Sensitivity of soil hydrogen uptake to natural and managed moisture dynamics in a semiarid urban ecosystem

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The North American Monsoon season (June-September) in the Sonoran Desert brings thunderstorms and heavy rainfall. These rains bring cooler temperatures and account for roughly half of the annual precipitation making them important for biogeochemical processes. The intensity of the monsoon rains also increase flooding in urban areas and rely on green infrastructure (GI) stormwater management techniques such as water harvesting and urban rain gardens to capture runoff. The combination of increased water availability during the monsoon and water management provide a broad moisture regime for testing responses in microbial metabolism to natural and managed soil moisture pulses in drylands. Soil microbes rely on atmospheric hydrogen (H_2) as an important energy source in arid and semiarid landscapes with low soil moisture and carbon availability. Unlike mesic ecosystems, transient water availability in arid and semiarid ecosystems has been identified as a key limited driver of microbe-mediated H_2 uptake. We measured soil H_2 uptake in rain gardens exposed to three commonly used water harvesting practices during the monsoon season in Tucson AZ, USA. *In situ* static chamber measurements were used to calculate H_2 uptake in each of the three water harvesting treatments *passive* (stormwater runoff), *active* (stored rooftop runoff), and *greywater* (used laundry water) compared to an unaltered *control* treatment to assess the effects of water management practices on soil microbial activity. In addition, soils were collected from each treatment and brought to the lab for an incubation experiment manipulating the soil moisture to three levels capturing the range observed from field samples. H_2 fluxes from all treatments ranged between -0.72 nmol m^{-2} s^{-1} and -3.98 nmol m^{-2} s^{-1} over the monsoon season. Soil H_2 uptake in the greywater treatment was on average 53% greater than the other treatments during pre-monsoon, suggesting that the increased frequency and availability of water in the greywater treatment resulted in higher H_2 uptake during the dry season. H_2 uptake was

significantly correlated with soil moisture (r = -0.393, p = 0.001, df = 62) and temperature (r = 0.345, p = 0.005, df = 62). Our findings suggest that GI managed residential soils can maintain low levels of H_2 uptake during dry periods, unlike unmanaged systems. The more continuous H_2 uptake associated with GI may help reduce the impacts of drought on H_2 cycling in semiarid urban ecosystems.

1 **Sensitivity of soil hydrogen uptake to natural and managed moisture dynamics in a**
2 **semiarid urban ecosystem**

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26 **Abstract**

27   The North American Monsoon season (June-September) in the Sonoran Desert brings
28   thunderstorms and heavy rainfall. These rains bring cooler temperatures and account for roughly
29   half of the annual precipitation making them important for biogeochemical processes. The
30   intensity of the monsoon rains also increase flooding in urban areas and rely on green
31   infrastructure (GI) stormwater management techniques such as water harvesting and urban rain
32   gardens to capture runoff. The combination of increased water availability during the monsoon
33   and water management provide a broad moisture regime for testing responses in microbial
34   metabolism to natural and managed soil moisture pulses in drylands. Soil microbes rely on
35   atmospheric hydrogen (H_2) as an important energy source in arid and semiarid landscapes with
36   low soil moisture and carbon availability. Unlike mesic ecosystems, transient water availability
37   in arid and semiarid ecosystems has been identified as a key driver of microbe-mediated H_2
38   uptake. We measured soil H_2 uptake in rain gardens exposed to three commonly used water
39   harvesting practices during the monsoon season in Tucson AZ, USA. *In situ* static chamber
40   measurements were used to calculate H_2 uptake in each of the three water harvesting treatments
41   *passive* (stormwater runoff), *active* (stored rooftop runoff), and *greywater* (used laundry water)
42   compared to an unaltered *control* treatment to assess the effects of water management practices
43   on soil microbial activity. In addition, soils were collected from each treatment and brought to
44   the lab for an incubation experiment manipulating the soil moisture to three levels capturing the
45   range observed from field samples. H_2 fluxes from all treatments ranged between -0.72 nmol m^{-2}
46   s^{-1} and -3.98 nmol m^{-2} s^{-1} over the monsoon season. Soil H_2 uptake in the greywater treatment
47   was on average 53% greater than the other treatments during pre-monsoon, suggesting that the
48   increased frequency and availability of water in the greywater treatment resulted in higher H_2
49   uptake during the dry season. H_2 uptake was significantly correlated with soil moisture (r = -
50   0.393, *p* = 0.001, df = 62) and temperature (r = 0.345, *p* = 0.005, df = 62). Our findings suggest
51   that GI managed residential soils can maintain low levels of H_2 uptake during dry periods, unlike
52   unmanaged systems. The more continuous H_2 uptake associated with GI may help reduce the
53   impacts of drought on H_2 cycling in semiarid urban ecosystems.

54 **Introduction**

55   Atmospheric H_2 is an abundant trace gas with a global average of 530 ppb (Schmidt,
56   1974; Novelli et al., 1999). The primary sources of atmospheric H_2 are identified as
57   photochemical oxidation, combustion of fossil fuels, and biomass burning (Novelli et al., 1999).
58   H_2 is an indirect greenhouse gas that contributes to climate change by competing for reactions
59   with hydroxyl (OH) radicals in the troposphere (Lee, Rahn & Throop, 2012). If OH radicals react
60   with H_2, they are no longer available to react with methane (CH_4), a potent greenhouse gas,
61   leading to more atmospheric CH_4 (Prather, 2003). H_2 is also a source of water vapor production
62   in the stratosphere, which directly impacts ozone (Lee, Rahn & Throop, 2012). It is estimated
63   that half of H_2 emissions are from human activity, disproportionately impacting atmospheric H_2

64 concentrations and the H_2 cycle of urban ecosystems (Novelli et al., 1999; Ehhalt & Rohrer,
65 2009). Thus, quantifying soil H_2 uptake in urban built landscapes is critical for understanding
66 potential H_2 sinks, and the role of GI on H_2 cycling in drylands.

67 Soil uptake is the primary sink for H_2 from the atmosphere and is dominated by high
68 affinity hydrogen-oxidizing bacteria (HA-HOB) (Conrad & Seiler, 1979; Conrad, 1996; Novelli
69 et al., 1999; Ehhalt & Rohrer, 2009; Khdhiri et al., 2015; Piché-Choquette & Constant, 2019)
70 that efficiently consume H_2 at atmospheric abundances. Annually, 75% of tropospheric H_2 is
71 oxidized by soil microbes for use as an energy source (Schmidt, 1974; Rhee, Brenninkmeijer &
72 Röckmann, 2006). The uptake of atmospheric H_2 into soils also contributes to the natural cycling
73 of H_2 and has been studied extensively (Smith-Downey, Randerson & Eiler, 2006, 2008;
74 Constant, Poissant & Villemur, 2009; Meredith et al., 2014, 2017; Greening et al., 2015; Khdhiri
75 et al., 2015; Piché-Choquette & Constant, 2019). Both field and laboratory studies have shown
76 that H_2 uptake increases with soil temperatures and drying (Smith-Downey, Randerson & Eiler,
77 2006, 2008; Meredith et al., 2017). Although microbial H_2 uptake varies during different life
78 stages and is more common during late growth stages and dormancy (Constant et al., 2010;
79 Meredith et al., 2014; Greening et al., 2015), recent studies have shown microbial uptake during
80 active growth (Islam et al., 2020), which may be stimulated by moisture availability in arid and
81 semiarid environments, highlighting the importance of H_2 for microbial metabolism in desert
82 biomes (Jordaan et al., 2020).

83 Arid lands account for roughly 41% of the Earth's terrestrial surface, support more than
84 one third of the world population, and are projected to expand with changes in climate (Wang,
85 Chen & Dong, 2006; Feng & Fu, 2013; Maestre et al., 2015; Huang et al., 2016; Prăvălie, 2016).
86 In arid and semiarid ecosystems, natural precipitation regimes are important determinants of
87 ecological activity (Noy-Meir, 1973; Huxman et al., 2004). However, changes in natural
88 hydrological processes due to human activity and management may be as important as natural
89 patterns of precipitation on biogeochemical cycling (Austin et al., 2004). As more of the world's
90 population inhabit and alter drylands, reliance on both natural and managed water sources will
91 also increase.

92 Tucson, AZ is a city in the Southwest United States which experiences strong seasonal
93 precipitation and increased reliance on green infrastructure (GI) water management practices.
94 The city is home to nearly 1 million residents and is located in the Sonoran Desert, a semiarid
95 ecosystem with two distinct rainy seasons, one during the winter months and one in the summer
96 (Dimmitt, 2000). Unlike the winter rainy season, the summer rains are caused by the North
97 American Monsoon which is characterized by a seasonal shift in the direction of the prevailing
98 winds from the Pacific to winds from the south and southeast, leading to extreme precipitation
99 events in the Southwest. The intensity of summer rain events accounts for half of the annual
100 precipitation and is met by the reduced ability of urban desert soils to rapidly infiltrate such large
101 volumes of water, which can lead to runoff and flash flooding. To combat stormwater runoff and

102 flooding during the North American Monsoon season, cities like Tucson have implemented GI
103 water management practices to mimic natural hydrological processes by directing and capturing
104 large volumes of rainwater in the soils.

105   GI techniques include greywater harvesting, rain water harvesting, bioretention basins,
106 and green rooftops. The implementation of these techniques can help mimic the natural water
107 cycle, alter abiotic factors like soil moisture and temperature, and increase microbe-mediated
108 processes that can alter biogeochemical cycling. For example, microbe-mediated fluxes of
109 important trace gases like carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) varied
110 with GI design (Grover et al., 2013; McPhillips, Goodale & Walter, 2017; Shrestha, Hurley &
111 Adair, 2018). Moreover, GI designed biofilters commonly used for stormwater management
112 acted as a sink for CH_4, and were a small source of N_2O during both wet and dry periods with
113 greater CH_4 emissions during extreme wet events (Grover et al., 2013). Although soil moisture
114 has been identified as the primary driver of fluxes, soil temperature was also reported as a driver
115 of small and variable soil N_2O fluxes and CO_2 emissions from roadside bioretention basins
116 (Shrestha, Hurley & Adair, 2018). In addition, flow-through bioretention basins (flat bottom soil
117 bed) using engineered soil media with high phosphorus and C content were sources of CO_2, N_2O
118 and CH_4 (McPhillips, Goodale & Walter, 2017). Although these studies highlight impacts of GI
119 on greenhouse gas emissions, they are constrained to moist temperate climates which may not
120 translate to understanding natural and managed water inputs from water harvested rain gardens
121 in desert urban ecosystems.

122   GI water management practices combined with the natural precipitation patterns in
123 dryland environments impact soil moisture and temperature which directly impact
124 biogeochemical cycling (Buzzard et al., 2021). Rain gardens irrigated with harvested water are
125 common GI techniques that alter the nutrient inputs, and the frequency and quantity of wetting
126 events. The soil moisture legacy in GI systems is also dependent on the local monsoonal
127 precipitation regime, which brings cooler temperatures and ensures water is replenished for
128 irrigation during periods of drought. These changes in precipitation imposed by this natural and
129 managed moisture regime provide a unique opportunity to directly measure these critical
130 environmental drivers to better understand the role of soil H_2 uptake in a dryland environment. In
131 this study, we use a residential GI rain garden to assess how seasonal precipitation and irrigation
132 from harvested water sources impact H_2 fluxes. To test the combined effects of seasonal
133 precipitation and GI water management on soil H_2 fluxes, we ask, (i) how does the precipitation
134 regime, specifically monsoons, of the Sonoran desert influence H_2 fluxes?; and (ii) do different
135 GI water harvesting techniques affect soil H_2 fluxes? Greater H_2 uptake has been observed in
136 ecosystems with high temperatures and variable soil moisture highlighting the sensitivity of H_2
137 to soil moisture availability in water-limited environments (Conrad & Seiler, 1985). Therefore,
138 we hypothesize that increased water availability observed during the monsoon season leads to
139 greater H_2 uptake and that soils from GI water harvesting rain gardens would result in more H_2

140 uptake during the dry season when managed basins continue to receive water through regular
141 irrigation.

Materials & Methods

143 Study system

144   Our study site is located at a residence in central Tucson, Arizona - with a mean annual
145 temperature of 17°C and the average annual rainfall is 32.2 cm (Paul R. Sheppard, Andrew C.
146 Comrie, Gregory D. Packin, Kurt Angersbach, and Malcolm K. Hughes, 1999). In November of
147 2017, a green infrastructure (GI) water harvesting system was installed by Watershed
148 Management Group Inc. at our study site; site pictures and study design are described in
149 (Buzzard et al., 2021). Specifically, three rain garden basins were dug to direct and capture
150 rainwater in a 3000 gallon plastic rain storage tank as described in (Buzzard et al. 2021). Three
151 GI treatment plots (1 m x 4 m) received different water inputs and sources (*passive* stormwater
152 runoff, *active* irrigated with tank-stored harvested rainwater, and *greywater* from laundry) along
153 with an unaltered control treatment area that represented the initial, flat pea gravel-lain condition.
154 All treatments were composed of four 1 m^2 batches within a 4 m by 1 m plot that received
155 limited municipal city irrigation to establish plants and were subjected to the same rainfall, but
156 differed in the inputs and frequency of irrigation from harvested water sources, and the type and
157 depth of the mulch layer as described in (Buzzard et al. 2021). Specifically, the *greywater*
158 treatment was irrigated with residential laundry water effluent and rain collected in the storage
159 tank. The *active* water treatment received rainwater irrigation from a rain storage tank that
160 collects and stores roof-top runoff, and may also receive overflow from the tank during large rain
161 events that can flood the basin. The *passive* treatment was a dug basin designed to collect
162 stormwater runoff and overflow from the active basin, yet both the *passive* and *control* (flat-
163 elevated landscape) water treatments received primarily incidental rain.

164 Soil monitoring system

165   We installed a meteorological station to measure microclimate variation at the site. We
166 collected local air temperature at 3 meters above ground using a climate sensor (VP-4, METER
167 Group, Inc., Pullman, WA, United States) and rain gauge to measure precipitation (ECRN-100,
168 METER Group, Inc., Pullman, WA, United States). The onsite rain gauge did not work between
169 the 165th and 239th day of the year, and precipitation data from a nearby weather station were
170 used to estimate daily precipitation in the area ("AZMET : The Arizona Meteorological Network
171 : Tucson Station Data Files"). In each treatment, we installed soil moisture and temperature
172 sensors (ECH2O 5TE, METER Group, Inc., Pullman, WA, United States) at 12.5 cm
173 belowground in the center of the treatment, connected to data loggers (EM50, METER Group,
174 Inc., Pullman, WA, United States) collecting hourly data from January 2018 to December 2018
175 (Buzzard et al., 2021).

176   Soil hydrogen fluxes

177   Soil H_2 fluxes were measured using vented static chambers during four campaigns 1) pre-
178   monsoon (June 6th), 2) mid-monsoon (August 8th), 3) late-monsoon (September 12th), and 4)
179   post-monsoon (November 14th), in response to variation in soil moisture throughout the
180   monsoon season and to assess variation in microbial activity across GI treatments. For example,
181   the pre-monsoon campaign was characterized by having high temperatures and low soil
182   moisture; the campaigns during mid-monsoon and late-monsoon season were characterized by
183   high temperatures and high soil moisture; and the post-monsoon campaign was characterized by
184   lower temperatures and intermediate (moist) soil moisture. To estimate H_2 fluxes, four
185   cylindrical PVC collars (20 cm diameter, 20 cm height, surface area = 0.0314 m^2) were installed
186   10 cm into the soil within each treatment one week prior to sampling. All gas sampling was
187   performed between 8:30 and 10:30 a.m. to reduce the effects of high temperatures experienced
188   during the summer months in Tucson, AZ. The mulch layer was removed from the soil collar 2
189   hours prior to sampling to reduce the effect of different mulch types and depths between
190   treatments and allow a direct assessment of the soil surface. Static vented chambers were placed
191   on the soil collar approximately 2 cm to ensure a proper seal and consistent headspace.
192   Immediately following chamber placement, 5 mL gas samples were collected using air-tight
193   syringes from the sampling port at four time points (0, 5, 10, and 15 minutes). All four
194   treatments were sampled at the same time with randomization of samplers (people) and
195   chambers between each batch and treatment to reduce operator-sampling biases. Syringes were
196   placed in a cooler to maintain temperature and reduce exposure to ultraviolet light until they
197   were transferred to the lab. A total of 64 gas samples were collected during a single morning for
198   each time period, totaling 256 gas samples over the monsoon season. H_2 was measured in parts
199   per billion using a reducing compound photometer (RCP model 910-105 series, Peak
200   Laboratories LLC, CA, USA) gas chromatography (GC) within 24 hr of sampling. Each gas
201   sample was measured in triplicates from 1 ml gas injections. Ultra zero grade air was used as the
202   carrier gas. Chamber height and temperature were measured during field sampling and used to
203   calculate H_2 fluxes for each sampling event based on the following equation:

204     $F = (\Delta C/\Delta t) * (P_a \, V/RT) * (1/A)$

205

206   Where F is the H_2 flux (nmol H_2 m^{-2} s^{-1}), $\Delta C/\Delta t$ is the rate of change of the H_2 concentration in
207   the headspace of the chamber through time, P_a is the atmospheric pressure (atm), V is the total
208   chamber volume (L) measured for each chamber and sampling event, R is the gas constant
209   (0.08206 atm L mol^{-1} K^{-1}), T is the temperature of air inside the chamber (K), and A is the
210   surface area covered by the chamber (0.0314 m^2). It is important to note that negative F
211   represents H_2 uptake into the soil, whereas positive F values represent emission of H_2 into the
212   atmosphere, so greater rates of H2 uptake correspond to more negative soil H2 flux values.

213   Soil moisture incubation experiment

214   To determine if moisture was the dominant influence on H_2 fluxes, we conducted a soil
215   microcosm experiment that altered soil moisture levels but with constant temperature. Soil
216   samples from each batch ($n = 4$) within each treatment ($n = 4$) were collected during the post-
217   monsoon sampling and were air dried for approximately seven days until they had a base soil
218   moisture level of roughly 2% gravimetric water content (GWC). GWC was calculated for all air
219   dried samples and water was added to increase the GWC to the three target levels, dry
220   corresponded to the low range of observed GWC values (2%), moist is the average range
221   observed (10%), and wet corresponded to the wet end of the range (20%). Each group
222   represented conditions observed in the field during the 2018 monsoon season. Soils were then
223   incubated at 25 °C for 7-8 days and then H_2 fluxes were measured for three different moisture
224   levels within 24 hours. Moisture levels were maintained during incubation by limiting
225   evaporative loss by covering vials with parafilm wax. Samples were randomized and vials were
226   closed using a rubber stopper for roughly 20 minutes where 1ml of air was removed using an air
227   tight syringe at regular intervals during the 20 minute period to calculate fluxes and directly
228   injected into the GC-RCP to measure H_2 concentrations. Empty serum vials were used as a
229   control and measured during the experiment.

230   GC Calibration

231

232   We used a tank of breathing grade air (Airgas, Al B300) as a working standard for this
233   study. We estimated the amount of H_2 in the breathing air tank to be 664 ppb H_2 by comparison
234   to atmospheric H_2 measurements. Specifically, we used the median H_2 peak areas in breathing air
235   and atmospheric gas measurements and assumed a representative value for typical atmospheric
236   hydrogen concentration of 530 ppb. For each round of field and lab H_2 measurements, we used
237   the median of at least 21 breathing air tank peak areas measured over the course of the sampling
238   event to calculate a GC response factor ([atmospheric H2]/[GC H2_peak_area]). The response
239   factor was used as a scaling factor for single-point calibration of all unknown samples for each
240   sampling event. This approach allowed us to account for possible drift in the GC response factor
241   between measurement days, which ranged from a median of 0.00306 ppb area-1 to 0.00361 ppb
242   area-1. The response factor varied by 5.4% (stdev) across all sampling periods and maintained a
243   smaller variation than the uncertainty of the GC-RCP analyzer of 10%.

244   Statistical analyses

245   All statistical analyses and figures were completed in R (R Core Team, 2012). Daily
246   averages for soil moisture and temperature from each treatment were calculated for the four in
247   situ flux sampling events. The gvlma package in R was used to assess if the model met statistical
248   assumptions (Peña & Slate, 2006). Visual inspection of residual plots did not reveal any extreme

249   outliers or obvious deviations from homoscedasticity or normality for soil H_2 fluxes. We used a
250   two-way mixed analysis of variance (ANOVA) to assess the effects of treatment and season on
251   soil H_2 fluxes. Effect size was determined by generalized eta squared (ges) with small (ges= 0.2),
252   medium (ges= 0.5), and large (ges= 0.8) following Cohen suggested values (Cohen, 1992).
253   Pairwise comparisons were assessed using Tukey's honest significant difference post hoc
254   methods. Soil H_2 fluxes from the microcosm experiment did not meet statistical assumptions for
255   kurtosis. However, results did not differ between transformed and non-transformed H_2 fluxes
256   data from the microcosm, thus nonparametric one way analyses were completed on non-
257   transformed data. A p-value of < 0.05 with Bonferroni adjustment was used to determine
258   statistical significance. Generalized linear regression was used to assess the individual effect of
259   soil temperature and soil moisture on H_2 fluxes.

260   **Results**

261   Meteorological Conditions

262   Meteorological data were used to measure local climate variability over the monsoon
263   season (Fig. 1; Table S1). In 2018, we recorded 342 mm of precipitation and an average air
264   temperature of 22.88 ± 6.34 °C at our site. The average daily air temperature in our study site
265   was similar for the first three sampling dates (i.e., pre-monsoon, mid-monsoon, late-monsoon),
266   ranging from 32.2 to 33.6 °C, but was much lower during the post-monsoon sampling (14 ± 3.62
267   °C). No precipitation was recorded in the week prior to each sampling event, with the exception
268   of the mid-monsoon sampling, which received 6.86 mm of rain the day before sampling.
269   However, prior to that rain event, conditions were relatively dry with no observed precipitation
270   for the previous 10 days. Soil and air temperature followed a similar temporal pattern with the
271   highest temperatures recorded between May and October (Fig. 1A; Tables S1 and S2), and the
272   greatest fluctuation in soil temperature was observed in the control treatment (Buzzard et al.,
273   2021).

274   In situ Soil Hydrogen Fluxes

275   We found that the interaction between green infrastructure (GI) treatment and increased
276   wetting events observed during the monsoon season significantly affected soil H_2 fluxes (Fig. 2;
277   Table 1; *F(9, 48) = 2.72, p = 0.012, ges = 0.338*). In addition, the mean H_2 fluxes from each
278   treatment differed across the four sampling points, with pre-monsoon and late-monsoon H_2
279   fluxes statistically different between treatments. During the pre-monsoon sampling period we
280   observed significantly higher H_2 uptake into the soil in the greywater treatment compared to the
281   passive and control treatments (Table S3). Whereas the passive treatment had a significantly
282   lower uptake into the soil compared to the other treatments during the late-monsoon (Table S3).

283   Soil Microcosm Hydrogen Fluxes

284   We used a microcosm experiment to test the direct effect of different soil moisture levels
285   on soil H_2 fluxes and did not find a significant difference between treatments (Fig. 3; H(3, 48) =
286   1.4, p = 0.706). However, the mean H_2 fluxes were statistically different between the three soil
287   moisture levels observed for each treatment (Table 1; H(2, 48) = 34.35, p < 0.001), with H_2
288   uptake significantly greater at wet moisture levels (20% gwc) than dry (2% gwc) and moist (10%
289   gwc) soil moisture levels (Table S4).

290   Abiotic Drivers of Hydrogen Fluxes

291   Soil temperature and moisture are known drivers of microbial diversity and activity. To
292   test the independent effect of temperature and moisture on H_2 fluxes we assessed the relationship
293   between soil H_2 fluxes from the *in situ* measurements independently with soil temperature and
294   moisture. We found an inverse effect of soil temperature and moisture on soil H_2 fluxes. Soil H_2
295   uptake decreased with increased temperature (r = 0.345, *p* = 0.005, df = 62; Fig. 4), and
296   increased with increased soil moisture (r = -0.393, *p* = 0.001, df = 62; Fig. 4).

297   **Discussion**

298   The primary goal of this study was to examine the interactive effects of green
299   infrastructure (GI) practices and seasonal precipitation on soil H_2 fluxes in a semiarid urban
300   ecosystem. We hypothesized that changes in soil microclimate driven by implementation of GI,
301   specifically changes in soil moisture variability, would lead to increased H_2 uptake in the soils
302   that would be further amplified by seasonal variability in precipitation during the monsoon
303   season. The field observations suggested that soil H_2 uptake was triggered by increased
304   precipitation during the seasonal monsoon across all treatments. In addition, soil H_2 uptake was
305   greater in the greywater treatment compared to the other treatments during pre-monsoon,
306   suggesting that the increased frequency and water availability in the greywater treatment resulted
307   in higher H_2 uptake during the dry season and may support greater microbial consumption of H_2
308   consistently throughout the year. H_2 uptake was significantly correlated with soil moisture and
309   temperature, which are key environmental factors impacted by both the seasonal precipitation
310   regime and GI water management practices.

311   The North American Monsoon triggers biological activity by bringing moisture and
312   cooler temperatures to hot-dry soils. However, the large quantities of rain with each storm may
313   lead to flooding and saturation of soils, reducing diffusivity of gases, these factors coupled with
314   lower infiltration rates and soil sealing of urban soils limit or decrease soil H_2 uptake. H_2 uptake
315   into soils is limited by abiotic and biotic processes under dry and wet soil conditions. For
316   example, under dry conditions H2 diffusion into soils is biotically limited by the presence of dry
317   inactive layers with reduced biological activity in desert soils (Fallon, 1982; Conrad & Seiler,
318   1985; Smith-Downey, Randerson & Eiler, 2008; Bertagni, Paulot & Porporato, 2021); while wet
319   soil conditions reduce movement into the soils, also leading to H2 diffusion limitation
320   (Yonemura, Kawashima & Tsuruta, 1999; Yonemura & Kawashima, 2000; Gödde, Meuser &

321 Conrad, 2000; Ehhalt & Rohrer, 2013). During the pre-monsoon season, H_2 uptake was lower in
322 the control and passive treatments, with greater uptake in the active and greywater GI treatments,
323 consistent with research showing that H_2 uptake even at low moisture levels may promote
324 microbial activity (Fallon, 1982; Conrad & Seiler, 1985; Smith-Downey, Randerson & Eiler,
325 2006, 2008). Additionally, studies have shown that under very low soil moisture conditions,
326 HOB activity is drastically inhibited (Paulot et al., 2021). As the monsoon season progressed,
327 increased soil moisture resulted in greater H_2 uptake across all treatments, suggesting semiarid
328 urban ecosystems are sensitive to changes in moisture availability and that there is increased
329 uptake throughout the monsoon season as long as there are continual rain events.

330   As temperatures decreased during the post-monsoon season, we observed median
331 moisture levels and similar soil H_2 uptake across treatments, suggesting an ideal moisture range
332 between 15 and 18% near 15 °C, which is within the ideal temperature range observed for
333 microbial H_2 uptake in the Mojave Desert (Smith-Downey, Randerson & Eiler, 2006). While
334 there are models that robustly assess temperature and moisture effects on H_2 uptake, our results
335 oppose current research that show H_2 uptake increases with increased temperature which may
336 correspond with limitations in our dataset (Ehhalt & Rohrer, 2011, 2013; Yashiro et al., 2011;
337 Bertagni, Paulot & Porporato, 2021). Specifically, our data capture a narrow range of
338 temperatures (12 to 39 °C) compared to the broad range (-20 to 100 °C) modeled in (Ehhalt &
339 Rohrer, 2011) and are missing a critical range between 16 and 27 °C which has been identified
340 as an optimal temperature range of soils with 19% moisture for peak H_2 uptake in the Mojave
341 Desert (Smith-Downey, Randerson & Eiler, 2008). In fact, our results suggest greater variability
342 in H_2 uptake at higher temperatures, with less uptake measured in the passive and control
343 treatments during the driest sampling period (pre-monsoon). Our findings highlight the
344 interaction of temperature and soil moisture as important abiotic drivers of H_2 uptake in semiarid
345 managed systems, with GI altered soil moisture or temperature leading to reduced but sustained
346 H_2 uptake.

347   The widespread implementation of GI water management practices alter soil moisture
348 legacy by irrigating rain garden basins at different frequencies and providing a more constant
349 water source during the dry season. More frequent and consistent soil moisture events in the
350 greywater compared to the other treatments can lead to shifts in the soil microbiome (Buzzard et
351 al., 2021), nutrient availability, and carbon inputs. Desert soils have low carbon availability, and
352 changes in the water inputs from GI may increase soil carbon by supporting vegetative growth,
353 root development, and increased soil microinvertabrate diversity and abundance (Pavao-
354 Zuckerman & Sookhdeo, 2017). The sustained availability of water and organic resources for
355 energy may further support organoheterotrophic soil microbes, such as *Actinobacteria,*
356 *Proteobacteria,* and *Chloroflexi* (Lynch et al., 2014; Leung et al., 2020; Jordaan et al., 2020),
357 leading to metabolically flexible microbiomes in GI treatments capable of more rapidly
358 switching between resources (Bay et al., 2021a,b). In addition, soil H_2 uptake models project that
359 greater HA-HOB activity is associated with higher temperatures, but can be limited if the

360   minimum soil moisture threshold is not met (Paulot et al., 2021), and further research should

361   address the uncertainty in HA-HOB activity in arid and semiarid urban ecosystems. As observed

362   in the greywater basin, our findings suggest that a more consistent soil moisture legacy was

363   important for microbial-mediated biogeochemical processes and highlights a sensitivity to

364   increased soil moisture in semiarid urban ecosystems.

365   Atmospheric trace gases, like H_2, are important for sustaining soil microbes during

366   periods of low resource availability and may also act to alleviate competition between

367   organoheterotrophs (Fierer, 2017; Bay et al., 2021a,b). Microbial communities with more diverse

368   metabolic strategies may be more resilient to changes in climate and anthropogenic disturbances

369   (Meyer et al., 2004; Allison & Martiny, 2008; Berney & Cook, 2010; Greening et al., 2014). As

370   climate changes, shifts in seasonal precipitation patterns may lead to longer dry periods and more

371   variable precipitation patterns in arid and semiarid regions of the Southwestern United States

372   (Zhang et al., 2021). Although recent work suggests that H_2 uptake may increase with warmer

373   temperatures observed at midlatitudes in the northern hemisphere, altered soil carbon and

374   reduced soil moisture may reduce microbial activity resulting in unknown feedbacks in

375   atmospheric concentrations (Paulot et al., 2021). Here, we show that water management

376   practices, like GI, buffer temperature extremes and reduce periods of drought, increasing H_2

377   uptake. Our findings suggest that GI managed residential soils can maintain low levels of H_2

378   uptake year around, above what would be sustained in unmanaged systems (i.e., our control

379   treatment), and may reduce the impacts of drought on H_2 cycling in semiarid urban ecosystems.

380   **Conclusions**

381   Atmospheric H_2 is impacted by changes in climate and increased anthropogenic

382   emissions. Characterizing the changes in microbial mediated soil H_2 uptake has important

383   implications for semiarid urban systems where local land management practices alter the abiotic

384   and biotic environment, increasing uncertainty in the atmospheric hydrogen cycle. Here, we

385   showed that environmental factors impacted by seasonal precipitation and GI water management

386   practices in the semiarid deserts of Arizona increased soil H_2 uptake during seasonally dry

387   periods. As temperatures and drought increase in the Southwestern United States, uptake of

388   atmospheric H_2 by soils may be reduced, unless cities continue to implement GI water

389   management practices, which decrease dry periods and support greater H_2 uptake. Continued

390   investigation into how managed systems impact soil microbial community composition and

391   function is suggested to better understand the distribution and functional role of HA-HOB

392   microbial communities in sustaining H_2 uptake in semiarid urban climates during drought. Our

393   findings highlight the interaction between natural and managed water regimes on soil H_2 uptake

394   as corroborated by field and lab measurements, reinforcing the unique role of H_2 in microbial

395   metabolism in semiarid urban landscapes.

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399

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Figure 1

Meteorological data measured hourly on site.

(A) Site level air temperature (°C) measured at 3 m aboveground. Light grey represents the hourly temperature. Dark grey line represents the smooth fit function from a generalized additive model estimation of air temperature. (B) Daily cumulative sum of precipitation (mm) for at the site. Dashed red lines represent the static chamber hydrogen sampling dates.

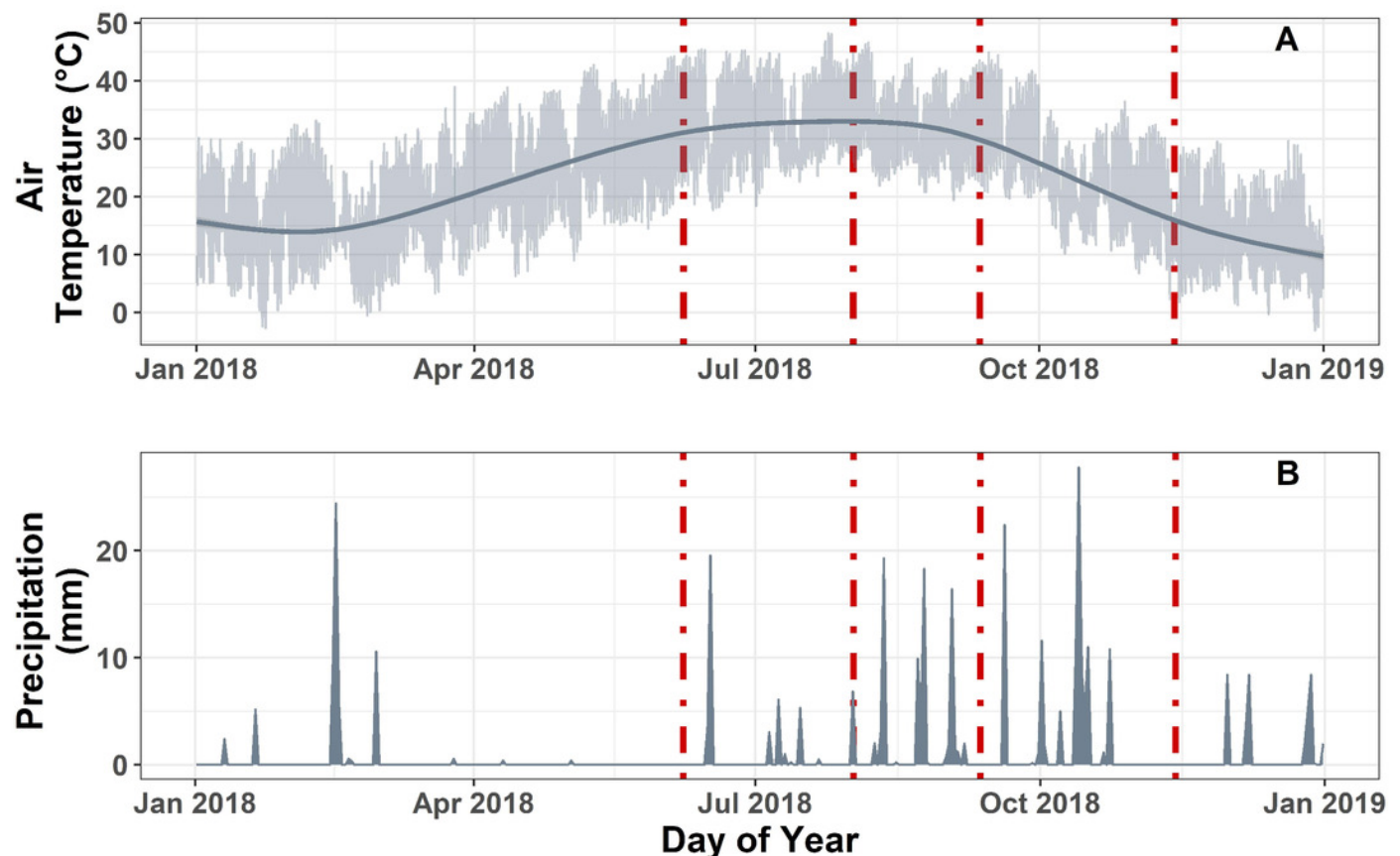



Figure 2

The effects of green infrastructure management and time during the monsoon season on soil hydrogen fluxes (nmol H_2 m^{-2} s^{-1}).

Boxplots displayed with point distributions for each batch within a treatment. The center line represents the median, and the lower and upper lines correspond to the first and third quartiles (25% and 75% quartiles). Whiskers correspond to the 95% confidence intervals. The two-way ANOVA presented F statistic, p-value and generalized eta squared (ges). The grey dashed line at 0 on the *y*-axis represents the transition between soil uptake (negative values) and emission into the atmosphere (positive values).

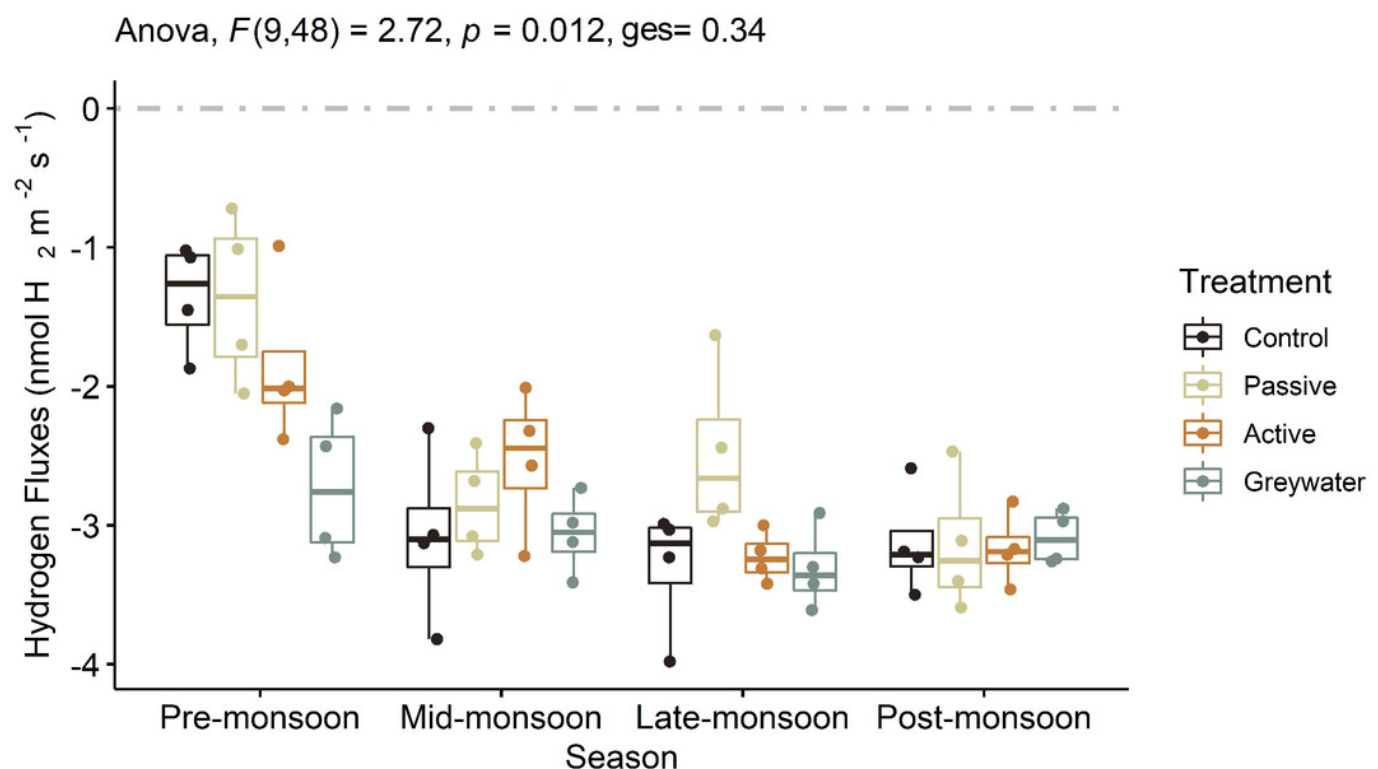



Figure 3

Microcosms assessing the effects of green infrastructure management and soil moisture on hydrogen fluxes (nmol H_2 m^{-2} s^{-1}).

Boxplots displayed with point distributions for each batch within a treatment. The center line represents the median, and the lower and upper lines correspond to the first and third quartiles (25% and 75% quartiles). Whiskers correspond to the 95% confidence intervals. The one-way nonparametric Kruskal-Wallis ANOVA was performed independently for both treatment and moisture level on H_2. Corresponding p-values are recorded with treatment first and moisture level second. The grey dashed line at 0 on the y-axis represents the transition between soil uptake (negative values) and emission into the atmosphere (positive values).

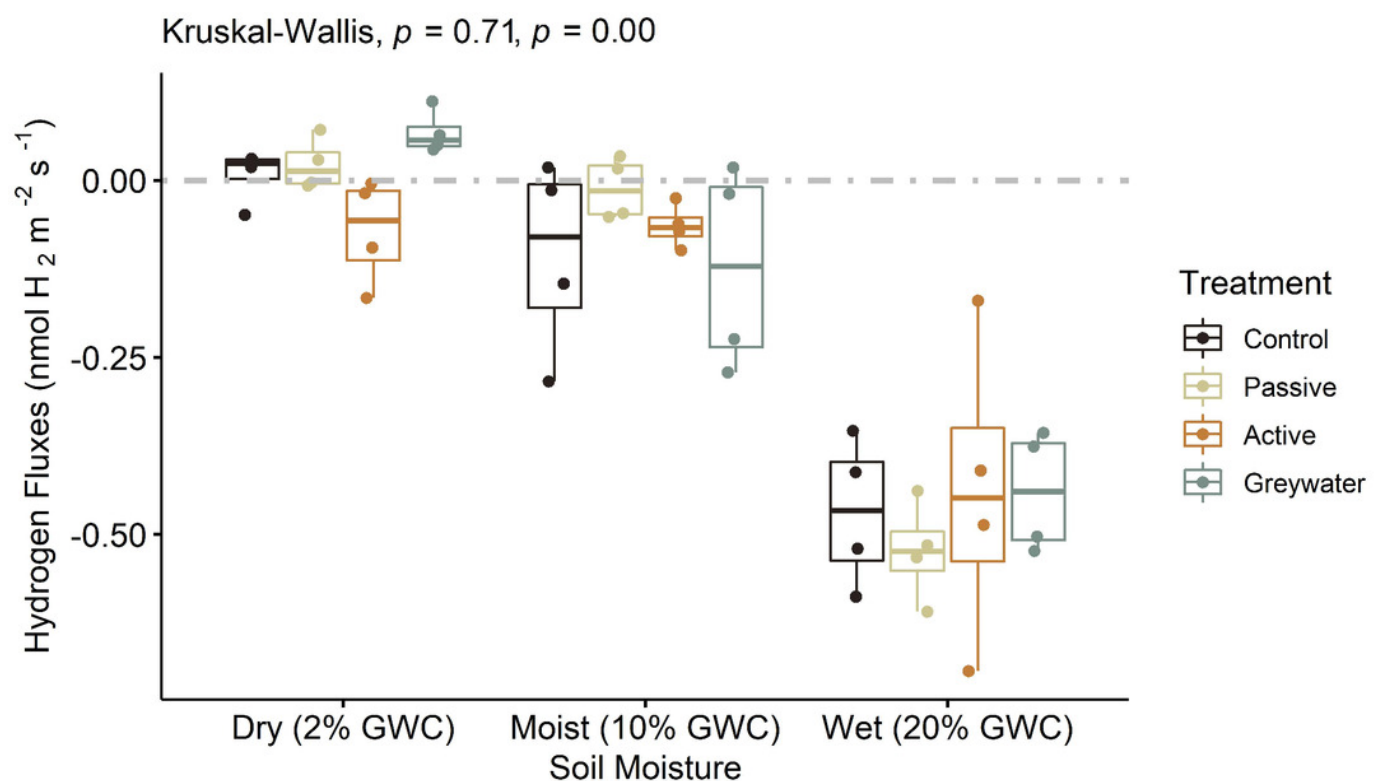
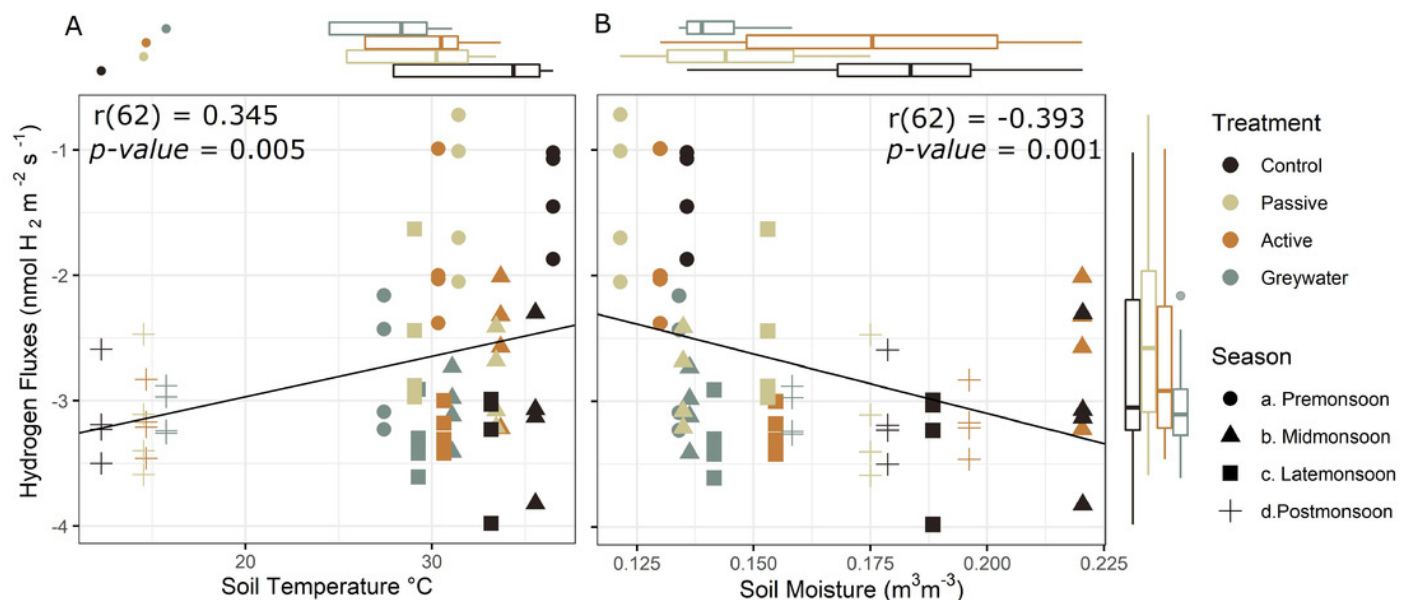



Figure 4

Effect of selected environmental drivers during in situ measurements of soil hydrogen fluxes (nmol H_2 m^{-2} s^{-1}).

(A) Positive correlation of hydrogen fluxes and soil temperature °C shows H_2 uptake into the soil is greater at lower temperatures, and (B) Negative correlation between hydrogen fluxes and soil moisture indicates that H_2 uptake increases with increased moisture. Boxplots display the median, 25th and 75th interquartile range, and whiskers show 1.5 times the interquartile for soil temperature (top left), soil moisture (top right), and soil hydrogen fluxes (right side) averaged during the in situ sampling period. Negative H_2 fluxes indicate uptake from the atmosphere into the soil.

Analysis of variance (ANOVA) assessing the effects of green infrastructure management and soil moisture on hydrogen fluxes (nmol H_2 m^{-2} s^{-1}).

Two-way ANOVA for assessing hydrogen fluxes as a function of treatment and season for in situ field sampling. One-way nonparametric Kruskal-Wallis ANOVA independently assessing hydrogen fluxes as a function of treatment and moisture level for microcosm lab experiment. DFn: Degrees of freedom in the numerator. DFd: Degrees of freedom in the denominator. Test Statistic: F for two-way parametric ANOVA; H for one-way nonparametric Kruskal-Wallis test.

Experiment Location	Effect	DFn	DFd	Test Statistic	p-value	p<.05	Effect Size
Field	Treatment	3	48	4.64	0.006	*	0.225
Field	Season	3	48	29.85	0.000	*	0.651
Field	Treatment:Season	9	48	2.72	0.012	*	0.338
Lab	Treatment	3	48	1.40	0.706		-0.036
Lab	Moisture Level	2	48	34.35	0.000	*	0.719