toilets.[23,24] However, these calculations rely upon a common but strong assumption – that all subsidized appliance replacement is additional. Yet, there are longstanding concerns that many participants in water- and energy-efficiency programs are free riders that would have undertaken the desired behavior in the absence of the subsidy (Joskow & Marron, 1992). Bennear et al. (2013) utilize data from Cary, NC to estimate that over 67 percent of the water savings associated with high-efficiency toilet rebates would have occurred without the rebates, increasing the cost of water savings to \$10.85/kgal if the lifespan of existing toilets was 15 years. Boomhower and Davis (2014) estimate that approximately half of individuals purchasing new energy-efficient refrigerators and appliances under a Mexican subsidy program were non-additional. This suggests that subsidies for replacement of appliances and fixtures may be considerably less cost-effective than commonly presumed.

An alternative approach to pecuniary incentives is to utilize informational campaigns and nudges rooted in pro-social norms to alter household behavior directly. This approach is now

[23]Costs of water savings in this and other papers we report utilize a variety of, often unspecified, assumptions on the use of nominal vs. real prices, discount rates, and the method used to attribute water savings to program costs. We do not attempt to resolve these differences; therefore comparisons should be made cautiously.

[24]They also find that a xeriscape rebate program cost \$4.51/kgal. The greater cost-effectiveness of the Las Vegas program may have been driven in large part by the greater potential year-round water savings from turf removal in Las Vegas relative to Albuquerque.

being mainstreamed through customer engagement programs for utilities such as WaterSmart Software and Opower (Brent et al., 2015). Ferraro and Price (2013) demonstrated that programs that go beyond information provision by comparing individuals' water use to their neighbors' can be highly cost-effective, reducing water use by nearly 5 percent at a cost of \$0.58/kgal. However, the ability of these behavioral interventions to provide sustained water savings remains controversial. Ferraro and Price (2013) found that effects attenuate quickly, yet in a follow-up study Bernedo, Ferraro, and Price (2014) report that effects remain policy-relevant six years later - reducing costs of water conservation to \$0.24/kgal. Allcott and Rogers (2014) suggest that repeated exposure to socially framed information provision on energy use may slow the rate of backsliding , yielding long-run conservation effects that decay relatively slowly. Indeed, while Las Vegas did not engage in targeted behavioral nudges, they did nonetheless utilize mail and television marketing to promote drought awareness and water conservation behaviors. Brelsford and Abbott (2017) provide suggestive evidence that these efforts may have played a significant role in explaining the large reductions in Las Vegas' per-capita water use in the mid-2000s.

Examining the wide range of cost-effectiveness estimates suggests that WSL compares favorably to many rebate programs, yet perhaps less so compared to informational/nudge-based programs. While our estimates suggest that WSL has not fully lived up to the the optimistic water savings and cost-effectiveness calculations of early pilot studies (Sovocool et al., 2006), it nevertheless has a number of attractive characteristics that have made it a vital part of Las Vegas' water policy toolbox. Its effects on individual water conservation have been demonstrably large (approximately 24% on average), while, at its best, norm-based messaging reduces water use by 5%. Reducing *outdoor* water use was especially important given that much of the water used outdoors does not return to Lake Mead and cannot be credited against Las Vegas' allocation of the Colorado River through return flow credits. As a result, WSL provided a cost-effective pathway to permanently augment Las Vegas' water supply through water conservation at a time when the city was beset by a severe drought and when alternative sources of supply were not readily available.

Finally, it is plausible that the WSL incentive program smoothed the way for Clark County's 2004 building code changes which limit the installation of turf in new residential construction. While these institutional linkages are merely suggestive, if this is the case, the WSL program might have indirectly supported large and significant subsequent water savings through the pathway of turf not installed, which is not included in this analysis.

How transferable are these findings to other cities? The physical and economic effectiveness of WSL was undoubtedly enhanced by the fact that Las Vegas' baseline Bermuda/ryegrass turf landscapes were highly water intensive and demanded year-round irrigation. Cities with more temperate climates and seasonal irrigation demands from landscaping may conserve far less water from turf removal and may also require larger subsidies to reach enrollment goals since the private benefits from reduced water bills will be reduced (assuming a similar water pricing regime). Similarly, as many cities have grown, the water intensity of landscapes has often fallen due to both exogenous (i.e. reduced lot sizes as land prices increase) and endogenous (e.g., building code restrictions, home ownership association restrictions) factors. This suggests that landscape subsidy programs modeled after WSL may be far more effective at reversing the entrenched legacies of profligate water use from historical development than addressing water use on newer parcels. Nevertheless, given the accelerating trend both in the US and globally of population growth in arid regions and as many historically temperate population centers are predicted to become warmer, more arid, or more variable in precipitation due to climate change – the experiences of Sunbelt cities like Las Vegas are likely to become more pertinent. Finally, while Las Vegas has relied heavily upon non-price water policies while maintaining relatively low water prices, there is likely untapped potential for complementarity between landscape subsidy programs and modest, politically feasible increases in water prices. Higher water rates broadly encourage cost-effective water conservation, but can also increase uptake of xeric landscaping (Brent, 2018) and may even facilitate social spillovers in adoption rates through information diffusion in peer networks (Bollinger, Burkhardt, & Gillingham, 2018). These feedbacks can lower the subsidy required to reach program enrollment goals – improving overall economic efficiency while also providing a potential source of revenues to partially fund the subsidy program. Viewed in this light, subsidies for turf removal can be a valuable part of the water policy portfolio for budget-constrained utilities looking to effectively enhance their existing supply by building future water efficiency into the urban landscape.

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A Appendix

A.1 WSL program participation

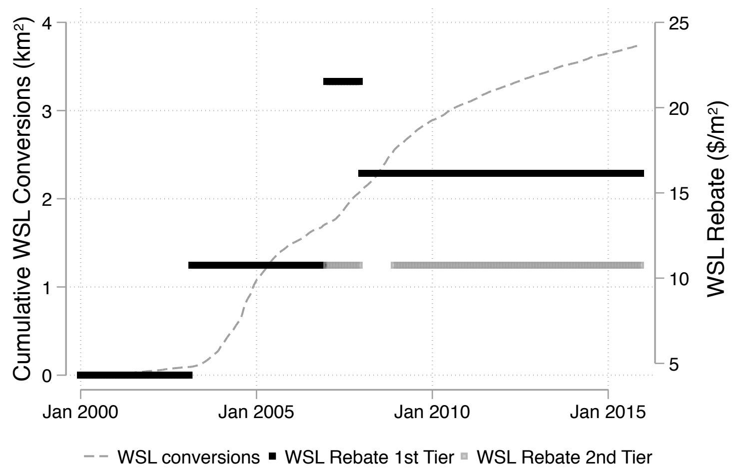

Figure A.1: Cumulative WSL conversion area in acres and the nominal WSL rebate at that time. We group WSL participants into four cohort groups based on the nominal rebate price they received.

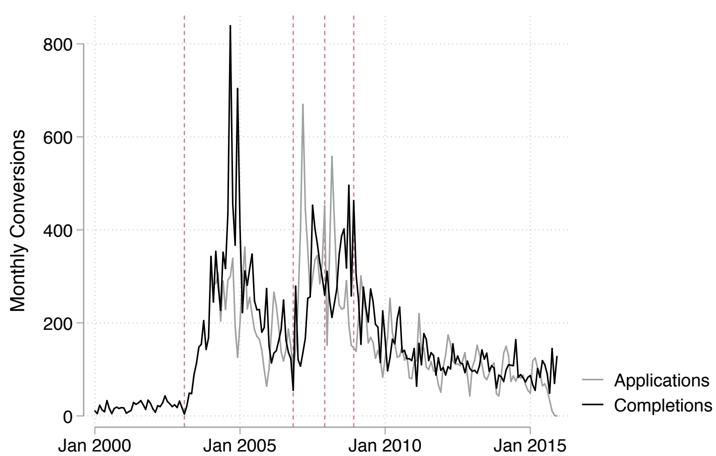

Figure A.2: Monthly WSL conversion applications and completions. Vertical lines denote changes in the rebate price structure, labeled in this analysis through the different cohorts.

A.2 Matching Tests

A.2.1 T-Statistics

In all models, differences are Treatment - Control. The All Data column compares WSL participants to all non-WSL homes in the data, using 2006 consumption. Otherwise, the models compare characteristics and consumption in the year before WSL treatment ($\tau = -1$). The "Pre-treatment Consumption" models in Table A.2 compare average consumption for all pre-treatment years.

Table A.1: T-statistics of differences in means between treatment and control groups. All Data compares WSL participants to all non-WSL homes in the data, using 2006 consumption. Rand is a random match within block groups. Assr includes exact match on block group and binned match on construction year[a] with Mahalanobis distance matching on indoor area and lot size. Assr+Gap adds the pretreatment winter/summer gap in consumption to the matched covariates in Assr. Cons uses 1 year lags of consumption before the treatment date across all four seasons with Mahalanobis distance matching.

	All Data	Rand	Assr	Assr + Gap	Cons
Construction Year	-1.266***	-0.376**	-0.0185	-0.00714	-0.111
	(-7.19)	(-3.28)	(-0.16)	(-0.06)	(-0.98)
Indoor Area (m^2)	16.09***	5.066***	0.593	0.666	-3.677***
	(27.99)	(6.46)	(0.79)	(0.89)	(-4.72)
Lot Area (m^2)	172.8***	58.21***	10.29*	16.65***	4.656
	(35.20)	(9.10)	(2.03)	(3.33)	(0.85)
Pool	0.107***	0.0348***	-0.00208	-0.0190***	-0.0171***
	(33.98)	(8.15)	(-0.48)	(-4.34)	(-3.93)
2012 Value ($)	7918.6***	2274.0**	219.6	158.7	-1084.9*
	(12.12)	(3.02)	(0.49)	(0.36)	(-2.43)
Spring Consumption (gal)	4989.9***	3024.0***	2200.3***	370.6**	262.1*
	(48.93)	(19.78)	(18.27)	(2.95)	(2.19)
Summer Consumption (gal)	11264.0***	7627.4***	5514.3***	1092.8***	1205.3***
	(58.08)	(29.14)	(25.15)	(5.02)	(5.47)
Fall Consumption (gal)	6827.0***	4299.7***	2836.5***	102.9	46.29
	(47.36)	(21.31)	(16.98)	(0.62)	(0.27)
Winter Consumption (gal)	1447.1***	740.8***	304.5***	-333.8***	-607.3***
	(20.47)	(5.66)	(3.72)	(-4.12)	(-7.08)
Annual Consumption (gal)	70876.1***	46351.0***	32739.7***	4650.3**	4220.4**
	(53.24)	(24.52)	(21.55)	(3.08)	(2.76)
Households	270,054	47,866	47,008	47,606	48,128

t statistics in parentheses; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

[a]semi-decadal bins are used for homes built before 2000, annual bins are used thereafter

Table A.2: T-statistics of differences in mean pre-treatment consumption between treatment and control groups for all years. The All Data match (which does not impute a τ value for control homes) includes pretreatment consumption for treated homes and pre-2006 consumption for control homes because this is the most typical treatment year for this dataset.

	All Data	Rand	Assr	Assr + Gap	Cons
Spring (gal)	5,017.9***	3,466.9***	2,436.3***	340.1***	742.3***
	(110.90)	(58.73)	(46.98)	(6.56)	(14.22)
Summer (gal)	11,536.8***	8,213.2***	6,057.8***	958.1***	2,196.9***
	(143.32)	(77.19)	(67.31)	(10.55)	(24.35)
Fall (gal)	7,718.1***	5,306.8***	3,710.3***	296.0***	1,104.4***
	(127.08)	(64.83)	(52.41)	(3.56)	(13.16)
Winter (gal)	2,385.2***	1,593.7***	909.4***	7.991	178.9***
	(56.20)	(33.32)	(19.51)	(0.17)	(3.93)
Annual (gal)	75,582.3***	53,098.6***	37,914.2***	4,760.8***	12,143.0***
	(139.62)	(76.05)	(61.88)	(7.67)	(19.45)
Observations	1,811,085	402,401	402,207	407,293	409,143

t statistics in parentheses; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

A.2.2 Kolomogorov-Smirnov Test Statistics

Table A.3: Left Column shows the combined K-S distance and right column shows the p-value for the corresponding match strategy. In most cases, the null hypothesis that the two treatment and control distributions are the same can be soundly rejected. This is not surprising given the significant differences in mean values shown from the t-tests in Tab. A.1.

	Random		Assr Alone		Assr + Gap		Cons	
Construction Year	0.068***	(0.00)	0.008	(0.50)	0.010	(0.22)	0.018**	(0.00)
Indoor Area (m^2)	0.043***	(0.00)	0.011	(0.13)	0.009	(0.30)	0.013	(0.05)
Lot Area (m^2)	0.077***	(0.00)	0.023***	(0.00)	0.030***	(0.00)	0.019***	(0.00)
Pool	0.041***	(0.00)	0.007	(0.66)	0.015*	(0.02)	0.013*	(0.04)
Assessed Value (dollars)	0.044***	(0.00)	0.013*	(0.04)	0.013*	(0.04)	0.013*	(0.04)
Spring	0.173***	(0.00)	0.131***	(0.00)	0.025***	(0.00)	0.014*	(0.02)
Summer	0.232***	(0.00)	0.185***	(0.00)	0.044***	(0.00)	0.036***	(0.00)
Fall	0.184***	(0.00)	0.140***	(0.00)	0.028***	(0.00)	0.014*	(0.02)
Winter	0.069***	(0.00)	0.042***	(0.00)	0.031***	(0.00)	0.049***	(0.00)
Annual	0.207***	(0.00)	0.161***	(0.00)	0.034***	(0.00)	0.021***	(0.00)

p-value in parentheses; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

A.3 Distributional Figures

The following figures present the mean and quantiles of household average monthly consumption in each season for WSL homes and their respective control groups.

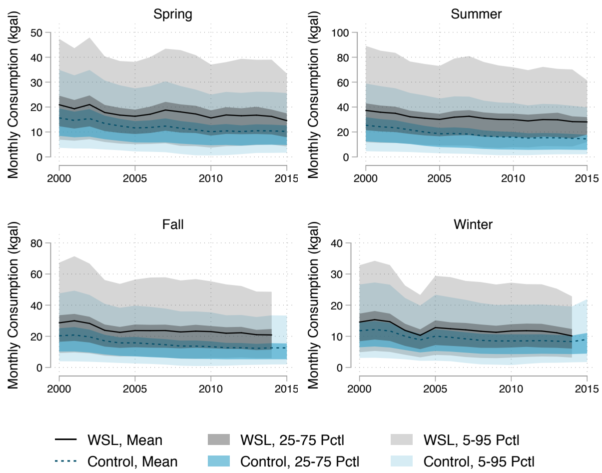

Figure A.3: All Data

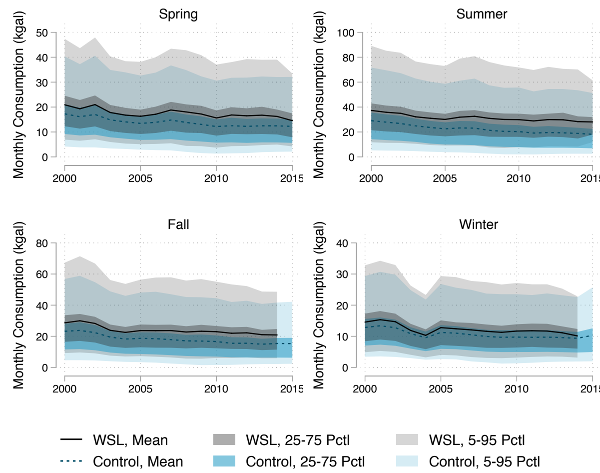

Figure A.4: Random Match within Block Group

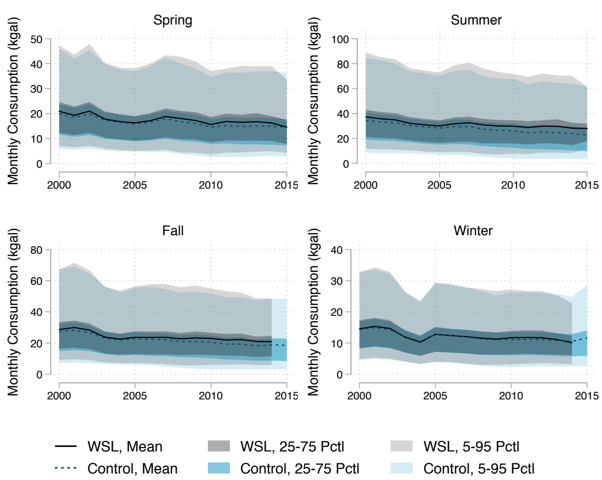

Figure A.5: Match on Consumption

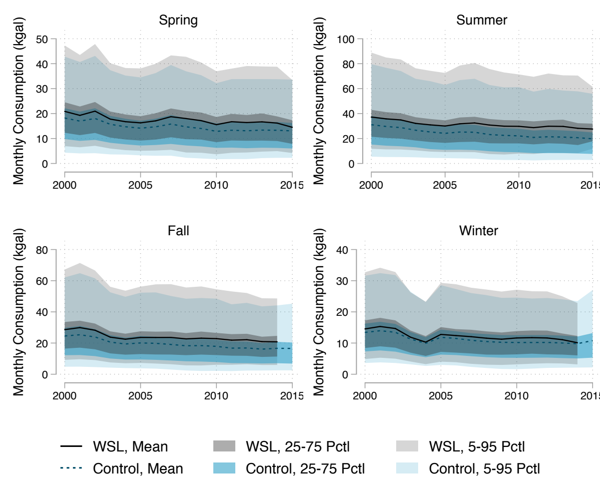

Figure A.6: Match on Assessor Alone

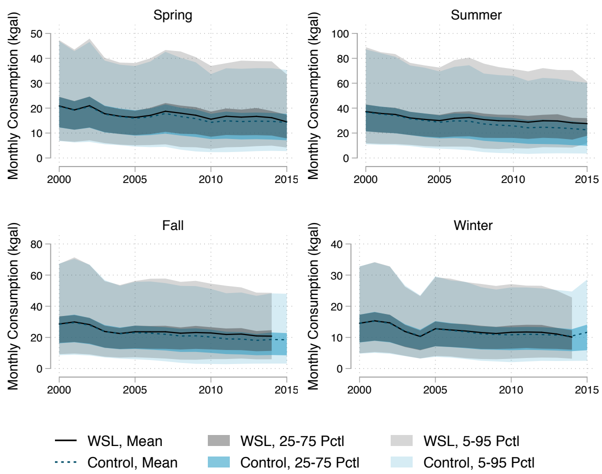

Figure A.7: Match on Assessor + Gap

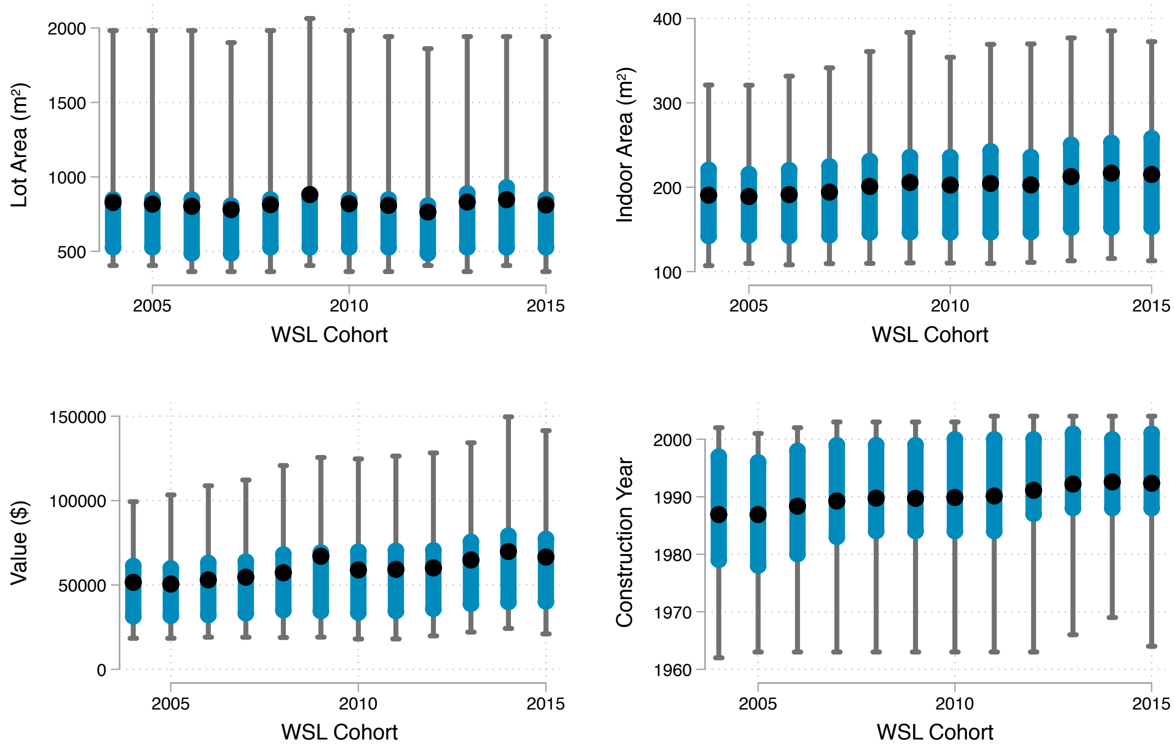

Figure A.8: Distribution of physical characteristics of WSL participating households, by WSL participation year. Black dots show the average characteristic, blue lines show the 25th to 75th percentiles, and the whiskers show the 5th to 95th percentile characteristics.

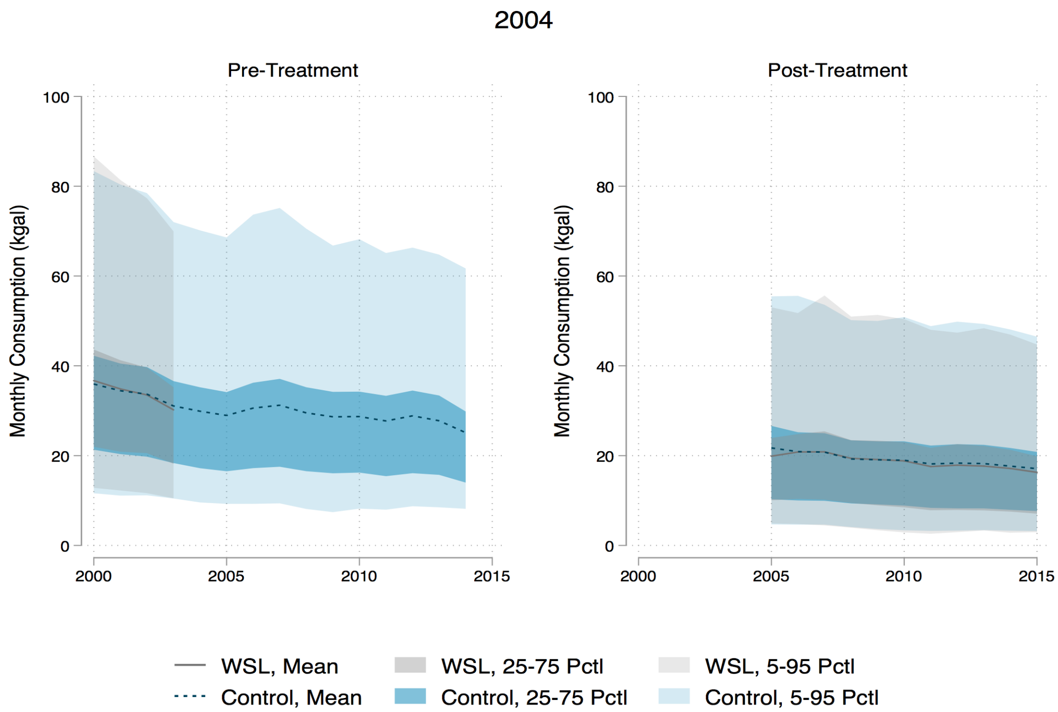

Figure A.9: This figure, when viewed in Adobe Reader, is an animated figure showing year by year differential trends. It is also available as an online video at https://tinyurl.com/FigureA9. The population for this figure is WSL participating homes only. In any given year Y, the "treatment" group (grey) consists of homes which completed their WSL conversion in year Y (cohort Y). Average monthly consumption for the treatment group is separated into two panels, the "Pre-Treatment", which shows the distribution of the groups consumption for years prior to Y, and the post-treatment panel, which shows consumption for years after Y. The "control" group consists of all WSL participating homes from cohorts $\neq$ Y. This group's consumption is also split into two panels: pre-treatment consumption, and post-treatment consumption. Because the control population includes WSL participating homes in cohorts spanning the full range of years, the pre and post-treatment consumption averages are fully covered, even through there is a variable population of homes in any given panel/year. Note then, that the treatment group from year Y is included in the control group in year Y+1, and vice versa. When the trends in consumption for WSL participating homes of each cohort are compared to the trend for all other WSL participating homes, there is no notable difference in the distribution of consumption between any of the various different treatment groups, nor evidence of a sustained differential trend. This is in marked contrast to the differential trends which are visible in all of the matched control group figures in Figs A.3 - A.7.

A.4 Supplementary Results & Tables

Table A.4 shows the full numerical results for the regressions represented by Eq. 1 and presented in Fig. 3. Table A.5 presents additional specification checks for the regressions represented by Eq. 2.

Table A.4: Event Study Regression Full Numerical Results.

	Spring		Summer		Fall		Winter	
$\tau = -15$	0.95	(0.62)	2.04	(1.47)	0.92	(0.89)	0.11	(0.60)
$\tau = -14$	1.08*	(0.48)	1.30	(1.03)	1.56*	(0.79)	0.73	(0.39)
$\tau = -13$	1.17**	(0.43)	1.46	(0.86)	1.40*	(0.67)	0.74*	(0.30)
$\tau = -12$	1.14**	(0.39)	1.49*	(0.72)	1.48**	(0.57)	0.82**	(0.27)
$\tau = -11$	1.30***	(0.33)	1.60*	(0.63)	1.67***	(0.49)	0.80***	(0.22)
$\tau = -10$	1.26***	(0.30)	1.88**	(0.59)	1.99***	(0.45)	0.97***	(0.21)
$\tau = -9$	1.48***	(0.26)	2.08***	(0.47)	1.78***	(0.39)	0.97***	(0.17)
$\tau = -8$	1.48***	(0.20)	2.15***	(0.38)	1.98***	(0.28)	1.07***	(0.15)
$\tau = -7$	1.30***	(0.17)	2.01***	(0.31)	1.74***	(0.22)	0.87***	(0.12)
$\tau = -6$	1.23***	(0.16)	1.81***	(0.26)	1.40***	(0.20)	0.64***	(0.10)
$\tau = -5$	1.12***	(0.15)	1.77***	(0.23)	1.51***	(0.19)	0.67***	(0.093)
$\tau = -4$	1.26***	(0.12)	1.82***	(0.19)	1.51***	(0.16)	0.80***	(0.084)
$\tau = -3$	1.12***	(0.094)	1.59***	(0.13)	1.34***	(0.13)	0.68***	(0.066)
$\tau = -2$	0.83***	(0.072)	1.13***	(0.089)	0.93***	(0.096)	0.44***	(0.053)
$\tau = -1$	0	(.)	0	(.)	0	(.)	0	(.)
$\tau = 0$	-3.62***	(0.15)	-8.63***	(0.35)	-4.64***	(0.17)	-1.15***	(0.100)
$\tau = 1$	-3.03***	(0.11)	-8.15***	(0.23)	-4.49***	(0.15)	-0.99***	(0.072)
$\tau = 2$	-3.07***	(0.12)	-8.40***	(0.25)	-4.76***	(0.17)	-0.95***	(0.081)
$\tau = 3$	-2.99***	(0.15)	-8.51***	(0.27)	-4.73***	(0.19)	-0.96***	(0.089)
$\tau = 4$	-3.06***	(0.15)	-8.61***	(0.30)	-4.78***	(0.20)	-0.95***	(0.097)
$\tau = 5$	-3.09***	(0.16)	-8.79***	(0.33)	-5.03***	(0.23)	-0.99***	(0.11)
$\tau = 6$	-3.39***	(0.18)	-9.06***	(0.37)	-5.10***	(0.26)	-1.06***	(0.12)
$\tau = 7$	-3.54***	(0.19)	-9.26***	(0.40)	-5.35***	(0.28)	-1.23***	(0.13)
$\tau = 8$	-3.65***	(0.21)	-9.56***	(0.42)	-5.48***	(0.30)	-1.23***	(0.14)
$\tau = 9$	-3.60***	(0.22)	-9.79***	(0.46)	-5.72***	(0.33)	-1.35***	(0.15)
$\tau = 10$	-3.86***	(0.26)	-10.3***	(0.50)	-5.80***	(0.35)	-1.41***	(0.17)
$\tau = 11$	-2.77***	(0.49)	-9.94***	(0.67)	-5.91***	(0.44)	-1.63***	(0.20)
2000	0	(.)	0	(.)	0	(.)	0	(.)
2001	-1.56***	(0.13)	-1.29***	(0.16)	1.42***	(0.15)	0.83***	(0.081)
2002	0.25	(0.15)	-1.93***	(0.21)	-0.11	(0.16)	0.26**	(0.093)
2003	-2.80***	(0.19)	-4.41***	(0.29)	-4.31***	(0.22)	-2.43***	(0.11)
2004	-3.69***	(0.21)	-5.44***	(0.32)	-5.57***	(0.25)	-4.02***	(0.14)
2005	-4.10***	(0.22)	-6.34***	(0.39)	-4.42***	(0.29)	-1.55***	(0.14)
2006	-3.28***	(0.24)	-4.58***	(0.41)	-4.38***	(0.32)	-1.81***	(0.14)
2007	-1.72***	(0.25)	-4.15***	(0.44)	-4.54***	(0.33)	-2.30***	(0.15)
2008	-2.69***	(0.26)	-5.84***	(0.49)	-5.39***	(0.39)	-2.77***	(0.18)
2009	-3.38***	(0.31)	-6.47***	(0.58)	-5.01***	(0.41)	-3.01***	(0.19)
2010	-4.47***	(0.32)	-6.46***	(0.57)	-5.27***	(0.43)	-2.78***	(0.19)
2011	-3.67***	(0.34)	-7.29***	(0.61)	-6.15***	(0.46)	-2.69***	(0.21)
2012	-4.06***	(0.36)	-6.82***	(0.65)	-6.19***	(0.50)	-2.67***	(0.22)
2013	-3.66***	(0.37)	-6.78***	(0.69)	-6.71***	(0.52)	-2.96***	(0.23)
2014	-3.75***	(0.37)	-7.28***	(0.70)	-6.16***	(0.52)	-3.08***	(0.23)
2015	-4.03***	(0.39)	-7.72***	(0.71)	-6.16***	(0.53)	-2.12***	(0.24)
Constant	19.4***	(0.28)	34.9***	(0.50)	26.8***	(0.37)	13.7***	(0.16)
R^2	0.050		0.075		0.071		0.043	
Households	24,127		24,127		24,127		24,127	
Observations	355,736		350,384		358,372		357,011	

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.5: Model 1 (preferred) is repeated from Table 3 for reference. Model 6 adds a linear trend in the control group, and is based off of Model 5. This model is indistinguishable from model 1 both statistically and practically: The total estimated difference over an entire year is less than two gallons. Model 7 includes homes while they are “in transition”. Model 8 drops the dummy variable κ that singles out pre-treatment WSL participating homes. Model 9 tests the results on a balanced panel of WSL participants.

		1	6	7	8	9
WSL Area	Spring	-26.21***	-26.11***	-23.44***	-27.28***	-26.24***
		(1.54)	(1.53)	(1.39)	(1.42)	(1.49)
	Summer	-67.70***	-67.55***	-62.51***	-69.29***	-67.06***
		(4.03)	(4.01)	(3.74)	(3.75)	(4.07)
	Fall	-43.03***	-42.84***	-39.03***	-43.90***	-41.99***
		(2.18)	(2.17)	(1.97)	(2.02)	(2.18)
	Winter	-11.94***	-11.84***	-10.52***	-12.25***	-11.72***
		(0.90)	(0.90)	(0.77)	(0.85)	(0.92)
Specification Change:		Baseline	Trend in Ctl	Add in-Trans	Drop κ	Balanced
Match Strategy		None	Assr + Gap	None	None	None
R^2	Spring	0.150	0.108	0.144	0.149	0.163
	Summer	0.348	0.244	0.332	0.347	0.373
	Fall	0.236	0.170	0.225	0.236	0.256
	Winter	0.092	0.070	0.089	0.092	0.104
Households		24,127	48,254	24,127	24,127	19,050
Observations	Spring	355,954	726,759	371,047	355,954	292,062
	Summer	350,419	720,444	369,601	350,419	287,012
	Fall	358,372	731,252	372,900	358,372	292,180
	Winter	357,011	730,939	373,631	357,011	290,580

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

A.5 Evidence for Returns to Scale in Area Treatment Effects

Eq. 2 in the main text implicitly assumes that the ATT of a m^2 of turf removed under WSL is constant, regardless of the quantity of turf removed.[25] To test for the potential of scale effects in the areal treatment effect, we slightly alter Model 1 to include a squared term of the total WSL conversion area a_{it}^2.

$$c_{it} = \zeta_i + \gamma_t + \beta_0 a_{it} + \beta_1 a_{it}^2 + +\beta_2 \kappa_{it} + \epsilon_{it} \tag{5}$$

Table A.6: Heterogeneity in water savings by WSL conversion area.

	Spring	Summer	Fall	Winter
WSL area (m^2)	-22.6***	-56.2***	-36.4***	-8.29***
	(3.91)	(10.9)	(4.86)	(1.65)
WSL area^2 (m^4)	-0.0057	-0.018	-0.010	-0.0057
	(0.0077)	(0.022)	(0.0097)	(0.0032)
R^2	0.150	0.350	0.237	0.093
Households	24,127	24,127	24,127	24,127
Observations	355,954	350,419	358,372	357,011

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The results in Table A.6 demonstrate that the squared term is both economic and statistically insignificant and negative, showing no evidence of a pattern of either increasing or decreasing returns in the size of the WSL conversion. Results using higher-order terms beyond a quadratic obtain the same basic result and therefore point to a linear relationship between turf removal and water savings.

[25] Alternatively, the baseline estimator can be interpreted as recovering the average marginal effect in the sample – the best fitting linear approximation to a nonlinear relationship.

A.6 Durability of WSL water savings

A.6.1 Motivation

Eq. 2 implicitly assumes that the effects of WSL are permanent. If, however, these effects attenuate over time, then our estimates reflect a sample-weighted average of these heterogeneous effects. A decline in effectiveness over time could be driven by a variety of causes: substitution toward other water-intensive uses (e.g., greater indoor water usage) in response to reduced water bills from outdoor watering, increased water needs of maturing vegetation, or gradual degradation of irrigation infrastructure. In this case the fact that we find estimates of water savings below the short-run effects in Sovocool et al. (2006) could simply reflect that our longer-run study reflects a mixture of short and long-run treatment effects.

The event study of Eq. 1 provides a fully nonparametric set of dynamic treatment effects of WSL while controlling for temporal observables. While useful for assessing the validity of our identification strategy, this model has its limitations for assessing the durability of water conservation gains from WSL. First, the event study provides an ATT for the entire landscape conversion as opposed to an areal treatment effect. Second, it is not possible to identify Eq. 1 if household fixed effects are employed rather than block group fixed effects (Borusyak & Jaravel, 2016) – creating potential problems of unobserved heterogeneity. Third, the event study – while offering a nonparametric specification of dynamic treatment effects – impose this at the cost of assuming that the treatment effects are uniform over calendar time. This creates the potential for bias if the magnitude of treatment effects (measured in time elapsed since treatment) varies in level based upon whether a household was an early or late adopter of WSL. Since early adopters of WSL necessarily contribute disproportionately to the population of homes with long post-conversion water histories, failure to control for time-varying heterogeneity of treatment effects can bias estimates of the durability of WSL.

A simple model with household fixed effects that allows us to estimate areal treatment effects that vary as a function of time since WSL adoption but that also controls for temporal heterogeneity in WSL's effectiveness is:

$$c_{it} = \zeta_i + \gamma_t + \sum_{j=1}^{4} d_{ji} a_{it} \times \left(\beta_j + \beta_{(j+4)} y_{it}\right) + \beta_9 \kappa_{it} + \epsilon_{it} \tag{6}$$

where y_{it} is the age, in years, of the WSL conversion, and d_{ji} is a dummy variable that is equal to 1 when household i is in one of four cohorts j and 0 otherwise. The coefficients on the interactions between the cohort indicators d_{ji} and WSL area, β_j for $j \in [1, 4]$, allow for a different baseline level ($y_{it} = 0$) of WSL effectiveness across temporal cohorts. The coefficients on the interaction between WSL conversion area a_{it} and WSL age y_{it}, β_j for $j \in [5, 8]$, allow us to test if there is a linear[26] growth or decline in the areal treatment effect over time for each cohort.

Given the use of annual fixed effects to control for shared temporal heterogeneity, there is an inherent tradeoff between identifying heterogeneity across a greater number of time-based cohorts and the ability to identify the temporal pattern of decay of the treatment effect within cohorts. Since we might expect that changes in program design could select participants from different household subpopulations, we define four cohorts to coincide with the changes in marginal WSL rebate value over time. Cohort 1 includes households which participated prior to 2007. Cohort 2 includes households which participated in 2007. Cohort 3 includes households which participated in 2008. Cohort 4 includes households which participated after 2009.

A.6.2 Results

Table A.7 presents estimates of Eq. 6. Once we separately control for the effects of cohort and WSL landscape age as in Eq. 6, the WSL-generated water savings appear to *increase* somewhat as the landscape ages for all seasons. The estimates of β_j for $j \in [5, 8]$ are all weakly negative, and are statistically significant for all seasons in cohort 1. Cohorts 2 and 3 have significant negative downward trends in water use with WSL landscape age

[26] We loosen the assumption of linearity below.

Table A.7: Results from Eq. 6, showing no meaningful decline in post-treatment water savings. WSL Area is in square meters.

	Spring	Summer	Fall	Winter
Cohort 1 × WSL Area	-19.6***	-54.6***	-32.4***	-6.94***
	(1.62)	(2.91)	(2.52)	(1.25)
Cohort 2 × WSL Area	-26.7***	-62.2***	-38.0***	-10.4***
	(1.49)	(2.03)	(2.09)	(1.34)
Cohort 3 × WSL Area	-23.3***	-56.3***	-33.9***	-9.60***
	(1.41)	(3.12)	(2.23)	(1.14)
Cohort 4 × WSL Area	-32.7***	-72.8***	-45.6***	-14.2***
	(2.66)	(2.85)	(1.87)	(1.54)
Cohort 1 × WSL Area × τ	-0.65*	-1.37***	-1.37***	-0.63***
	(0.26)	(0.35)	(0.26)	(0.18)
Cohort 2 × WSL Area × τ	-0.30	-1.71***	-1.32***	-0.31
	(0.22)	(0.50)	(0.33)	(0.19)
Cohort 3 × WSL Area × τ	-0.18	-1.34**	-1.32***	-0.30
	(0.21)	(0.49)	(0.33)	(0.18)
Cohort 4 × WSL Area × τ	0.50	-2.14	-1.70	-0.19
	(0.50)	(2.34)	(1.60)	(0.69)
R^2	0.151	0.351	0.238	0.093
Households	24,127	24,127	24,127	24,127
Observations	355,954	350,419	358,372	357,011

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

in summer and fall months only, while there are no significant effects of landscape age for the most recent cohort. Wald tests show that the cohort specific rebound effects can not be statistically distinguished from each other in any season, but they are, in aggregate, distinguishable from zero for every season except spring. Aggregating the seasonal effects suggest an increase in water savings of between 2% and 3% per year for all four cohorts.

Contrary to the finding of positive rebound effects in many studies of energy conservation investments, these analyses show no compelling evidence for a long-run rebound effect of WSL for water conservation in Las Vegas. The results of an alternate specification, in which the effect of the age of the WSL landscape is allowed to vary by year (rather than conforming to a linear slope), are shown in Fig. A.10 and provide a less parametric confirmation of this finding.

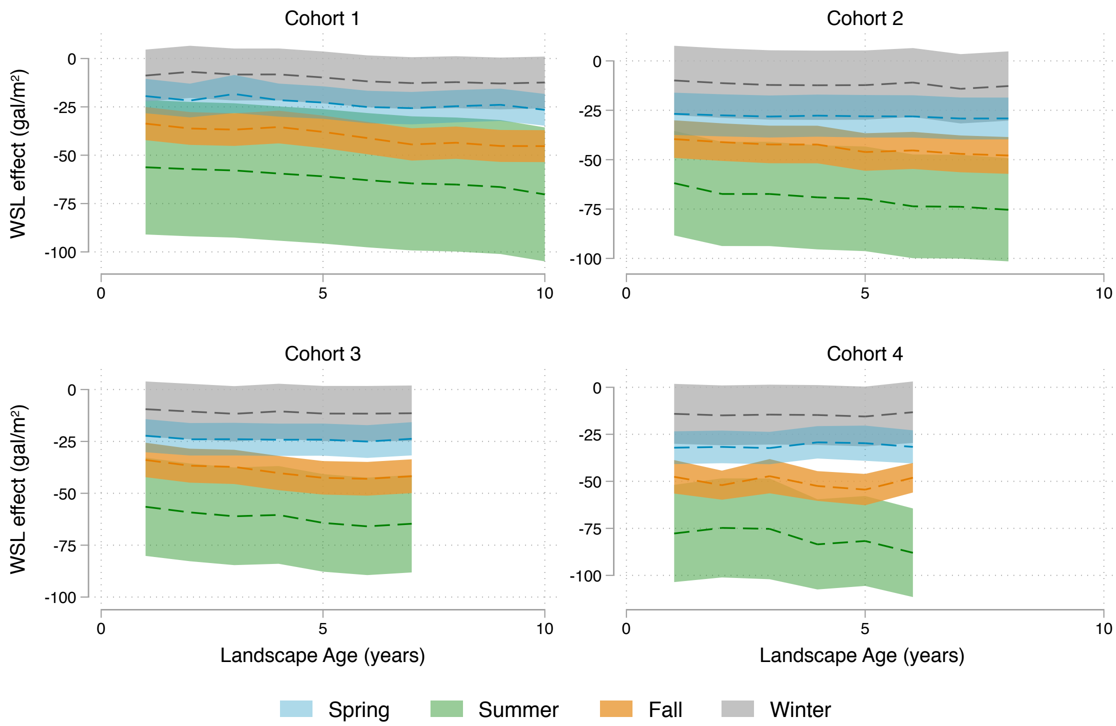

Figure A.10: Regression results showing the relationship between the age of a WSL conversion and the water savings generated. Cohorts are as defined in Table 1. Each season shows the best estimate for the aggregate WSL effect in the dashed line, and $\beta \pm \sigma$ in the filled area.