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**Effects of Drought on Habitat Quality for Native Bees
in Residential Gardens of Claremont, CA**

A Thesis Presented
by
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To the Keck Science Department
of
Claremont McKenna, Scripps, and Pitzer Colleges
In Partial Fulfillment of
The Degree of Bachelor of Arts

Senior Thesis in Biology

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Abstract

Over 1,500 of the 4000 bee species found in North America inhabit California. Native bees are declining however, largely due to climate change and agricultural intensification. Previous research shows that cities can sustain diverse bee communities, due to the diversity of ornamental flowers. Urban green space represents an opportunity for native bee conservation. Residential gardens provide lots of green space and are urban pollinator hotspots. Managing yards for increased floral resources and nesting habitat can benefit native bee communities. Turfgrass provides few floral or nesting resources and negatively correlates with bee diversity. The 2011-2017 California drought caused many homeowners to reduce turf cover, potentially benefiting pollinator habitat. We assessed the current status of pollinator habitat in residential yards of Claremont California and evaluated how the quality of habitat changed due to re-landscaping since 2011. Although in yards where changes were made, turfgrass decreased by a third of its original cover ($p < 0.0001$), it was not replaced by important floral or nesting resources like herbaceous plants ($p = 0.30$), bare ground ($p = .040$) or woody plants ($p = 0.89$). Even after landscaping changes, turfgrass covers on average a third of yards ($p < 0.0001$). This suggests that changes in landscaping over the course of the drought did not improve habitat for native bees in Claremont.

Introduction

Pollinators provide a crucial ecosystem service by supporting wild and cultivated plant communities. Almost 90% of the world's flowering plants are pollinated by animals (Ollerton et al., 2011). Bees are the most economically important pollinator group, and provide an estimated \$3.07 billion in pollination services in the United States alone (Losey & Vaughan, 2006).

Although the term “bees” is most commonly associated with honey bees, this term does not accurately reflect the diversity of the group. Honey bees represent only 8 out of the 20,000 bee species found globally. The most common honey bee species, *Apis mellifera*, is a social bee native to Europe and Africa. Due to their social nature and ability to pollinate a wide variety of crops, honey bees have historically been reared to provide much of the pollination for agriculture. Through transport honey bees have been introduced around the world, yet they differ greatly from most of their wild counterparts. The majority of bee species, hereafter referred to as “native bees”, differ from honey bees in that they are solitary and specialize on a smaller range of plants and have not been reared on industrial scales.

Although the global movement to “save the bees” has been focused on recent honey bee losses, there should be greater concern for native bees as they are experiencing more severe declines. Though managed honey bee populations in Europe and North America began to decline in the early 2000s, honey bees have been increasing on a global scale primarily due to high growth in countries like China and Argentina (Goulson et al., 2015). Although most bee species lack extensive historical population records making it difficult to prove large-scale declines in abundance, there is clear evidence of range reductions and local declines in the abundance and diversity of native bees. For example, local abundances of bumblebee species in North America, Asia, and Europe have declined since the 1950s (Williams & Osborne, 2009). The main drivers of native bee losses are due to land use changes caused by primarily agricultural intensification such as the loss and homogenization of

flowering plants, disturbances of nesting habitat, and widespread use of neonicotinoid pesticides. (Goulson et al., 2015) If actions are not taken to mitigate these pressures on wild bees, tens of countless unique species will likely be lost forever.

Native bees provide indispensable pollination services unmatched by honey bees, making their conservation a critical issue for global food security. Honey bee abundances have increased by 45% since the mid century, yet global demand for pollination has increased by 4 fold (Aizen & Harder, 2009). Increasing stocks of managed honey bees will not be able to compensate for losses in wild pollinators because many crops depend on pollination with specialized native bees. An analysis on 41 major crops grown globally found that while all crops have increased fruit set when visited by wild bees, only 14% of the same crops received similar benefits when visited by honey bees (Garibaldi et al., 2013). Wild bee diversity has been found to correlate with fruit sets greater than honey bee abundance in crops like apples (Blitzer et al., 2016; Mallinger & Gratton 2015). Beyond the intrinsic value of bees as unique species, the maintenance of wild bees and their pollination service is crucial for natural ecosystems and humans alike.

Surprisingly, focusing on urban environments could make substantial contributions to the conservation of native bees. Although urbanization does have some negative effects on native bees as it does with most taxa, bee communities have been found to have high levels of diversity and abundance in cities. A 2016 review found that since 2006, cities around the world including those in America, Canada, Germany, England, Australia, and Costa Rica maintain high native bee richness and abundance (Hall et al., 2017). Comparisons of natural, urban and rural regions within 12 large urban centers across England found that bee species richness were even higher in urban regions than in rural areas (Baldock et al. 2015). Similar comparisons of insect diversity in adjacent urban and rural cities around Germany found that while most insects, including flies and butterflies had lower levels of diversity in cities, bees had significantly greater species richness in urban areas

compared to rural landscapes (Theodorou, 2020). Though cities may not closely resemble or provide the same quality of habitat as intact natural landscapes, they contain a higher variety of flowering plants and nesting sites than increasingly homogenized agricultural areas and degraded natural landscapes (Hall et al., 2017). These findings suggest that cities can serve as refuges for bees extirpated from other land uses; managing cities to support bee communities can be an effective means to conserve a high diversity of species despite their ongoing declines. In addition to the promising evidence suggesting that bees could be successfully conserved in cities, increasing their diversity and abundance in cities can provide a number of benefits including: pollination export back to nearby rural areas, increased pollination services directly in cities, support of urban native plant communities, and engagement of urban communities in high-priority conservation.

Maintaining bee diversity in cities could serve as sources for the export of pollination services back to farms, thereby mitigating potential food insecurity. Previous research demonstrates that bees can travel from cities to agricultural lands to pollinate crops in agricultural lands, suggesting that maintaining wild bee diversity in cities can help restore pollination services in agricultural lands. A number of studies have demonstrated that florally diverse habitats surrounding farms can increase bee diversity and fruit set of various crops on farms (Garibaldi et al., 2013; Holzschuh et al., 2012; Morandin and Kremen, 2013). Although these studies have focused on pollination export from bees from natural habitat, cities, being florally diverse, can likely provide similar benefits to nearby agricultural lands. In the United States, over 78% of vegetables and 90% of fruits, nuts, and berries are grown in areas with rapidly expanding urban centers, suggesting there is high potential for urban bee assemblages to export local crops (Francis et al., 2012). Analyses based on the location and foraging distances of bees in Portland suggest that 30-50% of the bee community could potentially pollinate crops on farms adjacent to the city (Langellotto et al., 2018). Although the exact abilities of pollinators to cross habitat boundaries are not well understood,

evidence thus far suggests that cities can help the return of native pollinators and their pollination services to agricultural lands.

Native bees are crucial for pollination in urban agriculture, indicating that increasing urban bee diversity can help combat food insecurity directly in cities. Urban agriculture supports roughly 20% of the global food production, and is expected to play an increasingly important role in future food production (Armar-Klemesu, 2000). Native bee assemblages play an even greater pollination role in urban farms where managed honey bees are less common (Matteson & Langellotto, 2009). In New York City, 92% of the crops found in gardens were found to be dependent on bees for pollination, indicating that increasing pollination services can increase the supply of many commonly grown urban crops (Matteson & Langellotto, 2009). In gardens of San Francisco CA, tomatoes grown near sites with higher floral density were found to have higher fruit set as a result of more diverse local bee communities, regardless of impervious surface surrounding gardens (Potter & LeBuhn, 2015). In Iowa city, pollinator supply currently meets 72% of the city's demand, yet there are great discrepancies between areas, largely attributed to the relative proportions of vegetation surrounding urban gardens and farms (Zhao et al., 2019). These studies indicate that the diversity of native bees has a clear effect on urban food production.

Supporting bee diversity in cities can aid current conservation efforts to bolster native plants communities in cities. Though most research on the effects of pollinator declines on plants have focused on crops, native plants have similarly been observed to decline with pollinator losses. In the Netherlands and Britain, bee-pollinated plants have declined alongside declines in native bee diversity, while abiotically pollinated plants have increased (Biesmeijer et al., 2006). Without bees to sufficiently pollinate for further generations of native plants and increase gene flow, these plants are unlikely to persist. For example, roughly half the native plants extirpated from the city of Melbourne Australia are orchids, a family known to be dependent on specialized pollinators for adequate gene

flow (Hahs & McDonnell, 2014). Just like with crops, the average seed set in plant communities correlates with bee functional diversity, having a direct effect on their persistence (Fontaine et al., 2005). In cities, where native plants are especially vulnerable, wild bee diversity is therefore a crucial factor in the persistence of native plants.

Focusing urban bee conservation on cities can additionally promote the direct value of urban ecosystems, improving the ecological knowledge of urban citizens and their support of conservation. Extensive research showing that urbanization is correlated with reduced native biodiversity of most taxa has led most conservation efforts in cities to be focused on political and funding aspects rather than direct conservation of species in cities (McKinney, 2008; Hall et al., 2017). These same factors have led people in urban areas, especially those without resources to visit intact natural landscapes, to view conservation as something that happens “somewhere else” (Miller & Hobbes, 2002). Firsthand experience with nature is crucial for basic ecological knowledge and increases involvement with conservation issues (Miller & Hobbes, 2002). Focusing on conservation in cities and gaining support from the urban public for conservation will become increasingly important as roughly 60% of the world population is expected to live in urbanized environments by 2030 (United Nations, 2018). Bees, being ecologically important species that can be diverse in cities, present an opportunity for important and impactful conservation in urban environments, helping to increase the importance of urban ecosystems (Hall et al., 2017). Restored native bee communities can emphasize the importance of urban biodiversity for both policymakers and become an educational asset as accessible wildlife (Hall et al., 2017). A number of bee monitoring programs such as the “Great Pollinator Project” additionally involve nonscientists in the scientific process, further increasing ecological knowledge (Domroese & Johnson, 2017). With a large portion of urban outdoor space owned privately by citizens, urban conservation of bees will allow citizens to engage with important species where they live and not just “somewhere else” (Beumer & Martens, 2015).

Residential gardens can act as hotspots for urban bee diversity, suggesting that their management can be crucial for native bee conservation. A study replicated in four British cities found that residential and community gardens support the highest levels of pollinator abundance diversity of all urban land use types including other green spaces like parks (Baldock et al., 2019). Residential gardens additionally account for a large portion of urban green space, suggesting management of gardens for native bees can substantially increase the area suitable for native bees in cities. In Britain, between 45.5% and 61.6% of vegetation cover in cities is found in residential gardens (Bonham, 2019). Although community gardens support high amounts of bee abundance and diversity, they represent a smaller portion of urban greenspace cover than residential gardens (Baldock et al., 2019). Conversely, publicly managed greenspace like parks often covers a large portion of cities, but does not support as many bees as residential gardens (Baldock et al., 2019). Initiative aiming to promote bee conservation in cities would probably be better targeted at residential gardens.

In order to further increase bee diversity in urban residential gardens, it is necessary to understand bee habitat requirements and how the green space in many cities supports diverse bee assemblages. The two main determinants of native bee presence are floral and nesting resources. All bees require flowers, specifically their nectar and pollen, in order to feed. Wild bees communities, composed of species with different floral associations, require a diversity of floral resources. Bees are attracted to urban green space because it often contains a high diversity of flowering ornamental plants opposed to the monocultures on farmlands. As a result, gardens with higher herbaceous plant cover and floral abundance have greater bee diversity (Pardee & Philpott, 2014; Quistberg et al., 2016). Though urban areas have high levels of impervious surfaces, and as a result ground-nesting bees are particularly vulnerable in urban areas, high floral resources have been shown to compensate for the negative effects of impervious surfaces (Hülsmann et al., 2015). Other important factors

affecting the diversity of ground nesting bees aside from the amount of bare soil are those that restrict ground access like the relative cover of turf grass and mulch (Hostetler & McIntyre, 2001; Quistberg et al., 2016). Other habitat elements pertaining to nesting behavior in gardens like the availability of wood, or woody stems determine bee diversity, because cavity nesting bees utilize these materials to nest and rear young (Pardee & Philpott, 2014). Determining how to most effectively increase floral and nesting resources in urban green space is therefore crucial for native bee conservation.

The Southern California drought beginning in 2011 caused homeowners to alter garden composition, presenting an opportunity to investigate how local factors in residential gardens affect native bee assemblages. California is a native bee “hotspot” and over 1,500 of the 4000 known species documented in North America inhabit the state (Kremen et al., 2002). Southern California is one of the most highly urbanized areas in the country, and there is a large potential for residential gardens to support the native bee communities. A prolonged drought beginning in the early 2010’s altered the management of residential gardens, primarily by reducing turfgrass cover. Lawns composed of turfgrasses require large amounts of water to sustain, and many homeowners reduced turf cover in response to the drought. Residential gardens in the US are dominated by turfgrass, yet turf is known to be detrimental for bees as it restricts access to soils and provides few floral resources (Davis et al., 2017). Residential gardens may therefore support higher bee diversity after the drought, depending on what lawns were replaced with. In 2014, the Metropolitan Water District of Southern California (MWD) began a program in which rebates were distributed to homeowners that removed or reduced turfgrass. An analysis of the program indicated that the majority (70%) of participants fully removed lawns, while a fewer portion (11%) reduced lawn cover (Pincetl et al., 2019). Similarly, it is known that many kinds of ground cover like bare ground and shrubs replaced turfgrass in these gardens (Pincetl et al., 2019). Although these findings cannot account for changes

in landscaping in response to the drought independent of the rebate program, they suggest that the drought could have indirectly improved habitat quality in residential gardens of Southern California. To understand how much the drought improved habitat quality, changes in the area of turfgrass and other ground cover in gardens should be quantified. Additionally, to understand the effects of the drought on other habitat elements important to bees, changes in floral diversity and the number of nesting sites like wood and hollow stems must be investigated.

In this study, we quantified the changes in residential gardens in Claremont California as a result of the 2010s drought, and examined the effects of these changes on the wild bee communities. To do this we investigated 3 main questions: 1) What proportion of yards are currently composed of groundcover and vegetation types that impact bee diversity? 2) How did the composition of residential gardens change before and after the drought? 3) How did the changes in landscape composition affect the availability of floral resources and nesting habitat for native bees?

Methods

To quantify the composition of yard factors that affect the availability of nesting and floral resources for bees, area measurements of 1) Total yard area 2) turfgrass, 3) bare-ground, 4) gravel, 5) mulch, 6) impervious surfaces and 7) herbaceous cover were collected. Ground surveys of habitat elements are often time and labor intensive, and for urban ecological studies, conducting analyses on private property requires permission from homeowners. These factors can limit the number of sites that can be practically analyzed. To avoid these issues, we assessed local yard factors using imagery that is publicly available in Google Earth pro (GEP) and Google Street View (GSV) software. These softwares contain current and satellite and ground-level imagery, making it possible to record the composition of yards remotely.

We conducted two separate analyses, one on the current composition of yards, and another on the change in yard compositions. To determine the current state of yard composition, groundcover and vegetation factors were measured on the most recent satellite imagery available for every yard and converted into proportions of the total yard cover. GEP software contains a “Historical Imagery” setting which contains a collection of satellite imagery taken at different time points in the past. Though the 2010’s drought is generally defined as having spanned from 2011-2017, drought conditions have since reemerged in Southern California. Satellite imagery was available for every year since 2011, allowing us to see if yard compositions differed between years since the onset of the drought. Moving from the most current satellite imagery back in time, yards were remeasured using the same methods the first year where yard compositions differed from the current composition. For example, for one yard, measurements were taken on imagery from 2021 to determine the current composition. The yard composition looked the same as in 2021 in imagery between 2017 and 2020, but differed in 2016, so the change was recorded to have taken place in 2017, and measurements were taken again in 2016 to determine the composition before re-landscaping. If yards sites had no observable changes in composition, only the most recent imagery was recorded. For houses that changed, the proportion of a yard area of a given groundcover prior to landscape modification was subtracted from the current proportion of yard area of the same groundcover.

Area measurements

We recorded measurements of the total yard size, groundcover and vegetation by drawing along the perimeter of patches on GEP using the polygon tool. The area bound by each polygon was automatically calculated by GES software. Front yards were defined as the area between the front of a house and the sidewalk or the street where sidewalks were absent, and bound along the

direction of the street by fences, or other dividing elements, or by changes in landscaping between adjacent houses. In cases where there were shared landscaping elements such as shrubs between adjacent houses, we defined the border as being halfway between the shared element. Areas extending behind the front of houses, on either side of the yard were included if they were visible from the front of yards, and were commonly delineated by a gate. All yard characteristics recorded in the analyses were bound within these areas.

For individual ground cover or vegetation patches that were well defined in a yard, a polygon was drawn over the entire patch. For “mixed” patches where multiple ground cover types were unable to be distinctly separated, such as shrubs interspersed within an area of mulch, a polygon was drawn over the entire patch. Proportions of mixed areas consisting of each relevant cover within mixed polygons was visually estimated. The area of each cover present in a mixed patch was calculated as the product of the total mixed patch area and the estimated proportion of each cover type. The total area of a given category within each yard was the sum of all polygons of that category and the area estimated from mixed polygons.

Woody plant count measurements

In addition to area measurements, to measure the relative number of plants that could potentially be utilized by cavity nesting bees, we counted the number of woody shrubs, trees and pieces of wood visible on street-view imagery (GSV). We counted woody resources on GSV imagery that was taken closest in time to the satellite imagery used for area measurements. We additionally visually compared the GSV and GEP imagery to confirm they represented the same landscaping composition for a given yard.

Study sites

We studied landscaping practices in the city of Claremont, California, a residential suburb of Los Angeles. Front yards of residential homes were selected as study sites. Claremont follows a general trend of increasing property value from south to north. To account for these factors, study sites were randomly sampled, but stratified by two regions separated by Foothill Boulevard running east to west. We compiled a list of street names for each region, and sampled four streets from each list.

Streets with less than six residential homes with front yards facing the street were excluded from the study. For streets included in the study, data was collected from properties beginning with the southernmost property progressing further north for NS oriented streets, or beginning with the westernmost property progressing farther east for EW oriented streets. Up to thirteen houses were analyzed from each street. A total of 72 properties were included in the analysis, 31 from the northern region and 41 from the southern region. Houses on corner lots, lacking street view imagery, and with tree cover excluding the entire satellite view of a yard were excluded from the study.

Ground truthing

In order to assess the accuracy of our data collection, we got permission from homeowners to access three yards, and measured different areas measured beforehand on GEP in these yards by hand. In situ area measurements were conducted by using reel tape measures strung around tent pegs along the perimeter of a ground cover patch. Perimeter measurements of polygons are automatically calculated alongside the area measurements on GEP. Eleven polygons from 3 yards not included in the final dataset were assessed, with an average of 6.6% error \pm 6.0 (Table 1).

Polygon	Yard	In Person Measurement (m ²)	Google Earth Measurement (m ²)	Percent error (%)
1	1	34	33.2	2.4
2	1	28.7	28.5	0.7
3	1	27.6	26.7	3.3
4	1	36.4	34.6	4.9
5	1	35.2	35.2	0.0
6	2	38.45	32.6	15.2
7	2	29.85	26.8	10.2
8	2	21.6	24.8	14.8
9	3	15.54	15.8	1.7
10	3	38.72	43.7	12.9

Table 1. Area measurements collected by hand in yards compared to the same areas measured on Google Earth (mean percent error= 6.6% \pm 6.0).

Data Analysis

Data was recorded on Google Sheets and analyzed in the R statistical environment (R Studio version 1.4.1717). To standardize for yard size, absolute groundcover area measurements were converted into proportions of the total yard area. For each groundcover and measurement, proportion calculations were calculated as the area within a yard of a given groundcover divided by the total yard area.

To summarize the relative nesting resources for ground-nesting bees, a ground-nesting habitat score was calculated. The ground-nesting habitat score was defined as the ratio of known beneficial and detrimental ground cover (bare ground over the sum of turf grass, mulch, gravel and bare ground). This score was guided by previous research indicating that native bee abundance and diversity increase with bare ground and decrease with the other cover types (Quistberg et al., 2016; Egerer et al., 2019; Lanner et al., 2020). Mulch cover has shown to be negatively correlated with bee diversity because like turf grass, it restricts access to soils (Quistberg et al., 2016). Though some

types of mulch such as leaf litter have been shown to correlate with increased bee diversity because it does not restrict access to soils like mulch composed of wood pieces (Frakie et al., 2009), we recorded leaf litter as a separate factor. Leaf litter was not included in the ground-nesting score because no houses were found to have areas of leaf litter at any point in time. Although gravel in yards can be utilized for some ground nesting bee species (Cane, 2006), it was included as part of the detrimental groundcovers following other research that has categorized gravel as a groundcover that restricts access to soils to most ground nesting bee species (Egerer et al., 2019). Although impervious surfaces are known to be detrimental for ground nesting bee abundance and diversity, impervious surface area was not included in the score. This score was used to assess the change in nesting habitat due to landscape modifications, but impervious surfaces generally did not change even in yards where other elements did.

To summarize the relative nesting resources for cavity-nesting bees, a “cavity-nesting habitat score” was calculated as the sum of the number of shrubs, trees and pieces of wood per square meter of yard. By providing more sites where bees can nest, woody plants and pieces of wood have been shown to increase the diversity and abundance of cavity nesting species in urban gardens (Cane et al., 2006; Pardee & Philpott, 2014). To assess the change in both of the nesting scores, we subtracted the scores of a yard prior to landscape modification from the scores of the same yard in its current composition.

To assess trends in the composition of yards, separate histograms of the proportion cover of each of the groundcover and vegetation counts were created. To assess the relative quality of nesting habitat in yards, histograms were also created for ground nesting habitat scores and cavity nesting habitat scores. We also created histograms for the change in groundcover and vegetation area proportions as well as change in nesting habitat scores. We calculated means, standard deviations and

a one sample permutation test to determine significant differences from 0 for all area composition values, nesting habitat scores, and change calculations.

Results

In total 72 yards were assessed. Yards ranged in size from 58.5 m² to 1211.4 m², with an average area of 235.65 ± 21.39 m². Roughly half of the yards changed during the study period (changed= 34, no change=38). In the most recent measurements for 2021, turf and impervious surfaces took up the most of the yard space (Figure 1), both accounting for roughly one third of the total area (turf: mean= 0.30 ± 0.036 , $p < 0.0001$; Impervious surface: mean= 0.30 ± 0.02 , $p < 0.0001$). Bare ground accounted for the lowest proportional cover in yards (mean= 0.029 ± 0.01 , $p = 0.011$). Mulch and gravel had similarly low cover but higher than bare ground (mulch: mean= 0.058 ± 0.016 , $p = 0.0007$; gravel: mean= 0.055 ± 0.017 , $p = 0.002$). Herbaceous plants covered very little proportional area (Figure 1), accounting for only roughly 7.5% of the total yardcover (mean= 0.075 ± 0.015 , $p < 0.0001$).

For houses that did change, the greatest change occurred in turf cover, as turf cover reduced by roughly a third of its original cover (Figure 2) (mean proportional change= -0.29 ± 0.058 , $p = 0.0001$). Mulch and gravel additionally increased by similar proportions of their original cover, each increasing by roughly a third of the magnitude to which turf cover reduced (mulch: mean proportional change= 0.092 ± 0.03 , $p = 0.0019$; gravel: mean proportional change= 0.096 ± 0.035 , $p = 0.0019$). Impervious surfaces, bare ground and herbaceous cover did not change (impervious: mean proportional change= 0.0079 ± 0.0052 , $p = 0.15$; bare ground: mean proportional change= -0.031 ± 0.037 , $p = .040$; herbaceous cover: mean proportional change= 0.036 ± 0.029 , $p = 0.30$).

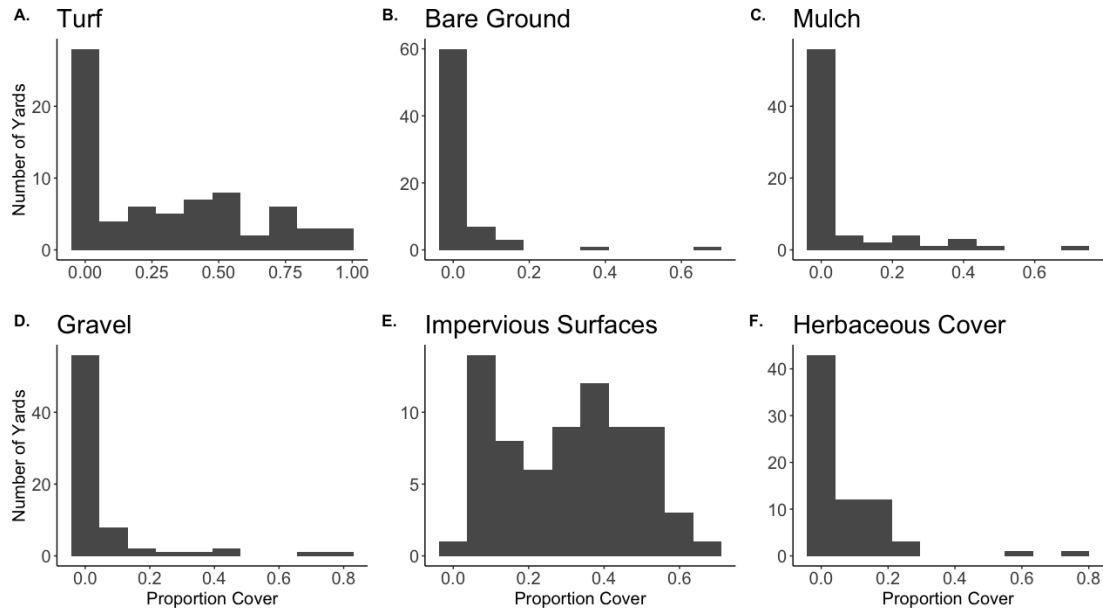


Figure 1. Histograms depicting the frequency distribution of the proportion of yard area composed by groundcover and vegetation across residential yards for a) Turf b) Bare ground c) Mulch d) Gravel e) Impervious surfaces and f) Herbaceous plants.

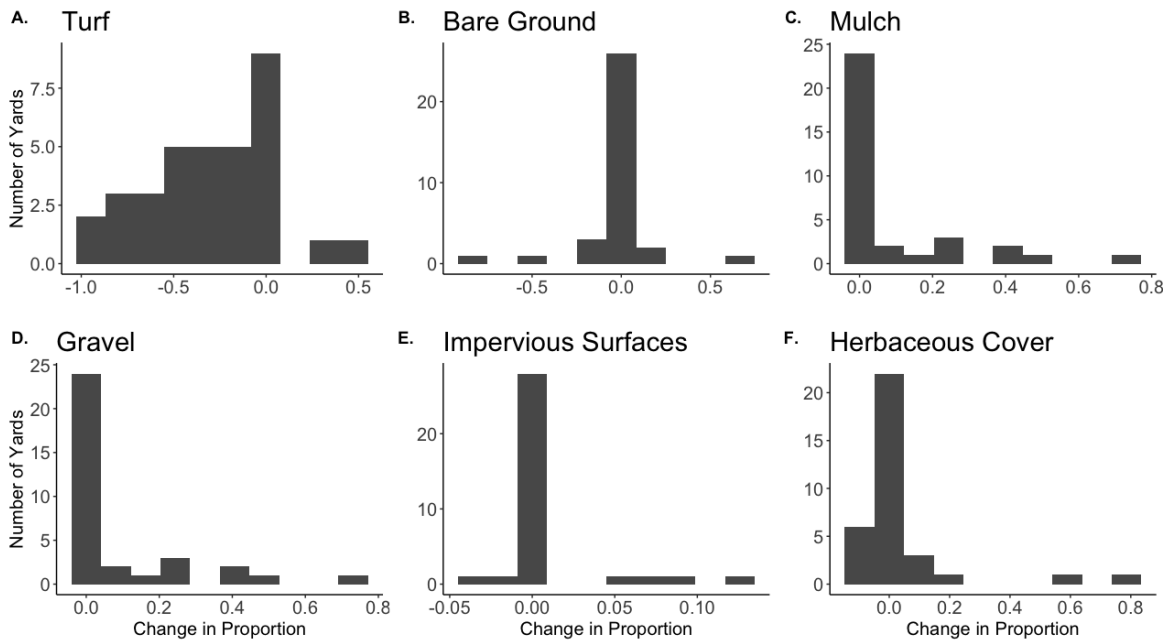


Figure 2. Histograms depicting the frequency distribution of the change in the proportions of yard area composed by groundcover and vegetation across residential yards for a) Turf b) Bare ground c) Mulch d) Gravel e) Impervious surfaces and f) Herbaceous plants.

Ground nesting bees had on average very low amounts of ground nesting space when compared to the amount of detrimental groundcover (Figure 3) (mean= 0.08 ± 0.02 , $p=0.0014$). There were approximately 0.03 woody resources for cavity nesting bees per square meter of yard, with the majority of yards providing extremely low resources (mean= 0.028 ± 0.004 , $p<0.0001$). Shrubs were the most common cavity nesting resource (61%), followed by trees (30%), and pieces of dead wood (9%).

Neither average ground habitat scores (mean score change= 0.08 ± 0.06 , $p=0.22$) nor cavity nesting habitat scores (mean score change= -0.14 ± 1.02 , $p=0.89$,) significantly changed in yards that re-landscaped between 2011 and 2021 (Figure 4).

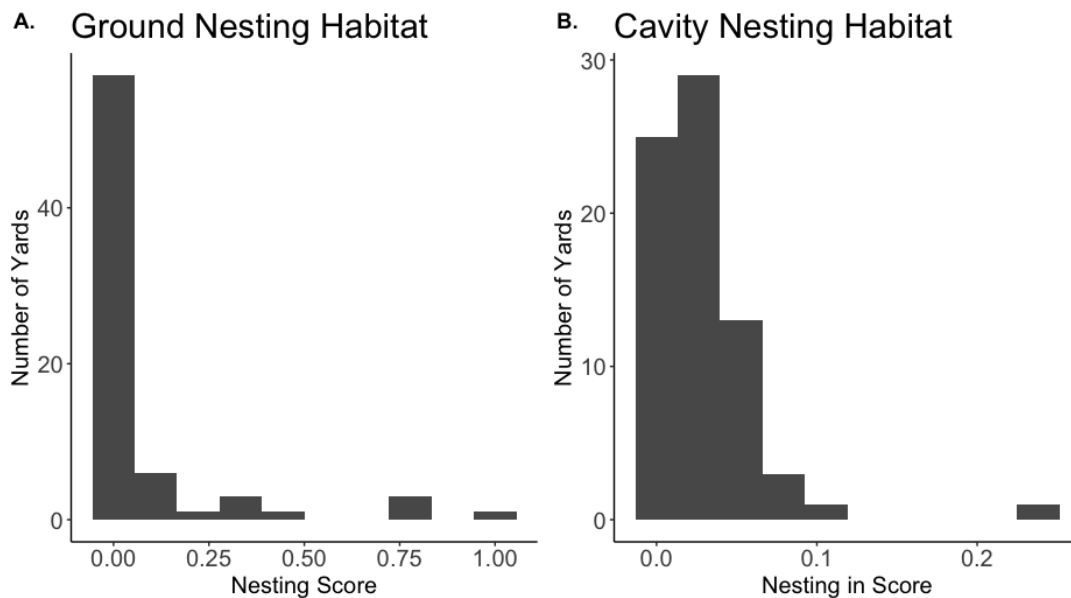


Figure 3. Histograms depicting the frequency distribution of the a) Ground nesting habitat scores and b) Cavity nesting habitat Scores across residential yards.

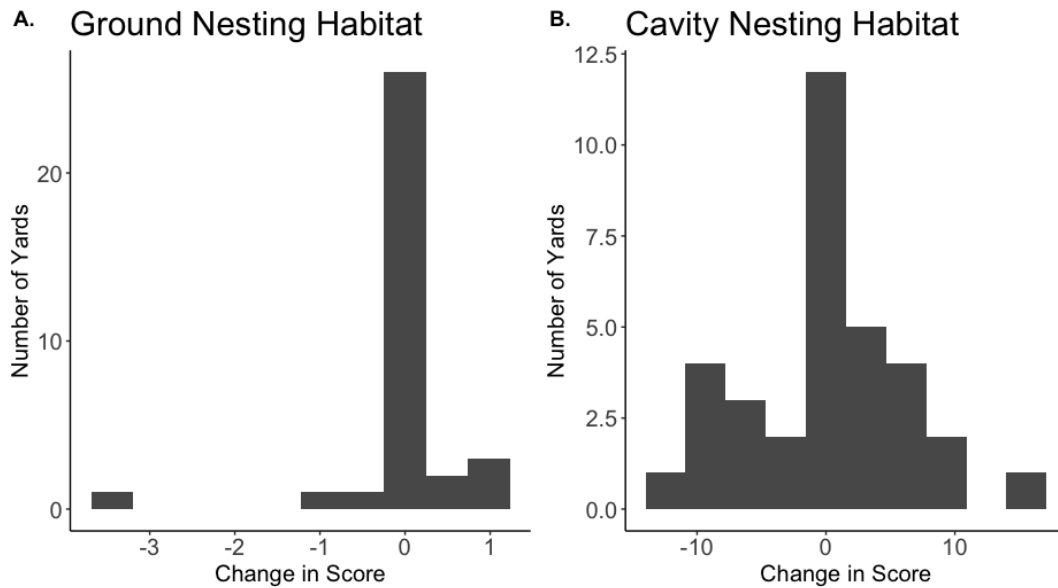


Figure 4. Histograms depicting the frequency distribution of the change in a) Ground nesting habitat scores and b) Cavity nesting habitat Scores across residential yards.

Discussion

Our first question addressed the current composition of residential yards and analyzed elements that affect floral and nesting resources for bees. Our research indicates that turfgrass and impervious surfaces represent a significant portion of yards, while herbaceous plants and bare ground were scarce, suggesting yards are currently limited in their ability to support native bees.

About half of the yards in our survey re-landscaped, which involved substantial (~30%) reductions in turf grass. Yet even so lawns still represent a significant portion of the total cover of residential yards. This is congruent with many previous analyses indicating the dominance of turfgrass in American urban and suburban landscapes (Burr et al., 2016; Lerman & Milam, 2016). Turf grasses encompass roughly 163,800 km² of the contiguous US, which is three times the area of the most widespread irrigated crops (Milesi et al., 2005). This also matches assessments of turfgrass rebate programs in California, as turfgrass still remains a major groundcover in yards where turf was only partially removed (Pincetl et al., 2017). The high proportion of lawns likely reduce the potential

diversity and abundance of native bees as turfgrass lacks floral resources and block access to open soils where native bees may nest. Numerous studies have found that lawns are negatively correlated with native bee abundance and richness (Pardee & Philpott, 2014). This suggests that roughly a third of the current yard cover in Claremont provides little to no benefits for native bees. If members of the Claremont community are interested in providing high-quality habitat, then decreases in turfgrass, paired with increases in floral diversity are needed.

It is important to note however that lawns may provide some degree of floral resources depending on their management. Lawns not treated with herbicides can allow flowering plant species such as dandelion (*Taraxacum sp.*) and clover (*Trifolium sp.*) to exist, providing pollen and nectar for bees (Lerman & Milam, 2016). Similarly, as mowing prevents the growth of weedy species, reduced mowing can increase bee abundance and diversity (Lerman & Milam, 2016). Given that turfgrass remains the dominant factor in most lawns and homeowners may prefer to keep them, changes in lawn management can be an alternate method to support native bee communities while retaining lawns.

Impervious surfaces encompassed similarly a third of the yards, indicating that they are also a dominant factor in yards. Areas with higher impervious surfaces have been shown to support less abundant and diverse bee communities. Additionally, high impervious surfaces are associated with greater numbers of cavity nesting species than ground nesting species, as impervious surfaces reduce the available ground surface (Fortel et al., 2014). If members of the Claremont community particularly wish to support ground nesting bees, reductions in the cover of impervious surfaces would be beneficial.

We found in our analysis that herbaceous plants only encompassed roughly 7.5% of the yard cover, indicating that they only comprise a small portion of yard cover. It is important to note that we were unable to account for the fact that some plants such as native species are slow growing and

may have been small at their initial planting, underestimating the floral resources that may ultimately be available after they grow. As a result, it is possible that the floral cover is currently greater in yards than we measured in our analysis. A number of studies have demonstrated that floral resources are a prominent determinant of bee diversity in urban gardens (Pardee & Philpott, 2014; Quistberg et al., 2016; Egerer et al., 2020). If flowering plants are abundant, they can compensate for the negative effects of impervious surfaces on urban bee diversity (Hülsmann et al., 2015). Given the high proportion of impervious surfaces in Claremont yards, further increases in herbaceous cover is necessary to support the local native bee communities.

Studies that have measured bee diversity with floral cover in urban gardens have found that bee diversity increased with flower cover up to moderate levels (26-50%) (Lanner et al., 2020). Considering the very low herbaceous cover found in Claremont, which are well below the moderate levels defined by Lanner and colleagues (2020), even small increases from current herbaceous cover could potentially increase the abundance and diversity of native bees.

Though the diversity of flowering species is important in predicting local bee diversity and abundance, it was difficult to identify the species of flowers present in yards using satellite and street view imagery. Many street view images were too blurry to see flowers in detail and plants were only able to be characterized as herbaceous or woody species. One reason why yards with higher floral diversity have increased bee diversity is that they contain a greater variety of species with different blooming periods, and can provide flowers over a greater span of the growing season (Wojcik et al., 2008). In addition to having limited resolution, street view imagery was taken at different times of the year around Claremont. Street view imagery therefore displayed varying flowering phenology assemblages, which would have caused issues in comparing floral diversity between yards. Future research replicating these methods could potentially pair this methodology with high quality geospatial video to control for time and more accurately identify flowering plants (Burr et al., 2018).

In spite of these limitations on assessing floral diversity, previous work suggests that metrics of herbaceous cover are a good proxy for floral resources. Although floral richness is often correlated with increased bee diversity in urban green space (Egerer et al., 2019), floral abundance has been shown to have a positive effect on bee diversity and can even be more important than floral diversity (Matteson & Langellotto, 2009; Ayers & Rehan, 2020; Lanner et al., 2020). Studies have used herbaceous cover as a proxy for flowering abundance, and herbaceous cover has been shown to correlate with bee abundance in residential yards (Pardee & Philpott, 2014; Quistberg et al., 2016).

Ground nesting scores on average were low indicating that yards provide little access to bare soil for ground nesting bee species. The majority of native bees are solitary, suggesting that the relatively low possible areas for them to nest are a major limiting factor for the diversity of bees in yards. These values were largely due to low bare ground cover, as the majority of yards provided no bare ground. The average cover of mulch and gravel was much smaller than turf, indicating that they had less of an effect on the scores than turf grass. The ground nesting score values would additionally have been smaller on average had impervious surfaces been included. If homeowners in Claremont wish to create yards that support ground nesting bees, we recommend that turf largely be reduced and replaced by bare ground. Though mulch and gravel accounted for a smaller proportion of total yard cover than turf, converting these areas to bare ground would increase the diversity of ground nesting bees (Quistberg et al., 2016).

Cavity nesting scores were relatively low, however the majority of yards had cavity nesting scores greater than zero indicating that most yards had resources that could potentially be utilized by cavity nesting bees. Increased number of trees and shrubs are positively correlated with bee species richness (Pardee & Philpott, 2014; Lanner et al., 2020), and further increases in the number of woody plants could increase native bee diversity. Dead wood was much less common in yards than

shrubs or trees, which may be due to them being less attractive to homeowners. Bee species who utilize dead wood as nesting sites have been found to comprise smaller proportions of urban bee communities than other above-ground nesting species (Lanner et al., 2020). Given that shrubs and trees are common in yards, increasing pieces of dead wood can help increase the number of cavity nesting bee species.

The majority of homes had some level of nesting resources, but had no amount of open bare soil, indicating that the yards assessed in the study provide more nesting resources for cavity nesting bees than ground nesting bees. Many studies have found that urban areas provide adequate nesting resources for cavity nesting bees, and cavity nesters have been found to represent a higher proportion of the native bee communities in cities (Cane et al., 2006; Matteson et al., 2008). The higher availability of woody nesting resources than bare soils found in this analysis provides further evidence that bias towards cavity nesting species in urban bee communities is a result of a lack of nesting opportunities for ground nesting bees.

Our second question addressed how yard compositions changed over the course of the drought period, and how these changes may in turn affect native bee communities. We found that generally turfgrass had been reduced, and was largely replaced by gravel and mulch. Herbaceous cover had not changed, and floral resources were not increased for native bee communities. These factors, combined with a lack of change in ground nesting habitat and cavity nesting habitat quality suggest that changes in landscaping due to the drought did not increase resources for native bee communities.

We had predicted that due to the high water usage required to maintain turf lawns, there would have been a reduction in lawns over the course of the drought. Due to the lack of nesting and floral resources provided by lawns, numerous studies have suggested that the removal of grass and replacement with floral resources is a principal way to increase bee abundance in residential gardens

(Pardee & Philpott, 2014). Although reductions in lawn would be beneficial in opening additional space for other types of groundcover or vegetation providing more resources for bees, the benefit to bee communities is dependent on the identity of what replaced the lawns.

Over half of the yards that did change during the drought had reduced turf cover. Turf changed by the most out of all factors, decreasing on average by a third of its original cover. This indicates that landscaping changes were predominantly due to reductions in lawn. These findings are in contrast to similar analyses of residential garden cover in St. Louis Missouri which found that turfgrass had low to no change across years (Burr et al., 2018). As this previous study was conducted in a region where drought is not a major threat, this difference is suggestive that the drought was the primary driver of turf reduction, in support of our predictions.

There were no significant changes in herbaceous cover over the course of the drought despite large decreases in relative turf cover, providing no additional floral resources. Although studies have shown that highly abundant floral resources can compensate for the negative effects of impervious cover on native bee abundance and richness, the consistent high impervious cover and low herbaceous cover in Claremont despite changes in other yard factors indicates that bee communities are largely limited by impervious cover.

Water usage and costs may be driving the lack of increases in herbaceous cover. If homeowners are reducing turf to reduce water usage, they may not want to increase herbaceous cover for the same reasons. Though drought tolerant herbaceous plants require less water, and research has shown that households are willing to adopt drought tolerant plants due to the low cost of maintenance they require (Fan et al., 2017), it may be that a lack of knowledge regarding drought-tolerant plants limits their use. Previous research has also indicated that education about the low water usage of certain landscaping plants can increase consumer perceptions of the value of those plants (Knuth et al., 2018), so informing community members on drought tolerant herbaceous

species could increase floral resources in residential gardens. However, the lack of increase in herbaceous cover may be also driven by limits to which homeowners will tolerate unfamiliarity with respect to the relative cover of lawn and herbaceous cover. One study found that 50% replacement of turf with colorful plants was deemed acceptable, but 75% was not (Nasauer, 1993). Although the current average herbaceous cover in Claremont is well below the 50% limit deemed acceptable by homeowners in the previous study, it may be that replacing lawns with a higher proportion of herbaceous cover defies aesthetic preferences or social norms. Future studies could investigate the limits to which homeowners in Claremont tolerate the replacement of turf with herbaceous cover.

Impervious cover largely did not change over the course of the drought. Considering that impervious surfaces provide little resources for native bees and they comprise large portions of yards, the lack of change in impervious surfaces likely did not support native bees. It was anecdotally observed that the driveways constitute a large fraction of the impervious area in residential yards. Impervious surfaces may not have changed because costs and perceived issues regarding the practicality of alternate types of driveways have been shown to prevent the adoption of alternative driveway materials (Cote & Wolfe, 2014). We suggest that if Claremont residents wish to support native bees, but cannot decrease impervious surfaces due to economic or technical barriers, they can increase herbaceous plants or bare ground elsewhere to make up for the lack of floral and nesting resources in driveways.

We found that mulch and gravel cover had changed by similar amounts, and together increased by over two-thirds of the proportion of yard area lost by turf grass. The lack of change in ground nesting scores is largely due to homeowners replacing most of the area where turfgrass was removed with mulch and gravel, paired with few increases in bare ground cover. The replacement of turf with mulch and gravel likely did not increase bee diversity because these factors are correlated with lower overall bee richness, especially that of ground nesting bees (Quistberg et al., 2016).

The similarities between the change in mulch and gravel may suggest they provide similar functions in converted yards. There are a number of reasons why homeowners may have chosen to opt for mulch or gravel instead of bare ground. While bare soils are prone to higher water loss as their exposure to the air and sun increase evaporation, mulches are commonly used to increase the water retention (Kazemi & Safai, 2018). Additionally, mulches and gravels may provide aesthetic purposes, being highly visible and more attractive than bare ground and are commonly used to prevent the emergence of unwanted weed plants (Skroch et al., 1992).

An illuminating analysis for the future would be to survey the bee communities present in yards of Claremont and to correlate the local bee diversity with the landscaping factors measured in this analysis. Although previous studies have done similar analyses in other regions (Pardee & Philpott, 2014; Hülsmann et al., 2015; Quistberg et al., 2016; Lanner et al., 2020), it has yet to be done in Southern California. Southern California contains a diverse native bee community with species that may respond differently to these factors than bee assemblages elsewhere. The findings from this analysis could additionally determine the thresholds for the proportional area of different groundcovers and vegetation that are required for specific bee species of interest.

Urban environments are important for the conservation of native bee communities, as their diverse and abundant floral resources support rich populations of bees excluded from other areas. There is large potential for cities to support even higher abundance and diversity of native bees with alterations to a few main aspects of urban green space. As residential yards contain a large portion of the greenspace found in cities, and are under the direct control of citizens, the decisions made by citizens can have direct effects on the conservation of native bees. In California where an exceptionally high number of wild bee species have evolved, urban residential gardens provide important habitat for a large number of these species to inhabit (Frankie et al., 2009). As droughts in recent years have caused shifts in the composition of residential gardens (Pincetl et al., 2017), it is

crucial to determine how these shifts alter the potential habitat for native bee communities. Our findings show that the drought has caused significant changes to turf grass, yet it remains a dominant cover in residential yards. Of all variables examined, turfgrass, mulch and gravel changed by the most, with mulch and gravel replacing the majority of reduced turfgrass area. Bare ground, an important determinant of the diversity of all bees and especially ground nesting bees, did not increase, while cover types that block access to the ground largely replaced turf. Additionally, on average, landscaping changes did not involve changes in woody plants such as trees or shrubs, indicating that nesting opportunities for cavity nesting bees did not improve. Herbaceous cover, the primary determinant of bee diversity in urban environments, did not increase over the course of the drought and currently represents a small portion of the greenspace present in front yards. These findings indicate that although the drought caused significant homeowners to change landscaping practices in their yards, these changes did not improve habitat for native bee communities. We suggest to Claremont residents that wish to modify their yards to support the local abundance and diversity of native bees, to replace lawns with flowering herbaceous plants and woody plants, and to leave open soil in areas where bare ground or gravel are otherwise used.

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