Evapotranspiration of residential lawns across the United States

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Key Points:

- ET per unit ground area of residential lawns in six US cities was largely driven by incoming solar radiation rather than yard landscape type
- However, water-conserving and wildlife-friendly yard landscape types had smaller lawns, leading to lower volumetric ET losses per household
- Lawn ET per unit ground area was higher in arid cities, illustrating de-coupling of lawn ET from regional climate patterns due to irrigation

Abstract

Despite interest in the contribution of evapotranspiration (ET) of residential turfgrass lawns to household and municipal water budgets across the United States, the spatial and temporal variability of residential lawn ET across large scales is highly uncertain. We measured instantaneous ET (ET_{inst}) of lawns in 79 residential yards in six metropolitan areas: Baltimore, Boston, Miami, Minneapolis-St. Paul (mesic climates), Los Angeles and Phoenix (arid climates). Each yard had one of four landscape types and management practices: traditional lawn-dominated yards with high or low fertilizer input, yards with water-conserving features, and

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yards with wildlife-friendly features. We measured ET_{inst} *in situ* during the growing season using portable chambers and identified environmental and anthropogenic factors controlling ET in residential lawns. For each household, we used ET_{inst} to estimate daily ET of the lawn (ET_{daily}) and multiplied ET_{daily} by the lawn area to estimate the total volume of water lost through ET of the lawn (ET_{vol}). ET_{daily} varied from 0.9 ± 0.4 mm d^{-1} in mesic cities to 2.9 ± 0.7 mm d^{-1} in arid cities. Neither ET_{inst} nor ET_{daily} was significantly influenced by yard landscape types and ET_{inst} patterns indicated that lawns may be largely decoupled from regional rain-driven climate patterns. ET_{vol} ranged from ~ 0 L d^{-1} to over 2,000 L d^{-1}, proportionally increasing with lawn area. Current irrigation and lawn management practices did not necessarily result in different ET_{inst} or ET_{daily} among traditional, water-conserving, or wildlife-friendly yards, but smaller lawn areas in water-conserving and wildlife-friendly yards resulted in lower ET_{vol}.

Plain Language Summary

Turfgrass lawns in residential yards can have significant water requirements. However, it is difficult to estimate how much water is consumed by lawns in households that vary in landscape type, management, and climate both within and across different cities. We visited 79 residential households in the United States and measured water use, or evapotranspiration (ET), of turfgrass lawns in six cities with different climates and yard management practices. Lawns used 0.6 - 1.3 mm of water per day in humid cities, and 2.2 - 3.6 mm per day in hot and dry cities. Lawn water use was more strongly influenced by climate, particularly solar radiation, than yard landscape type when comparing lawns of similar sizes. However, we found that most yards with conventional landscape types had much larger lawns than yards designed for water conservation or certified to be wildlife friendly. Therefore, the total estimated water use of lawns in each yard differed considerably among households. We conclude that widespread adoption of alternative yard landscape types such as xeriscaping, rain gardens, and wildlife-certified may effectively reduce lawn water consumption in US cities.

1 Introduction

Although irrigation of residential lawns can constitute up to 70% of household water budgets (Balling et al., 2008; Haley et al., 2007; Mini et al., 2014; Reyes et al., 2018; St. Hilaire et al., 2008), the actual water use of turfgrass lawns exposed to different climatic, environmental, and management conditions is highly uncertain. Plant water use depends both on plant physiological characteristics and environmental conditions that are highly modified by human activities. Therefore, water use of residential lawns is likely affected by biotic factors and abiotic conditions, as well as lawn management practices. All of these factors can be highly heterogeneous, particularly in urban areas where transitions in natural and built structures often occur at the scale of city blocks (Cadenasso et al., 2007; Cristiano et al., 2017; Digiovanni-White et al., 2018; Pataki et al., 2011; Sisser et al., 2016), such that evapotranspiration (ET) of urban lawns can be highly variable (Bijoor et al., 2014; Litvak et al., 2014; Saher et al., 2021).

It has long been known that potential and actual turfgrass ET is primarily driven by incoming solar radiation and may reach extremely high rates when unshaded with unlimited access to soil water (Feldhake et al., 1983). Potential ET (ET_0, mm h^{-1}) is ET of a reference vegetated surface that is flat, uniform, and extensive, with vegetation completely covering the ground and receiving unlimited soil water supply (Penman, 1948; Monteith, 1965). ET_0 is largely driven by radiative fluxes and environmental variables, and approximates the theoretical maximum ET from a vegetated surface under given environmental conditions (Allen et al., 1998). ET_0 is widely adopted as a basis for watering recommendations of urban vegetated landscapes across the US and globally (Al-kofahi et al., 2012; Hartin et al., 2018; Nouri et al., 2013; Padullés Cubino et al., 2017; Saher et al., 2021; Salvador et al., 2011). According to this approach, landscape water needs are estimated as a fraction of ET_0 by multiplying by correction coefficients that depend on percent vegetative cover, landscape composition, weather conditions, and other factors (Costello et al., 2000; Kumar et al., 2012; Litvak and Pataki, 2016). Landscape coefficients determined from qualitative landscape assessments rather than empirical measurements tend to overestimate actual landscape watering requirements (Bijoor et al., 2014). For example, *in situ* measurements of turfgrass ET in southern California showed that wintertime turfgrass ET, as well as ET of turfgrass shaded by tree canopies or buildings, may be significantly lower than recommended irrigation inputs (Litvak et al., 2014). Moreover, current irrigation practices often exceed municipal recommendations resulting in significant over-irrigation of turfgrass lawns (Litvak et al., 2014; Saher et al., 2021).

Given the increasing frequency of drought in many regions and the introduction of water conservation measures, residential lawn management practices may be changing (Cook et al., 2012; Hughes et al., 2013; Liang et al., 2017; Sisser et al., 2016; Warner et al., 2022). For example, some homeowners opt for a lower intensity of lawn management (i.e., less frequent water and/or fertilizer applications) in an effort to reduce the environmental impact of their lawns (Carrico et al., 2018; Eisenhauer et al., 2016; Suh et al., 2016; Warner et al., 2022; Watson et al., 2019). In addition, a growing number of homeowners reduce or eliminate turfgrass lawns in their landscape, especially in arid regions where rebate programs have been developed to incentivize the replacement of lawns with drought-tolerant vegetation (Bollinger et al, 2018; Grant et al., 2020; Matlock et al., 2019). In wetter regions, yard landscape types involving water retention features, such as rain barrels and/or water retention gardens designed to collect and absorb stormwater, are becoming increasingly common (Coleman et al., 2018; Morash et al., 2019; Koppelaar et al., 2021; Stacy et al., 2021). There is also growing interest among landowners in designing their yards to support local wildlife and biodiversity, e.g., yards certified by the National Wildlife Federation, with features that reduce lawn size in favor of other vegetation (https://www.nwf.org/garden-for-wildlife/certify; Belaire et al., 2016; Hansen et al., 2020; Cavender-Bares et al., 2020; Lerman et al., 2021; Mumaw and Mata, 2022).

As ET of urban residential lawns is simultaneously affected by both environmental conditions and yard landscape type and management decisions, there is a need to understand both environmental and anthropogenic factors that determine lawn ET. Because virtually all environmental factors are altered in contemporary cities, including atmospheric composition, air temperature and humidity, and soil water content (Calvo et al., 2013; Digiovanni-White et al., 2018; Hall et al., 2016; Harvey et al., 2014; Vahmani and Hogue, 2015), and climatic differences among cities are also altered by anthropogenic climate change (IPCC, 2021), environmental and anthropogenic factors are not always easily discernible. In this study, we defined environmental factors as the parameters that were not directly affected by homeowners (climatic differences among cities), and anthropogenic factors as the parameters that directly resulted from human actions (yard landscape type and management practices). We considered residential yards with four types of yard landscape types and management practices: traditional high-input lawns (lawn-dominated yards that are often maintained by a lawn-care company), traditional low-input lawns (generally self-maintained with minimal fertilizer input), water-conserving (containing water retention features in mesic climates and drought-tolerant landscaping in arid climates), and wildlife-friendly (certified as Wildlife Habitats by the National Wildlife Federation).

The goal of this study was to quantify ET of residential turfgrass lawns and its variability within and across cities in the US, and to identify the factors that determine lawn ET across climate zones, lawn care practices, and yard landscape types. We measured instantaneous ET of individual lawns using portable static chambers that were specifically developed to estimate ET of small lawns with heterogeneous surroundings (Bijoor et al., 2014; Litvak et al., 2014). We asked: (1) What is the ET of residential turfgrass lawns within cities in the US and what are the differences among cities? (2) How much of the variability in ET of residential turfgrass lawns is driven by environmental factors, such as climatic differences among studied cities? (3) How much variability in ET is driven by anthropogenic factors, such as different yard landscape types and management practices? We hypothesized that ET of residential lawns would vary from moderate in cities with mesic climates and water-conserving landscape types to very high in cities with arid climates and traditional (lawn-dominated) landscape types. Here we refer to cities in humid and wet climates as “mesic” and cities with low humidity and annual precipitation as “arid”. Specifically, in yards with traditional landscape types that involve substantial irrigation and fertilizer inputs, we expected lawn ET to approach the theoretical maximum of ET_0, and to be controlled mostly by environmental drivers (Penman, 1948; Monteith, 1965) for water-unlimited grass surfaces. In yards with water-conserving landscape types, we expected lawn ET to be lower than ET_0, especially in arid cities where we expected to observe a pronounced contrast in ET between irrigated and less intensively managed lawns.

2 Materials and Methods

2.1 Site selection

This study was conducted in six Metropolitan Statistical Areas (hereafter “cities”), representing a gradient of climates and ecoregions across the United States: Boston (Massachusetts), Minneapolis-St. Paul (Minnesota), Baltimore (Maryland), Miami (Florida), Los Angeles (California), and Phoenix (Arizona; the cities are listed from humid to dry climates; Table 1). We refer to Boston, Minneapolis-St. Paul, Baltimore and Miami as the “mesic” cities and Los Angeles and Phoenix as the “arid” cities. In each city, we randomly chose study locations from the pool of households fitting the following criteria: residential parcels that were owned by median income single-family households (with a median annual income ranging from $45,000 in Miami to $105,000 in Boston); records indicated that the homes in each parcel were built at least 10 years ago. The selected study sites were used for a broader assessment of the impacts of yard management on biodiversity, ecosystem function and social governance (Lerman et al., 2021; Larson et al., 2020, 2022; Padullés Cubino et al., 2020). The detailed site-selection criteria and procedures are presented in supporting information (Text S1) and Padullés Cubino et al. (2020).

To classify the selected yards based on landscaping styles and management practices, we asked the homeowners to fill out an online questionnaire (details in Padullés Cubino et al., 2020). The survey results were used to distinguish four types of residential yards: traditional high-input lawns, traditional low-input lawns, water-conserving, and wildlife-friendly (Fig. 1). We placed each yard in one of the four categories based on the landscaping in the front yard and/or back yard (Text S1). Traditional high-input yards were maintained by a professional lawn care company according to typical yard management practices (regular mowing, irrigation, and fertilizer application) or were fertilized at least 3x per year by the householder. Traditional low-input yards were maintained by householders themselves and, according to their responses to the online questionnaire, fertilized less than three times during the previous year. Water-conserving yards included features intended to reduce impacts on surface hydrologic fluxes. Thus, in Los Angeles and Phoenix (arid cities), we classified the yards as water-conserving when they contained features such as 'xeriscaping' (e.g., drought-tolerant vegetation) or drip irrigation systems. In Boston, Minneapolis-St. Paul, Baltimore, and Miami (mesic cities), we classified the yards as water-conserving when they contained water-retention features, such as rain gardens or rain barrels. We classified the yards as wildlife-friendly when they were certified as Wildlife Habitats by the National Wildlife Federation for their provision of food, clean water, shelter for local fauna, and reducing lawn in favor of other covers (such as leaf litter, meadows) to support pollinators, while also adopting certain sustainable practices (https://www.nwf.org/garden-for-wildlife/certify). Water-conserving yards had their hydrology feature installed at least three years ago, and the wildlife-friendly yards had been wildlife-certified at least three years before the study (Table S1).

We aimed to collect data in 16 yards per city, with four yards for each landscape type. In Boston, we studied 12 yards because of the absence of yards with water-conserving features. We did not measure ET at 9 yards that did not have turfgrass lawns. In total, we collected ET measurements in 79 residential yards across the six cities (average 13 per city). Measured lawns were located in either front and/or backyards (Table S1). In most traditionally landscaped yards (both high- and low-input), turfgrass lawns were present in both front- and backyards except in Phoenix, where turfgrass lawns were mostly present in backyards (only one traditional high-input and three traditional low-input yards had turfgrass lawns in front yards) and one yard in Miami that was managed as traditional high-input but had no turfgrass lawn. In the arid cities of Los Angeles and Phoenix, water-conserving and wildlife-friendly yards either had turfgrass in backyards only, or no turfgrass at all, with only one exception of a wildlife-friendly yard in Phoenix where a turfgrass lawn was located in the front yard. Turfgrass lawns were absent in 3 water-conserving yards, 5 wildlife-friendly yards, and one traditional high-input yard (Table S1).

In addition to the residential sites, we collected soil volumetric water content (VWC) at multiple non-residential locations in each city, for comparison with natural soil moisture levels in each climatic zone. For each city, we established a pool of non-residential locations with reference vegetation of the specific area. From this pool, we randomly selected 3-5 reference sites within city limits in largely unmanaged public parks ("interstitial sites") and 3-5 reference sites outside city limits in largely intact natural areas, most of which had limited or restricted public access ("natural sites") that met logistic requirements of the study, such as legal and physical access and safety of researchers (, Table S2).

2.2 On-site measurements

We performed *in situ* measurements from April – August of 2018, during the peak growing season in each climatic zone, while avoiding peak precipitation months (Table 1). We chose a different measurement period for each region to capture peak lawn ET in each city, reflecting the local climate and seasonality. We measured instantaneous ET of turfgrass lawns (ET_{inst}, mm h^{-1}) between 10 AM – 4 PM local time (11 AM – 3 PM on most lawns) using clear cuboid PVC chambers (28 cm width x 18 cm height) with HOBO U23-001 Pro v2 dataloggers (Onset Computer Corporation, Bourne, MA, USA) attached inside the chambers (Bijoor et al., 2014; Litvak et al., 2014; Fig. S1). The dataloggers recorded atmospheric temperature (T, °C) and relative humidity (rh, %) every 2 s. On each lawn, we measured ET_{inst} at 6 locations representative of sun and shade variability at the lawn surface to capture the site-specific light/shade distribution of the lawn by following the procedure described by Litvak et al. (2014). Whenever turfgrass lawns were present in both the front and backyard, we made six ET_{inst} measurements in the front yard, immediately followed by 6 measurements in the backyard. Measurements were made by placing the chambers on turfgrass for 30 seconds. Between the measurements, we held the chambers in a nearby shady location for at least 1 minute to equilibrate with ambient conditions and prevent overheating of the dataloggers.

At each of the six ET_{inst} measurement locations per site, we also measured the illuminance of incoming solar radiation using a handheld EMMA Digital Multifunction Environmental Meter (Dwyer, Michigan City, IN, USA), VWC at 0-6 cm depth (m^3 m^{-3}, using ML3 ThetaProbe; Dynamax Inc., Houston, TX, USA), and the height of the grass. We estimated the intensity of incoming solar radiation (I_0, W m^{-2}) as 0.0079 × illuminance (lux). We measured wind speed at 2 m height (u, m s^{-1}) before and after ET_{inst} measurements using a handheld EMMA Digital Multifunction Environmental Meter.

We estimated the lawn area (A_{lawn}, m^2) of each yard from digitized parcel maps, which we made through careful evaluation of hand-sketched maps made on-site, in combination with satellite images from Google maps. For the yards that had no lawns, we set $A_{lawn} = 0$ m^2.

For VWC, we made additional measurements in the other, non-lawn groundcovers present in the yards (near the most abundant broadleaf plant species; 3-12 measurements per yard), at interstitial reference sites (3-18 measurements per site) and at natural reference sites (3-18 measurements per site). In Miami, no soil moisture measurements were made at the natural sites due to logistical reasons.

We used the data from HOBO U23-001 Pro v2 data loggers located inside the chambers to calculate water vapor pressure (e, Pa) and vapor pressure deficit (D, kPa) of the air. We obtained ambient T and rh by extracting the data from HOBO U23-001 Pro v2 data loggers right before the chambers were placed on the grass.

2.3 Calculations of instantaneous lawn ET

We derived ET_{inst} from a nearly linear ($R^2 > 0.99$) increase of the mass density of water vapor inside the chambers (ρ_v, kg m^{-3}) during the first 20 seconds of chamber placements on turfgrass. We calculated ρ_v using the ideal gas law:

$$\rho_v = \frac{e}{R_v(273.15+T)}, \qquad (1)$$

where *e* is the water vapor pressure inside the chambers in Pa, $R_v = 461.5$ J K^{-1} kg^{-1} is the gas constant for the water vapor and *T* is temperature in K. To quantify the rates of growth of ρ_v inside the chambers, we used the slopes of linear functions fitted to 10-second intervals of ρ_v plotted versus time ($d\rho_v/dt$). The maximum $d\rho_v/dt$ reached during chamber placements on turfgrass ($d\rho_v/dt_{MAX}$) were used to calculate ET_{inst} similarly to ET_{ch} in Eq. 2 below.

2.4 Validation of the chamber methodology

Chamber methods always require validation by a robust independent evaluation of ET (Alam et al., 2018; Cohen et al., 2015; McLeod et al., 2004; Qubaja et al., 2020). To validate our method, we compared ET measured with the chamber against gravimetric (i.e., weight-based) ET measurements using cut-out samples of locally available sod (i.e., turfgrass-covered surface soil). To ensure our portable chambers provided reliable turfgrass ET estimates across disparate climatic zones, we conducted these tests in three cities: Irvine, CA (Mediterranean climate with hot summer), Salt Lake City, UT (cool semi-arid climate), and Tallahassee, FL (humid subtropical climate). We used 4-8 samples of turfgrass placed in 25.4 cm x 25.4 cm x 5 cm (length x width x height) plastic trays with no drain holes (Fig. S2) and watered generously. The only path for the water to escape from the samples was via ET. We left the turfgrass samples in ambient conditions, mostly in the full sun, for the entire duration of the test. Every hour, we placed the chamber on top of each turfgrass sample for 30 seconds. Between these measurements, we left the chamber in a nearby shady location for at least 1 minute. Right after the chamber applications, we weighed each sample on a balance (AdventurerPro AV 3102 and Scout SKX Portable Balance, OHAUS Corporation, Parsippany, NJ, USA), which was also placed outside in a shady location, and immediately returned the samples to their original locations. Overall, chamber measurements and weighing took no more than 2 minutes per turfgrass sample during each hour; the rest of the time the samples were left undisturbed.

As the weight of the turfgrass samples decreased steadily over the course of the day due to ET water losses, we calculated hourly gravimetric ET (ET_g, mm h^{-1}) as a simple difference between the weights of each sample taken at hourly intervals. We averaged $d\rho_v/dt_{MAX}$ at the beginning and the end of every hour to represent mean hourly ET rates for the chamber. The comparison between hourly averaged $d\rho_v/dt_{MAX}$ and ET_g revealed the sensitivity of $d\rho_v/dt_{MAX}$ to temperature differences between the location of turfgrass samples and the shady area where the chamber stayed between applications (ΔT, °C). We took this temperature sensitivity into account and calculated chamber ET (ET_{ch}, mm h^{-1}) as

$$ET_{ch} = 3.6 \times 10^6 \frac{h}{\rho_{H_2O}} \left(\frac{d\rho_v}{dt}\right)_{MAX} + 0.07\Delta T, \qquad (2)$$

where h = 0.18 m is the chamber height, $\rho_{H2O} = 10^3$ kg m^{-3} is the density of water, 3.6 $\times 10^6$ is the coefficient converting the units from m s^{-1} to mm h^{-1}, and $0.07\Delta T$ is a term that accounts for the residual variability caused by ΔT. We used Equation 2 to calculate ET from chamber measurements at the study lawns.

The results of these tests were consistent across the cities with sufficient accuracy for surveying ET of turfgrass lawns (RMSE = 0.08 mm h^{-1}, Fig. S3). We attribute the observed divergence of chamber-based ET from gravimetric ET to the natural variability of instantaneous ET under ambient conditions, which was captured by the chambers, versus integrated hourly water losses, which were detected by gravimetric measurements. Our method tends to somewhat underestimate ET of turfgrass in semi-arid cities (Irvine and Salt Lake City) compared to a humid city of Tallahassee (Fig. S3). Therefore, our ET measurements in the arid cities may be somewhat underestimated.

2.5 Penman-Monteith-based estimation of turfgrass ET

We used ET_0 to approximate ET_{inst} of water-unlimited turfgrass lawns in each city independently from chamber measurements. To estimate ET_0, we substituted environmental variables collected *in situ* to the modified Penman-Monteith equation (Allen et al., 1998; Birdsall, 2013a; 2013b):

$$ET_0 = \frac{\Delta}{\Delta+\gamma}\frac{R_N}{694.5(1-9.46\times10^{-4}T)} + \frac{\gamma}{\Delta+\gamma}D(0.030+0.0576u) \quad (3)$$

where Δ is the slope of saturation vapor pressure as a function of temperature at the ambient temperature and γ is the psychrometric constant calculated as described by Birdsall (2013b), R_N is net radiation, and T, D, and u were obtained as described above. R_N was calculated from linear regressions ($R^2 \geq 0.96$; $p < 0.001$) between R_N and R_S (incoming shortwave radiation, W m^{-2}; Fig. S4) at California Irrigation Management Information System weather stations located on grass lawns (CIMIS, 2021) and National Ecological Observatory Network flux towers located on grasslands (NEON, 2021).

2.6 Estimation of daily ET and volumetric ET losses

We approximated diurnal changes of instantaneous lawn ET using Gaussian functions (following Litvak et al., 2014):

$$ET_{inst}(t) = a\,exp\left(-\frac{1}{2}\left(\frac{t-t_0}{b}\right)^2\right), \quad (4)$$

where $ET_{inst}(t)$ was obtained from chamber measurements as described above (Eq. 2), a is the maximum ET_{inst} assumed to happen at solar noon, t is the time of ET_{inst} measurements, t_0 is the timing of solar noon on the day and location of ET_{inst} measurements (e.g., gml.noaa.gov/grad/solcalc), and b characterizes the width of diurnal ET_{inst} distribution. We set b = 2.5 to realistically represent diurnal ET_{inst} patterns during the growing season and used Equation 4 to calculate a. Then, we estimated daily ET (ET_{daily}, mm d^{-1}) using analytical integration of Gaussian functions:

$$ET_{daily} = \int_{-\infty}^{+\infty} ET(t)dt = ab\sqrt{2\pi}. \quad (5)$$

We estimated volumetric ET losses from studied lawns (ET_{vol}, L d^{-1}), i.e., the volume of water lost due to lawn ET, for each household, as the product of ET_{daily}, estimated using Equations 4-5 above, and cumulative lawn area in every yard:

$$ET_{vol} = ET_{daily} \cdot A_{lawn} \qquad (6)$$

2.7 Statistical analyses

We performed all statistical analyses in R (R Development Core Team, 2020) with the significance level $\alpha = 0.05$. For the yards with lawn in the front and back yards we averaged ET_{inst} and other variables, so that all yards had a single ET_{inst} estimate. To evaluate the differences between cities and yard landscape types (considered as independent variables) for each environmental parameter – I_0, D, VWC, and grass height (considered as dependent variables), we performed analysis of variance (ANOVA) followed by Tukey's Honest Significant Differences (HSD) test. When the application of ANOVA was restricted by non-homogeneity of the data, we applied the nonparametric Kruskal-Wallis Rank Sum Test (KWRS) and Pairwise-Wilcoxon Rank Sum Test (PWRS). For comparison of VWC between lawn, other ground covers, and reference sites in each city, we used ANOVA/Tukey HSD for each city except in Phoenix, where we used KWRS/PWRS due to non-homogeneity of the data. Because of the regional differences in maximal VWC and the lack of inter-regional calibration of soil probes, the comparison of VWC among the cities would not be informative; therefore, we did not analyze statistical differences across cities. To derive an empirical model of ET_{inst} as a function of environmental parameters, we performed a series of linear regression analyses, assessing the significance of each related variable (I_0, D, VWC, grass height) to explain variability in ET_{inst} (see more details below, Results 3.2). We combined the regressions from significant relationships between ET_{inst} and I_0, D and VWC to construct empirical models of ET_{inst} in each city.

3 Results

3.1 Comparison of instantaneous ET and other variables among cities and yard landscape types

ET_{inst} of individual turfgrass lawns varied from ~ 0 mm h^{-1} in some lawns on some dates in Boston, Minneapolis-St. Paul, Baltimore, and Miami to 0.73 ± 0.25 mm h^{-1} at a lawn in Phoenix (Fig. 2a; Table S3). ET_{inst} in Phoenix was higher by 0.7 mm h^{-1} than in Los Angeles (ANOVA; $p = 0.02$) and much higher (by 2.1 - 2.6 mm h^{-1}) than in the other cities ($p < 0.0001$). ET_{inst} in Los Angeles was marginally higher than in Miami ($p = 0.02$) and significantly higher than in Boston, Minneapolis-St. Paul, and Baltimore ($p \leq 0.001$). There were no significant differences in ET_{inst} among the mesic cities (i.e., Boston, Minneapolis-St. Paul, Baltimore, and Miami; $p = 0.52$). ET_{inst} was not significantly different among the yard landscape types in each city ($p > 0.09$).

Differences in latitude, diurnal changes, yard-specific shade regimes, and – in some cities – variations in cloudiness caused I_0 above the lawns to vary substantially among and within the cities (Fig. 2b; Table S3). The maximum I_0 of 518 Wm^{-2} was observed in Phoenix, and the minimum I_0 of 28 Wm^{-2} was observed in Boston. I_0 in Phoenix, Los Angeles and Miami was significantly higher than Boston (ANOVA, $p < 0.01$). I_0 in Minneapolis-St. Paul (280.2 ± 70 Wm^{-2}) was highly variable and did not significantly differ from the other cities.

D varied from 0.5 kPa in a yard in Boston to 6.7 kPa in a yard in Phoenix (Fig. 2c; Table S3). D in Phoenix was significantly higher than in other cities (KWRS; $p < 0.001$ for all), while D in Baltimore was significantly lower than in other cities ($p < 0.01$ for all). D was the most variable in Boston, where it ranged from 0.5 – 4.2 kPa, and the least variable in Miami, where it ranged from 1.5 – 2.6 kPa.

VWC of the lawns was the most variable in yards in Baltimore (range of 0.4 m^3m^3), and the least variable in Minneapolis-St. Paul (range of 0.1 m^3m^3; Fig. 2d; Table S3). VWC in the lawns did not differ between yard landscape types ($p > 0.2$ for all cities). Variability of VWC in the non-lawn portion of the yards was similar among the cities (range of 0.2 – 0.3 m^3m^3). Reference site VWC was the most variable in Baltimore (range of 0.5 m^3m^3) and the least variable in Los Angeles (range of 0.1 m^3m^3).

We observed $A_{lawn} = 0$ m^2 (i.e., no turfgrass lawn present in either front yard or backyard) in 4 yards in Los Angeles (3 water-conserving and 1 wildlife-friendly), 3 yards in Miami (2 wildlife-friendly and 1 traditional), 1 wildlife-friendly yard in Phoenix, and 1 wildlife-friendly yard in Minneapolis-St. Paul (Table S1).

In the yards where turfgrass lawns were present, A_{lawn} ranged from 2 m^2 in a wildlife-friendly yard in Los Angeles to 2,500 m^2 in traditional yards in Baltimore (Fig. 6a). Lawn areas were significantly higher in Baltimore than in Minneapolis-St. Paul (ANOVA; $p = 0.04$) and both arid cities ($p < 0.02$). In Minneapolis-St. Paul and Phoenix, the lawns in high-input and low-input traditional yards were significantly larger than the lawns in water-conserving (for Minneapolis-St. Paul, $p = 0.02$ and $p = 0.02$; for Phoenix, $p = 0.02$ and $p = 0.06$) and wildlife-friendly yards (for Minneapolis-St. Paul, $p = 0.02$ and $p < 0.05$; for Phoenix, $p = 0.001$ and $p = 0.04$). In Los Angeles, the lawns in low-input traditional yards were significantly larger than the lawns in water-conserving and wildlife-friendly yards ($p = 0.02$ for both). Lawn areas in water-conserving yards were the largest in Miami, followed by Baltimore, Minneapolis-St. Paul, Phoenix, and Los Angeles.

3.2 Modeling ET_{inst} and comparison with ET_0

ET_{inst} of individual turfgrass lawns linearly increased with I_0 in all cities (Fig. 3a). In Phoenix, the slope of the ET_{inst} (I_0) relationship was marginally higher than in Los Angeles ($p = 0.04$) and significantly higher than in the rest of the cities (ANOVA; $p < 0.0001$). In Los Angeles, the slope was higher than in Boston, Baltimore, and Miami ($p \leq 0.04$), and significantly higher than in Minneapolis-St. Paul ($p = 0.003$). In Miami, the variability in ET_{inst} resulted in a very low R^2 of the ET_{inst} (I_0) relationship (Table 2). In Boston, Minneapolis-St. Paul, Baltimore, and Miami, the slopes were not significantly different from each other ($p \geq 0.9$). When we combined these four cities together, the ET_{inst} (I_0) relationship was highly significant ($R^2_{adj} = 0.62$; $p < 0.0001$) with a slope of $(5.0 \pm 0.3) \times 10^{-4}$.

The residuals of the ET_{inst} (I_0) relationships varied from -0.18 to +0.21 mm h^{-1}. The residuals were not significantly different among the cities and yard landscape types within each city ($p \geq 0.7$; 0.2). The residuals were not correlated with either grass height or lawn sizes. In Baltimore and Miami, the residuals of the ET_{inst} (I_0) relationships were negatively correlated with VWC and D, correspondingly (Fig. 3b). We combined the regressions from Fig. 3 (a and b) to construct empirical models of ET_{inst} in each city (the equations for each of these models are shown in Table 2; Fig. 3c shows empirically modeled ET_{inst} plotted against measured ET_{inst}). For Boston, Minneapolis-St. Paul, Los Angeles, and Phoenix, the final model of ET_{inst} included I_0 as the only explanatory variable ($p < 0.001$; Table 2); in Baltimore, ET_{inst} was additionally explained by VWC ($p = 0.036$) and for Miami the final model included I_0 and D as explanatory variables ($p = 0.031$).

ET_0 calculated using Eq. 3 and *in situ* environmental variables was a good predictor of average ET_{inst} for Los Angeles (Fig. 4). In Boston, Minneapolis-St. Paul, Miami, and Baltimore, ET_0 was higher than ET_{inst} by 0.09 ± 0.07 mm h^{-1}. In Phoenix, ET_0 was lower than ET_{inst} by 0.08 $\pm$ 0.16 mm h^{-1}. The landscape coefficients for residential lawns, calculated as $k_L = ET_{inst}/ET_0$, varied from 0.5 - 0.6 in mesic cities to 1.0 in Los Angeles to 1.3 in Phoenix (Fig. 4).

3.3 Daily ET and volumetric ET losses

Estimated ET_{daily} varied from 0.6 ± 0.6 mm d^{-1} in Boston to 3.2 ± 1.1 mm d^{-1} in Phoenix (± SD; Fig. 5; Table S3), ranging from ~ 0 mm d^{-1} in some traditional yards in Boston and Minneapolis-St. Paul to a maximum of 5.5 mm d^{-1} in a wildlife-friendly yard in Phoenix. ET_{daily} was significantly lower in mesic cities (Boston, Minneapolis-St. Paul, Baltimore, and Miami) than in arid cities (Los Angeles and Phoenix; ANOVA; $p = 0.001$). There were no significant differences in ET_{daily} between any of the mesic cities ($p > 0.3$), or between the two arid cities ($p > 0.3$). We also did not find significant differences in ET_{daily} among the yard landscape types in each city ($p > 0.1$ for all).

In 9 yards where turfgrass lawns were not present (Table S1), ET_{vol} was equal to 0 L d^{-1} (Eq. 6). In the yards where turfgrass lawns were present, ET_{vol} ranged from ~ 0 L d^{-1} in some yards in Boston and Minneapolis-St. Paul (similar to ET_{daily}) to over 2,000 L d^{-1} in a high-input traditional yard in Boston. ET_{vol} averaged per yard landscape type were highest in low-input traditional yards in Baltimore and lowest in water-conserving yards in Los Angeles (Fig. 6b). While several yards in Baltimore with very large lawns had particularly high ET_{vol} (Fig. 6a and 6b), there were no significant differences in ET_{vol} among the cities. However, mean ET_{vol} in water-conserving and/or wildlife-friendly yards were much lower than in traditional yards in several cities and especially in Los Angeles and Phoenix. Across cities, ET_{vol} in wildlife-friendly yards were lower than in traditional yards ($p < 0.04$) and ET_{vol} in water-conserving yards were lower than in traditional yards, although this was only marginally significant ($p < 0.07$). In Los Angeles, ET_{vol} of water-conserving and wildlife-friendly yards were 677 L d^{-1} and 685 L d^{-1} less than in low-input traditional yards ($p = 0.03$ and $p = 0.046$). In Phoenix, ET_{vol} of water-conserving yards were 644 L d^{-1} less than high-input yards ($p = 0.049$) and ET_{vol} of wildlife-friendly yards were 610 L d^{-1} less than high-input yards, although this was only marginally significant ($p = 0.065$). ET_{vol} of water-conserving yards were significantly higher in Miami compared to the rest of the cities ($p \leq 0.001$). Note the importance of including the yards with $A_{lawn} = 0$ m^2 in this analysis; these yards represent the minimum of the range of lawn sizes, allowing for interpretation of the effect of non-traditional yard landscape types on ET_{vol}.

3.4 Soil moisture in non-lawn yard cover types and natural reference sites

VWC in lawns was significantly higher than in non-lawn groundcovers of the yards in Boston ($p = 0.005$), Miami ($p = 0.03$), Los Angeles ($p < 0.001$), and Phoenix ($p = 0.004$). In

Boston, Los Angeles, and Phoenix, the difference between VWC in lawns and non-lawn groundcovers reached ~ 0.10 m^3m^{-3} (Fig. 7).

VWC in lawns was significantly higher than reference sites in Boston (ANOVA; $p = 0.03$), Los Angeles ($p = 0.001$), and Phoenix ($p < 0.001$). In Miami, VWC in lawns was not significantly different from reference sites ($p > 0.99$).

In the arid cities of Los Angeles and Phoenix, there was a clear pattern of the VWC in lawns being greater than VWC of non-lawn groundcovers of the yards, and VWC of non-lawn groundcovers being greater than that of reference sites (Fig. 7). The insertion of soil moisture probes in the desert soils at the reference sites in Phoenix was not feasible due to the dry conditions. In Minneapolis-St. Paul and Baltimore, VWC did not significantly differ among the lawns, non-lawn groundcovers in the yards, and reference sites (ANOVA; $p > 0.1$ for all).

Because of the regional differences in maximal VWC and the lack of inter-regional calibration of soil probes, the comparison of VWC among the cities would not be informative; therefore, we did not analyze statistical differences among cities.

4 Discussion

Our results supported the hypothesis that ET of residential lawns per unit ground area would be higher in cities with arid climates – represented by Los Angeles and Phoenix – and lower in cities with mesic climates – represented by Boston, Minneapolis-St. Paul, Baltimore, and Miami. We observed significantly higher mean and maximum ET_{inst} and ET_{daily} in Phoenix and Los Angeles compared to other cities (Fig. 2a and 5). We also hypothesized that ET of residential lawns per unit ground area would be higher in yards with traditional landscape types that may follow common irrigation practices and lower in yards with water-conserving and wildlife-friendly features that may adopt water-conscious and environmentally friendly practices. When considering ET_{inst} and ET_{daily}, our results did not support this hypothesis. Instead, we found that ET_{inst} is mostly driven by I_0 (Fig. 3), and the management types of the yards did not explain any residual variation in our empirical models. In the arid cities of Los Angeles and Phoenix, where we expected a noticeable contrast between lawns in traditional and water-conserving yards, we observed high ET_{inst} that was equal to or exceeded ET_0 (Fig. 4), regardless of yard landscape type. Our hypothesis was supported, however, when considering volumetric water losses caused by ET in each yard: ET_{vol} was higher in traditional yards, which had larger lawns than water-conserving and wildlife-friendly yards.

4.1 ET of residential turfgrass lawns

ET_{daily} of turfgrass lawns (as estimated from ET_{inst}) in this study was consistently lower than in previous studies that reported turfgrass ET of open, sun-exposed experimental plots during the growing season in various climate regions in the US (Amgain et al., 2018; Beard, 1973; Duble, 1996; Feldhake et al., 1983; Wherley et al., 2015). As the main driver of lawn ET is I_0 (Feldhake et al., 1983; Litvak et al., 2014; Shashua-Bar et al., 2009), these differences likely arise because lawns in this study were often partially or fully shaded. Residential lawns are typically located next to houses and other buildings and are often surrounded by trees and other shadow-casting objects. Differences in light regimes are a likely reason that explains why previously reported daily ET rates measured during the growing season were approximately twice as high (3 – 6 mm d^{-1} in mesic environments and 8 – 12 mm d^{-1} in more arid environments; Amgain et al., 2018; Beard, 1973; Duble, 1996; Feldhake et al., 1983; Wherley et al., 2015) as the estimated ET_{daily} in the present study (0 – 3.3 mm d^{-1} in mesic cities and 1.4 – 5.5 mm d^{-1} in arid cities).

In situ measurements of ET_{inst} of unshaded versus shaded turfgrass lawns in public parks and arboretums in Los Angeles by Litvak et al. (2014), which used the same chamber method as in this study, support the important role of shading effects. Indeed, ET_{inst} of Los Angeles residential lawns from the present study (0.30 ± 0.09 mm h^{-1}; Fig. 2) was in close agreement with ET_{inst} of the lawns in Los Angeles parks that were shaded by 70 – 80% tree cover (0.32 ± 0.15 mm h^{-1}) and less than half the ET_{inst} of unshaded lawns in the parks (0.76 ± 0.19 mm h^{-1}). Daily ET in unshaded parks (Litvak et al., 2014) were in good correspondence with established daily ET rates of turfgrass from lysimetry studies in hot and dry environments (Beard, 1973; Duble, 1996; Feldhake et al., 1983). Turfgrass ET is strongly controlled by radiation because its even canopy surface is poorly coupled to the bulk atmosphere, and therefore experiences high humidity within the canopy (Feldhake et al., 1983; Litvak et al., 2014; Shashua-Bar et al., 2009). Close correspondence between ET_{inst} of residential and park lawns with similar light intensities indicates the consistency of turfgrass water use under conventional lawn care practices.

Compared to ET_{inst} of experimental turfgrass plots (which are open and sun-exposed), our *in situ* findings of residential lawn ET_{inst} better take into account local environmental conditions in residential yards, including lawn light and species variability. In addition, sparser grass cover, thatch or fallen leaves on top of the grass canopy, and the presence of certain weeds may also contribute to lower ET_{inst} of residential lawns.

4.2 Differences between mesic and arid cities

One of the goals of this study was to compare ET of residential yards among cities based on *in situ* measurements. To make this possible, we used specific criteria to select comparable study locations in each city (Text S1), developed an empirical methodology applicable across locations (Fig. S3), and strategically scheduled the timing of the measurements in each city (Table 1). We made most *in situ* measurements during the peak growing season to capture peak ET in each climatic zone while avoiding periods of frequent and heavy precipitation that would have interfered with our measurements (Table 1). We scheduled the measurements as close as logistically possible to the time of expected peak annual ET in each city in an effort to collect a short record of observations that allowed for comparison across regions and to capture the most prominent inter-regional differences.

We assessed whether this experimental design, in which the measurements occur at different times in each city, allows for rigorous comparison of peak growing season ET of residential lawns among cities. As has been established by previous studies (Feldhake et al., 1983; Litvak et al., 2014), I_0 is the most important factor controlling diurnal and seasonal changes in ET of turfgrass lawns. Therefore, the ideal timing of the measurements is on the days when I_0 approaches its annual maximum. Because of the changes in cloudiness, rains, and constantly changing shading regimes, determining the timing of the highest I_0 in each individual yard without continuous *in situ* observations is virtually impossible. To circumvent this difficulty, we evaluated the quality of our ET dataset using the times of theoretical maxima of I_0 in each city. We obtained daily insolation calculated from latitude and longitude of each city for each day of our field measurements (https://data.giss.nasa.gov/modelE/ar5plots/srlocat.html) and compared them to maximum insolation in 2018 that was reached on June 16-17 in Miami and on June 18-20 in Boston, Minneapolis-St. Paul, Baltimore, Los Angeles, and Phoenix. The timing of our measurements in Boston, Minneapolis-St. Paul, Baltimore, Miami, Los Angeles, and Phoenix corresponded to 90.9 ± 3.7%, 93.0 ± 2.0% 99.5 ± 0.5%, 95.9 ± 2.1%, 99.0 ± 0.4%, and 99.8 ± 0.2% of the corresponding maximum annual insolation in each city. The linearity of the relationship between I_0 and ET_{inst} (Fig. 3a) allowed us to correct ET_{inst} and ET_{daily} for possible underestimation of seasonal peak values by applying linear multipliers. Thus, for Boston, where deviation from the day with maximum insolation was the highest among the cities, the multiplier is 1.10 ± 0.05. This correction will increase ET_{inst} in Boston by 0.01 mm h^{-1} (note that the methodological error of our chamber measurements is 0.08 mm h^{-1}; Methods 2.4) and ET_{daily} by 0.1 mm d^{-1} and have no effect on the results of the statistical comparison of ET_{inst} and ET_{daily} among the cities, described in Results 3.1 and 3.3 and discussed below. The correction factors for other cities are even smaller and also have no effect on the observed patterns of ET_{inst} and ET_{daily} across the cities. Therefore, we conclude that our experimental design produced a reasonably good representation of seasonal maximum ET of residential lawns in studied cities, allowing for useful comparisons.

In accord with the initial hypothesis, residential lawns in mesic cities had lower ET_{daily} than the lawns in arid cities (Fig. 5). This is in stark contrast with the pattern of daily ET of the surrounding natural reference ecosystems (Table 1), according to the study by Lu & Zhuang (2010) that used eddy covariance and satellite data to calculate daily ET in April through August of 2004 and 2005. During the peak growing season, daily ET was significantly higher in mesic regions than in arid regions (Lu & Zhuang, 2010). This mismatch highlights the large degree of decoupling of residential lawns from regional climate and precipitation patterns, as well as the dominance of anthropogenic factors in driving ET of residential lawns. A global analysis of satellite-based land cover and 1 km resolution ET revealed a worldwide pattern of higher urban ET compared to non-urban settings in arid climates and lower urban ET compared to non-urban settings in mesic climates, on a monthly time scale (Mazrooei et al., 2021). While our short data record may not be directly compared to this finding, our results suggest that ET of residential lawns may contribute to this general pattern.

Although we did not have access to data on irrigation rates of individual yards, irrigation is a primary anthropogenic factor driving differences between residential lawn ET and regional rates of ET. A previous study showed that 64 – 92% of households in the studied cities irrigate their lawns (Locke et al., 2019). As precipitation in Los Angeles and Phoenix was extremely low during the measurement months (0.3 mm and 0.5 mm, respectively), irrigation was almost certainly the primary cause of high VWC that we detected (Fig. 7). Our results also indicate that the difference between VWC of residential lawns and interstitial and natural reference sites in Los Angeles and Phoenix ($\Delta VWC = 0.2 – 0.3\ m^3\ m^{-3}$) is significantly larger than the difference between residential lawns and reference sites in the mesic cities ($\Delta VWC < 0.15\ m^3\ m^{-3}$; $p < 0.001$; Fig. 7). Large differences in VWC of residential lawns and surrounding ecosystems combined with higher D (Fig. 2) results in amplified ET in Los Angeles and Phoenix relative to natural conditions.

4.3 Environmental and anthropogenic factors controlling ET variability

I_0 explained most of the variability in ET_{inst} of residential lawns in most studied cities. However, I_0 was not a good predictor of ET_{inst} in Phoenix and Miami (Table 2). In addition, ET_{inst} in these two cities diverged significantly from *in situ* ET_0 (Fig. 4). We speculate that unexplained ET_{inst} variability in Phoenix may be caused by highly heterogeneous microclimatic, soil, and grass conditions of residential lawns. Many yards studied in Phoenix contained dry patches of grass and topsoil, especially in sunlit patches, as opposed to greater grass biomass and more moist topsoil in the shade. Also, the combination of very high D (Fig. 1), small lawn sizes (Fig. 6a), and large contrasts in VWC between the lawns and their surroundings (Fig. 7) may have caused edge effects, i.e., advection of hotter and drier air to the lawn surface (Oke , 1979). In contrast, in Miami there was a strong negative relationship between the residuals of the $ET_{inst}(I_0)$ relationship and D (Fig. 3b and Table 2). We postulate that local atmospheric D was influenced by lawn ET_{inst}, which may negatively feedback to suppress ET_{inst}. This phenomenon, as well as micrometeorological edge effects, may influence ET_{inst} at very localized spatial scales and introduce an additional level of complexity to modeling lawn ET.

Variability in ET_{inst} unexplained by empirical functions of I_0 (Table 2) may have been caused by anthropogenic factors such as landscape type, but this was not detected by our statistical analyses, likely due to high variability within yard management categories. Water-conserving and wildlife-friendly yards in particular vary greatly in landscape type, which may influence VWC in the adjacent lawn. In addition, three water-conserving yards in Los Angeles, two wildlife-friendly yards in Miami, and one wildlife-friendly yard in Minneapolis-St. Paul, as well as Los Angeles and Phoenix, had no lawns at all (Table S1; one traditional yard, located in Miami, also had no lawn). Since there were no lawns in these yards, we were unable to include them in our analysis of ET_{inst} and ET_{daily}. This resulted in small sample sizes, limiting our ability to detect the direct influence of yard landscape type and management on ET_{inst} and ET_{daily}.

Plant biological characteristics, such as species compositions and leaf area, and community processes, such as successional dynamics and competition, strongly influence the responses of ET to soil moisture variation and nutrient availability in natural environments (Wang et al., 2019). In residential yards, soil moisture variations are minimized by irrigation and nutrient contents are enhanced through fertilizer application. While our study was designed to capture different applications of irrigation and fertilizer, many lawns experience non-limiting soil VWC and nutrient contents, as well as even canopies with high boundary layer resistance that reduce the exposure of leaves to the bulk atmosphere. Therefore, the effects of turfgrass physiological characteristics on ET are effectively reduced. Under these conditions, physical processes such as solar intensity may largely drive ET (Jarvis, 1985). Therefore, despite compositional differences of lawns in the studied cities (Wheeler et al., 2017; Trammell et al., 2019), species composition is not likely to strongly influence lawn ET, although it may explain some of the variability unaccounted for by atmospheric variables.

4.4 ET under unlimited soil water supply

In situ ET_0 was a good predictor of ET_{inst} in Los Angeles (Eq. 4), indicating that the lawns in Los Angeles operated at the theoretical maximum of turfgrass ET (Allen et al., 1998). In Phoenix, *in situ* ET_0 was lower than ET_{inst}, which may seem paradoxical (Fig. 4). However, the discrepancy between actual ET_{inst} and *in situ* ET_0 in Phoenix was observed at $D = 5 \pm 1$ kPa (Fig. 2c). We previously reported $ET_{inst} >$ *in situ* ET_0 for lawns in parks in the Los Angeles Metropolitan area that were exposed to D reaching 5 kPa. $ET_{inst} >$ *in situ* ET_0 indicates that empirical coefficients in Eq. 3, which were initially intended for environments with $rh \geq 45\%$ (Allen et al., 1998), do not accurately represent ET of small, urban, water-unlimited turfgrass lawns under high D conditions. ET_{inst} of residential lawns in all studied mesic cities was lower than ET_0 (i.e., $k_L < 1$). $k_L < 1$ may reflect relatively sparse turfgrass cover, physiological differences of turfgrass species, and the presence of weeds, fallen leaves or thatch on top of grass cover. If the sum of irrigation and precipitation inputs received by these lawns exceed $k_L \cdot ET_0$, the excess water inputs will be lost to drainage and/or runoff and contribute to environmental issues caused by urban lawns.

While we did not measure the irrigation rates of the households in the present study, the lack of positive correlation between ET_{inst} and VWC indicates that ET of residential lawns was not limited by soil water supply. Hence, residential lawns received either sufficient or excessive amounts of water from precipitation, irrigation, and possibly other urban water sources (D'Aniello et al., 2021; Hibbs and Sharp, 2012; O'Driscoll et al., 2010; Pilone et al., 2021). Baltimore was the only city where ET_{inst} was correlated with VWC. However, the correlation was negative (Fig. 3b), reflecting soil water depletion by ET and suggesting that the water inputs were sufficient but not excessive to sustain ET. Note that VWC in residential lawns in Baltimore was not significantly different from natural and interstitial reference sites, indicating that VWC of these lawns was not significantly altered by irrigation (Fig. 7). This is supported by previous findings that fewer households in Baltimore irrigate their lawns (64%) compared to the other studied cities (70 - 85% in the mesic cities and 90 - 92% in the arid cities; Locke et al., 2019).

Non-limiting VWC, indicated by the lack of positive correlation between ET_{inst} and VWC (Fig. 3) and non-limiting soil nutrient content, indicated by the similarity of ET_{inst} as well as ET_{daily} between high- and low-input traditional yards, directly stem from human actions, such as irrigation and fertilization of residential lawns. Specifically, our results show that irrigation largely decouples soil water content of residential lawns in arid cities from regional climatic and hydrologic conditions (Fig. 7). All in all, our results highlight the role of human actions in shaping ET of residential lawns across the US by alleviating typical constraints on ET.

5 Conclusions and implications

Our study evaluated ET of residential lawns within six cities in the US and the differences among cities to understand the role of environmental and anthropogenic factors in ET variability. Based on *in situ* measurements of ET_{inst}, we estimated that ET_{daily} varied from 0 - 3 mm d^{-1} in Boston, Minneapolis-St. Paul, Baltimore, and Miami (mesic cities) and from 1 - 5 mm d^{-1} in Los Angeles and Phoenix (arid cities) during the peak growing season in each region. Contrary to our expectations, we did not detect differences in ET_{inst} or ET_{daily} of residential lawns located in yards with different landscape types (traditional high- and low-input, water-conserving, and wildlife-friendly) in any of the studied cities. Instead, we found that residential lawn ET is a largely physically driven process, shaped by incoming solar radiation. There is a strong environmental (climatic) component influencing variability in ET within and across cities, though in arid cities, ET is likely greatly enhanced by irrigation as an anthropogenic driving factor that alleviates soil moisture limitations.

However, while lawn ET per unit ground area (ET_{inst} and ET_{daily}) was not significantly lower in water-conserving or wildlife-friendly yards than in traditional yards, households with these landscape types generally had much smaller lawns or no lawns at all, resulting in lower total volumetric lawn water losses per yard. Therefore, encouraging homeowners to adopt these alternative yard practices will promote water conservation if lawns are replaced with vegetation that has lower transpiration rates. Previous studies have shown that even large trees tend to have much lower transpiration rates than irrigated lawns, due to the high leaf area index of lawns, which can exceed even closed canopy natural forests (Litvak et al., 2014; Litvak et al., 2017).

Hence, xeriscaping, rain gardens, and wildlife-friendly yards may all be advantageous for water conservation if adoption of these landscape types reduces lawn area.

Our *in situ* measurements also demonstrate that, due to the shade from residential buildings, trees, and other objects, turfgrass lawns in residential settings have lower ET_{inst} compared to fully sunlit turfgrass lawns. Coupling lower ET_{inst} with small, shaded lawn areas is promising to limit volumetric ET losses (ET_{vol}). This water-conserving strategy may be more appealing to homeowners than completely replacing lawns, which have recreational, aesthetic, and cultural value. Reducing lawn sizes can also minimize other environmental impacts from residential yards, mitigate homogenization of biodiversity, and curb water-wasting practices. The ultimate success of strategies to manage ET fluxes from residential yards will depend on the long-term adoption and resilience of yard landscape types, management practices, and irrigation rates in future residential landscapes.

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Conflict of Interest

The authors declare no conflict of interest relevant to this work.

Open Research

Data Availability Statement

Primary and processed data associated with this manuscript are available from HydroShare http://www.hydroshare.org/resource/5ccf158f4cd5497e9576511fc41836b3 (Grijseels et al., 2022). Figures were created in R (R Core Team, 2020), package *ggplot2* (Wickham, 2016) and SigmaPlot. Artist impression renderings were created with *Lumion Pro Student*. Data from the NOAA National Centers for Environmental Information () was used to give an overview of the climate normals for each studied city in this manuscript. Data from California Irrigation Management Information System (CIMIS) and the National Science Foundation's National Ecological Observatory Network (NEON, 2021) flux tower NOGP (Northern Great Plains Research Laboratory) were used for the creation of Figure S4.

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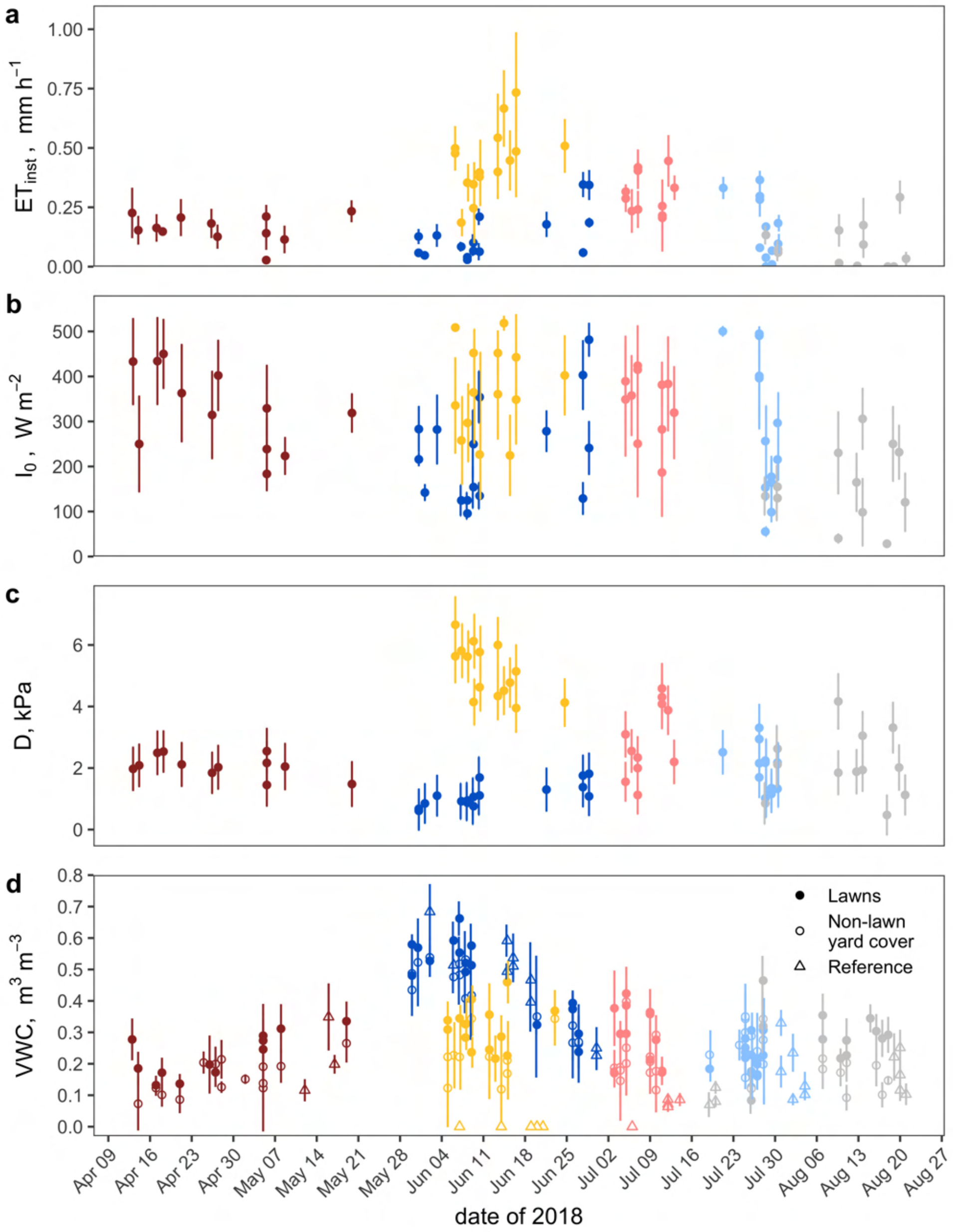
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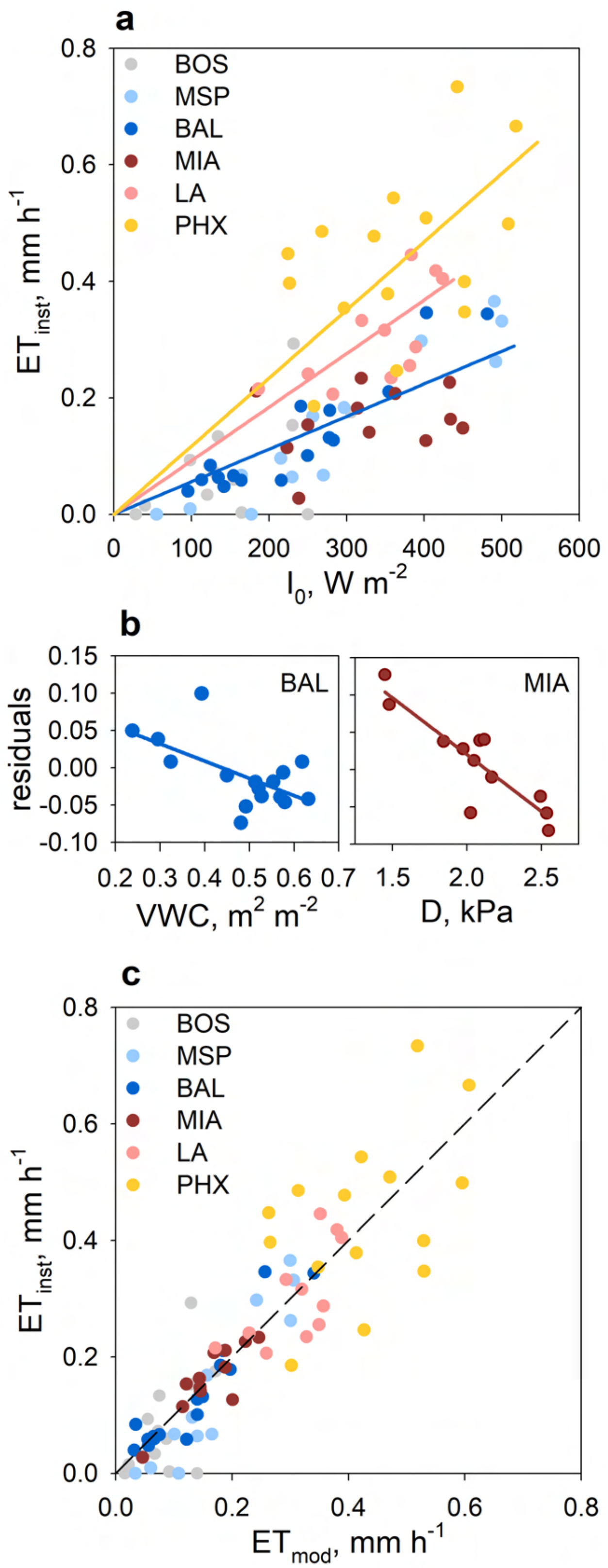
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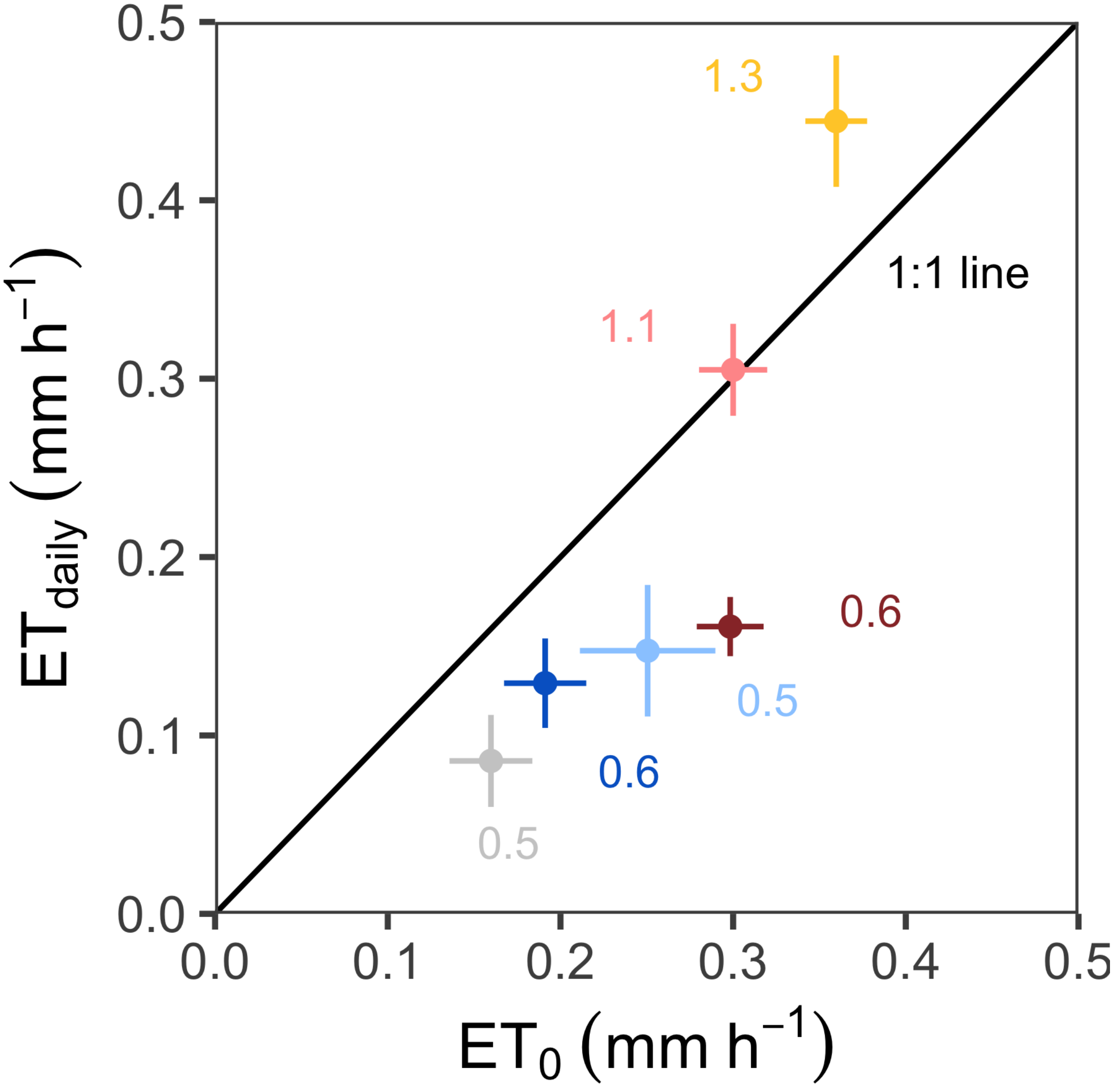

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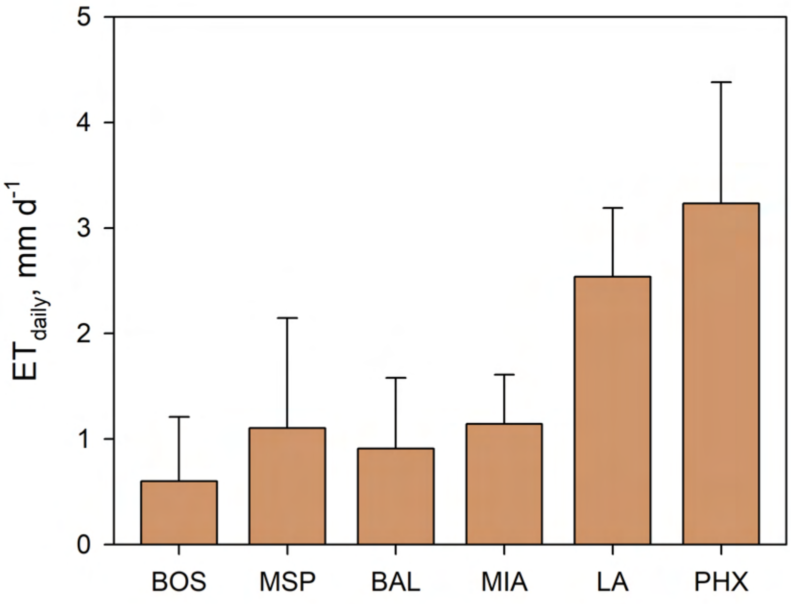
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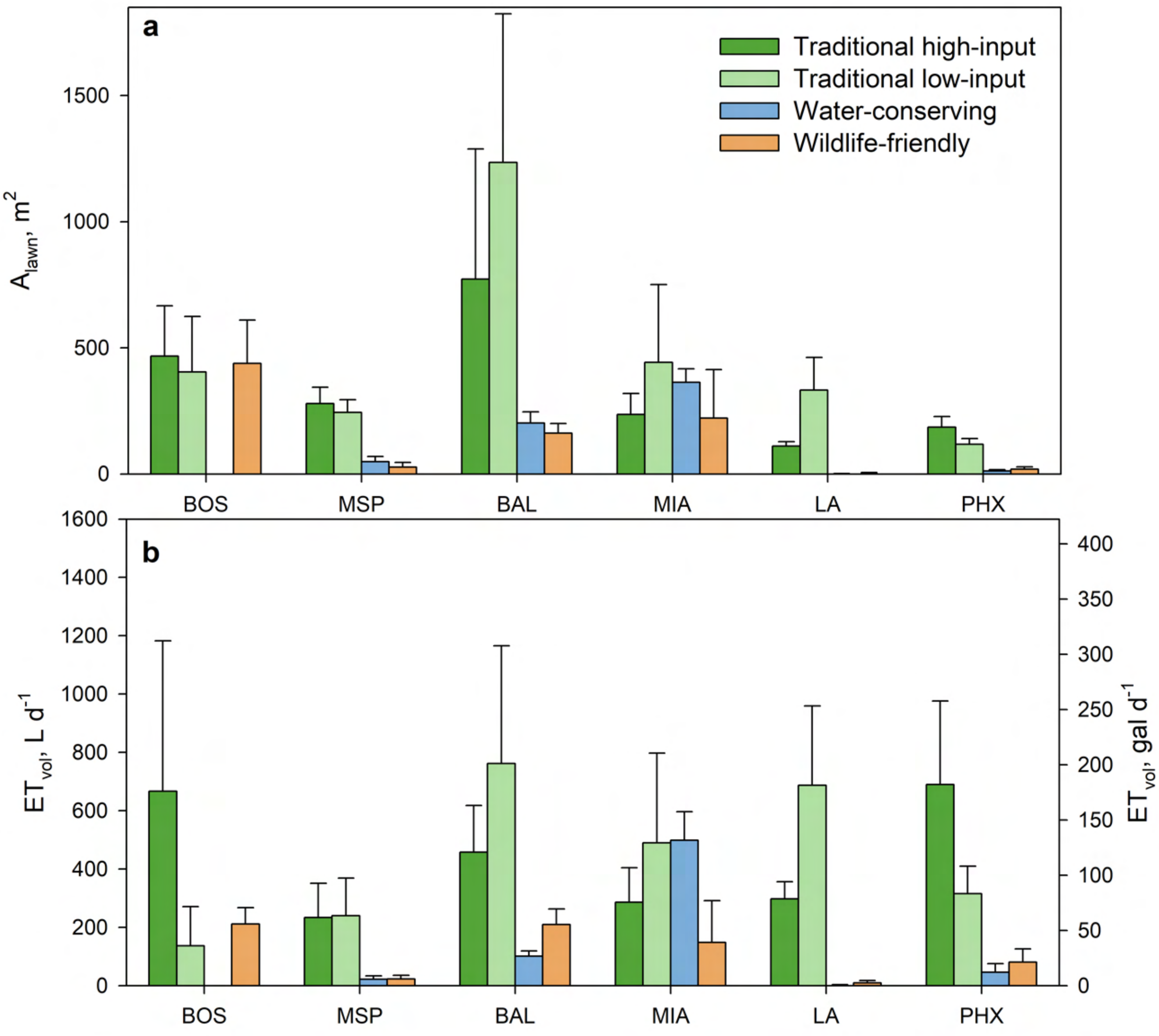
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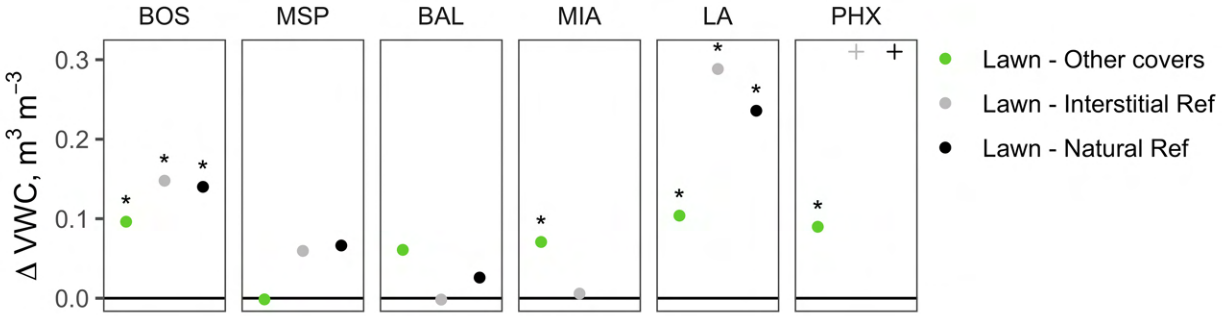
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Table 1. Cities where study sites were located, numbers of studied yards with lawns in each city, averaged lawn sizes, months in 2018 when the measurements were made in each city, ecoregions as defined by the U.S. EPA (www.epa.gov/eco-research/ecoregions-north-america), NOAA average climatological precipitation and temperature for each region during measurement months (Arguez et al., 2010), and the natural reference ecosystem of each region.

Figure 1. Artist's generalized rendering of yards with traditional, water-conserving and wildlife-friendly landscape types. Most traditional yards (left) have lawns in the front and in the back of the house, and sometimes on the sides. Water-conserving yards (middle) contain water retention features (e.g., rain barrels and water retention gardens) or xeriscaping features (e.g., rock gardens and succulent plants). Wildlife-friendly yards (right) have features that support local wildlife (e.g., native plants and birdbaths). See text for more details. Image: courtesy of Alexander H. Vincent.

Figure 2. (a) Instantaneous evapotranspiration (ET_{inst}; measured between 10 AM – 4 PM), (b) the intensity of incoming solar radiation (I_0), (c) vapor pressure deficit (D) and (d) volumetric water content of the soil (VWC) measured onsite at studied residential lawns. Each point represents one yard, including all four yard landscape types. The data from the lawns in front- and backyards were averaged to obtain one datapoint per yard. For VWC, the data from other ground covers within studied yards, and reference sites (interstitial and natural) are also shown. The measurements were made during the growing season in each city (Table 1). Error bars show one standard deviation for ET_{inst}, I_0, and VWC (n = 4 - 6) and one propagated measurement error for D (n=1). Zero VWC values at reference sites in Los Angeles and Phoenix correspond to extremely dry soil conditions.

Figure 3. (a) Instantaneous evapotranspiration of residential lawns (ET_{inst}) plotted against the intensity of incoming solar radiation (I_0) shown with linear regression lines for Boston, Minneapolis-St. Paul, Baltimore, and Miami combined (blue line), Los Angeles (pink line), and Phoenix (yellow line). (b) Residuals of the regressions shown on panel (a) for Baltimore and Miami versus volumetric water content of the soil (VWC) and vapor pressure deficit of the air (D), correspondingly. (c) Instantaneous evapotranspiration of residential lawns (ET_{inst}) plotted against empirically modeled ET for each city (ET_{mod}; see Table 2 for details), shown with a 1:1 line. Each data point represents one yard (data from lawns in front- and backyards were averaged).

Table 2. Equations and coefficients related to empirical modeling of instantaneous ET (ET_{inst}) in each city. Equations show the final model for ET_{inst} in each city as selected with a stepwise forward model selection procedure. Regression coefficients were derived from the regressions in Fig. 3 and adjusted R^2, p-value and the standard deviation of the residuals (root mean square error, or RMSE) is given for each regression.

Figure 4. Instantaneous evapotranspiration of residential lawns (ET_{inst}) averaged for each city plotted against ET_0 (Equation 3; RMSE = 0.14), shown with a 1:1 line. The numbers indicate landscape coefficients calculated as $k_L = ET_{inst}/ET_0$. Error bars represent one model error (horizontal) and one standard error of the estimate (vertical).

Figure 5. Estimated daily ET (ET_{daily}, mm d^{-1}) of studied residential lawns averaged for each city. Error bars show one standard deviation.

Figure 6. (a) Lawn areas in studied residential yards (A_{lawn}, m^2) averaged for each yard landscape type. (b) Volumetric water losses caused by ET of residential lawns in the studied yards (ET_{vol}, L d^{-1} and gal d^{-1}) averaged for each yard landscape type. Note that no data was collected in water-conserving yards in Boston. Error bars show one standard error for the lawn areas and propagated error for ET_{vol}.

Figure 7. The difference in average volumetric water content (ΔVWC) between the studied residential lawns and other ground covers within studied yards, interstitial reference sites, and natural reference sites (no measurements were made at natural reference sites in Miami). VWC was measured at 10-16 residential yards and 3-5 reference sites in each city. Asterisks indicate significant differences according to two-way ANOVA/Tukey HSD or KWRS/PWRS (see Methods) with $p < 0.05$. Plus symbols indicate that VWC was assumed to be zero at the reference sites in and near Phoenix that did not allow for the insertion of soil moisture probes due to extremely dry soil conditions (not included in statistical test).

Metro area	**Abbr.**	**Number of yards with lawns in each yard type (lawn size in m^2 ± SD)**					**Measure-ment months**	**Ecoregion**	**Average precip. (mm $month^{-1}$)**	**Average temp. (C)**	**Natural reference ecosystem**
		overall (n = 80)	traditional high-input	traditional low-input	water-conservation	wildlife-friendly	2018				
Boston, Massachusetts	BOS	12	4 (467 ± 399)	4 (404 ± 440)	-	4 (329 ± 326)	Jul, Aug	Eastern Temperate Forest	86.1	22.7	Northern hardwood forest, pasture
Minneapolis-St. Paul, Minnesota	MSP	13	4 (278 ± 131)	4 (244 ± 100)	3 (55 ± 32)	2 (35 ± 30)	Jul	Eastern Temperate Forest/Great Plains	102.6	23.2	Oak savannah, tallgrass prairie, bluff prairie, maple-basswood forest
Baltimore, Maryland	BAL	16	4 (773 ± 1032)	4 (1235 ± 1179)	4 (202 ± 88)	4 (161 ± 78)	May, Jun	Eastern Temperate Forest	94.6	19.5	Oak and tulip poplar forest
Miami, Florida	MIA	13	3 (235 ± 166)	4 (504 ± 454)	4 (364 ± 106)	2 (221 ± 386)	Apr, May	Tropical Wet Forests	107.8	25.5	Pine rockland, subtropical hardwood hammock, coastal hammock, pine flatwoods
Los Angeles, California	LA	11	4 (111 ± 33)	4 (333 ± 259)	1 (1 ± 1)	2 (9 ± 3)	Jul	Mediterranean California	0.3	22.9	Chaparral shrubland
Phoenix, Arizona	PHX	15	4 (221 ± 107)	4 (181 ± 128)	4 (11 ± 12)	3 (19 ± 18)	Jun	North American Deserts	0.5	32.7	Sonoran Desert

equation	**city**	**coefficients**	**R^2_{adj}**	**p**	**RMSE**
$\boldsymbol{ET_{inst} = kI_0}$	BOS	$k = (5.6 \pm 1.0) \times 10^{-4}$	0.30	0.0009	0.072
	MSP	$k = (6.1 \pm 0.5) \times 10^{-4}$	0.79	<0.0001	0.057
	LA	$k = (9.2 \pm 0.5) \times 10^{-4}$	0.47	<0.0001	0.060
	PHX	$k = (11.7 \pm 10.2) \times 10^{-4}$	0.09	<0.0001	0.132
$\boldsymbol{ET_{inst} = k_1 I_0} + (\boldsymbol{y_0} + \boldsymbol{k_2 VWC})$	BAL	$k_1 = (6.1 \pm 0.4) \times 10^{-4}$ $y_0 = 0.10 \pm 0.04$ $k_2 = -0.23 \pm 0.08$	0.79 0.34	<0.0001 0.036	0.028
$\boldsymbol{ET_{inst} = k_1 I_0} + (\boldsymbol{y_0} + \boldsymbol{k_2 D})$	MIA	$k_1 = (4.6 \pm 0.5) \times 10^{-4}$ $y_0 = 0.33 \pm 0.05$ $k_2 = -0.15 \pm 0.03$	0.00 0.76	<0.0001 0.031	0.028