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Cities and the Environment (CATE)

Volume 15 | Issue 1 Article 4

9-30-2022

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McEachern, John R. (2022) "Evidence for the Effects of Wind on the Biogeography of Soil Mites in Urban Tree Wells," *Cities and the Environment (CATE)*: Vol. 15: Iss. 1, Article 4.
DOI: 10.15365/cate.2022.150104
Available at: https://digitalcommons.lmu.edu/cate/vol15/iss1/4

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Evidence for the Effects of Wind on the Biogeography of Soil Mites in Urban Tree Wells

The theoretical predictions of island biogeography have been applied successfully by a number of researchers studying the population and community structures of invertebrates living in large urban parks and remnant natural areas. Few, however, have examined the biogeography of smaller patches and the role that specific dispersal techniques play in shaping species distributions. In this study, I examine the impact of several biogeographical and environmental factors, including wind channelization effects, on the abundance of soil mites in small, urban tree wells in Westminster, Maryland. By testing five models that include the variables of well area, isolation, and dominate wind direction, I account for all possible directions in which channelization effects may be directing wind flow most frequently, therefore accounting for the impact of wind dispersal on mite distribution. As one would expect if mite abundances were impacted by the dominate direction of wind flow on a given street, only one of these models significantly explained the pattern of mite abundances found from sampling the tree wells. While the low power of the models requires that these results be viewed as inconclusive, the unusually high amount of variance explained by the significant model ($R^2 = 0.76$), along with its agreement with better established biogeographical relationships, does suggest that future research into the role of wind as a factor in the biogeography of passively dispersing urban invertebrates may be worthwhile.

Keywords

urban ecology, biogeography, soil invertebrates, soil mites, urban forests, wind dispersal

Acknowledgements

I would like to thank Dr. Holly Martinson for her help with finding equipment and designing the statistical models used in this study. I also want to thank Dr. Elizabeth Engle, Dr. Jason Scullion, and Peter McEachern for their support in developing this project and the Westminster Tree Commission for allowing me to collect soil samples from the tree wells under their care. Funding for this study was provided by the McDaniel College Research and Creativity Grant.

This article is available in Cities and the Environment (CATE): https://digitalcommons.lmu.edu/cate/vol15/iss1/4

INTRODUCTION

As of 2018, approximately 55% of the world's human population lives in urban areas, a number which is expected to increase to 68% by 2050 (United Nations 2018). As urban areas continue to grow, they provide both opportunities and challenges to the plants and animals that live in the areas that they expand into. Among the most important factors affecting the structure and composition of urban plant and animal communities are biogeographical features such as habitat fragmentation, isolation, and heterogeneity (Gibb and Hochuli 2002; Gomes et al. 2011; Xu et al. 2018). As such, the study of urban biogeography is becoming increasingly important.

One area of biogeographical theory that has been usefully applied to urban ecosystems is that of island biogeography. Pioneered by McArthur and Wilson (1967), island biogeographical theory posits that the structure of communities inhabiting isolated habitat patches is determined in part by the interaction between the area and isolation of the patch, with patch area having a positive impact on variables such as diversity and abundance, and isolation having a negative impact. An urban adaptation of the theory models cityscapes as a set of habitat "islands" of varying sizes and isolations, separated by unsuitable or difficult to traverse areas, such as streets, parking lots, and built-up areas (Fattorini 2016). A number of researchers using this approach to study the distributions of urban wildlife, especially invertebrates, have found population and community structures in large greenspaces and remnant natural areas that align with the predictions of the theory (Faeth and Kane 1978; Miyashita 1998; Bolger et al. 2000; Sadler et al. 2006; Fattorini 2014). Fewer studies, however, have investigated the biogeography of the smaller habitat patches which make up much of the non-impervious land cover in many cities (but see Goddard et al. 2010) and the role that specific dispersal techniques play in shaping species distributions. Understanding these features of urban invertebrate biogeography may help to inform ways of designing urban spaces that better support the many important ecosystem services that these organisms provide, including pollination, soil creation, pest control, and opportunities for environmental education (Lavelle et al. 2006; Kremen et al. 2007).

In this paper, I examine the distribution of soil mites (Acari) in tree wells – small, isolated patches of soil where street trees are planted (Figure 1b) – through the lens of island biogeographical theory. More specifically, I test whether or not the variables of patch area and isolation impact mite abundance in ways consistent with the theory. In addition, I investigate how mite abundance is affected by the presence of wind channelization effects, which occur when winds blow parallel to a city street, funneling air between buildings along its length (Klein and Clark 2007; Aliabadi et al. 2019). Because many soil mites are known to disperse passively by air (Szymkowiak et al. 2007; Lehmitz et al. 2011), these and other urban wind effects may impact their ability to colonize isolated tree wells distributed along the length of a street. Wells are generally relatively small in area and so are likely vulnerable to stochastic population reductions, suggesting that dispersal, and thus the dominant direction of wind channelization on a given street, may play an important role in shaping population structures of individual tree wells (Thomas 2000; Öckinger et al. 2009). If this is indeed the case, it may further be expected that mites will be distributed throughout the wells located on a given street in a pattern that is biased by the prevailing direction of winds being funneled by the channelization effect.

Because biogeographical variables often interact with habitat quality to affect population and community structures, I also test the relationship between mite abundance and two additional environmental variables: dominant substrate type and lead concentration. Substrate type can affect microclimate and the availability of food for soil organisms (Haskell 2000), while lead, in high concentrations, can have negative impacts on invertebrate health and reproductive success (Fountain and Hopkin 2004; Santorufo et al. 2012). Both of these variables play important roles in shaping urban and roadside environments in particular and may represent additional factors which help to determine invertebrate distribution and abundance in tree wells.

METHODS

Study Area and Tree Well Selection

This study was performed in the City of Westminster, Maryland, using tree wells selected from those along the city's two main roads: West Main Street, which runs northwest-southeast (n = 9), and Pennsylvania Avenue, which runs north-south (n = 6; Figure 1a). Each of the tree wells selected contained at least some natural detritus or mulch where soil mites were likely to be found. As much as possible, groups of multiple tree wells located adjacent to each other along the length of the street were selected, as this allowed for simpler isolation measurements (see below). Area and isolation were also measured for (but no invertebrate samples were taken from) a large ornamental planting bed, located just south of the southernmost sampled well on Pennsylvania Avenue. Before taking any soil or invertebrate samples from the wells, permission was first sought from and granted by the Westminster Tree Commission.

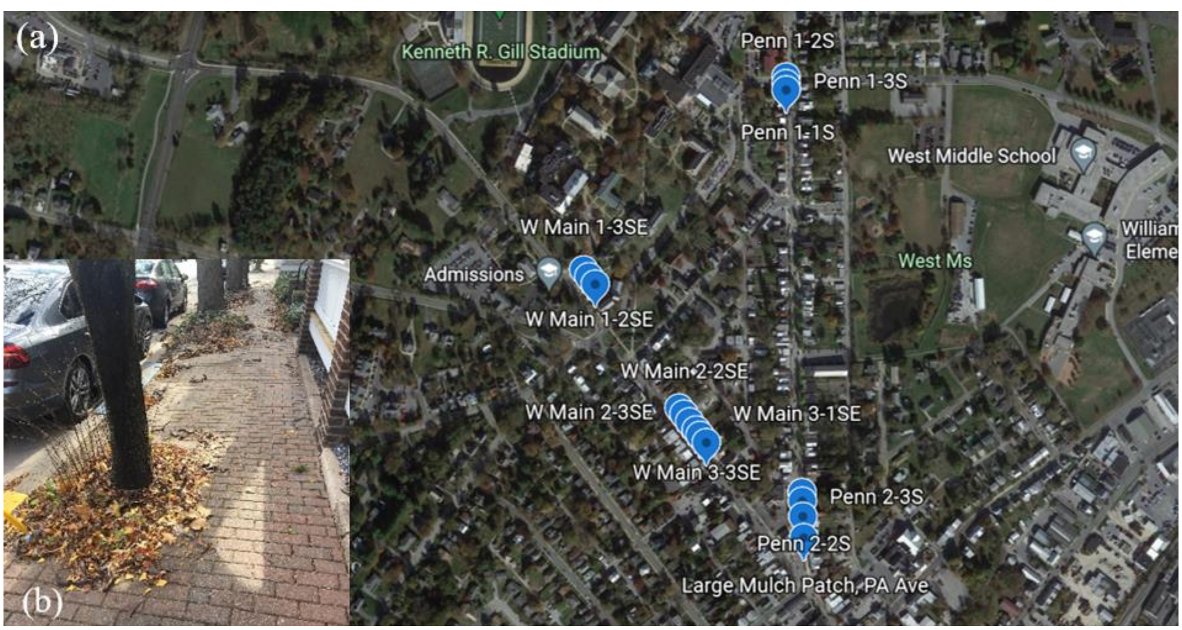

Figure 1 – (a.) The Westminster, Maryland study area, with tree well locations marked with blue flags. (b) Tree wells located on Pennsylvania Avenue in Westminster, Maryland.

Biogeographical and Environmental Variables

The two primary biogeographical variables on which data were collected for each tree well were area and isolation. The area of each well was calculated using either the area of a square formula (*A=lw*) or, for one well which was triangular in shape, the area of a triangle formula (*A=1/2hb*). The area of the large planting bed located on Pennsylvania Avenue, though irregular in shape, was estimated using the area of a square formula. The measurements needed for these calculations were taken in centimeters using Keson 50 m fiberglass field tape.

The isolation of each well was quantified by measuring the distance from the selected well to its two closest neighbors on either side. This was done under the assumption that the inhospitality of the sidewalk between the wells represented the main obstacle to active dispersal by soils mites, due to their poor active dispersal abilities (Lehmitz et al. 2012), their preference for moist habitats (Gergócs and Hufnagel 2009), and evidence that similar impervious surfaces impede movement in other ground-dwelling invertebrates (Niemelä and Kotze 2009; Bennett and Gratton 2012; Korányi et al. 2021). Again, distances were measured in centimeters using field tape, except in one case in which the measurement tool on Google earth was used to measure the distance between the large planting bed on Pennsylvania Avenue and the nearest sampled well. Due to a lack of time and resources for collecting more direct data on local wind conditions, isolation measurements were also used as proxies for the impact of unidirectional wind channelization effects (see Statistical Analysis section below).

Data on the dominant substrate type and lead concentrations in the soil were also collected for each well. With respect to dominant substrate type, each well was characterized as being dominated primarily by detritus (dead leaves and wood from the tree growing in the well), mulch, or bare soil, depending on which substrate type appeared to cover the largest area of the well. To obtain information on the concentration of lead in the soil of each well, soil samples were sent to the University of Delaware Soil Laboratory for testing. All samples consisted of 5 to 6 soil cores, each approximately 5.08 cm in depth, and were collected, mixed, packaged, and mailed according to laboratory guidelines for a soil lead screening in undisturbed soils (University of Delaware Soil Laboratory n.d.).

Mite Collection and Sorting

The wells selected for the study were sampled for soil mites three at a time on five days between September 1 and September 29, 2020. Each well was divided into four quadrants and a random number generator was used to select two from which a sample of detritus or mulch totaling approximately 250 mL was collected. Detritus and mulch, rather than soil, were collected even from wells dominated by bare soil due to the higher likelihood of finding mites in these substrates (Haskell 2000) and the greater ease with which mites are filtered from them. Each of the selected quadrants for a given well contributed about half the material in the 250 mL sample. The exception to this was a single well which was triangular in shape and which was divided into halves of which only one was chosen at random for sampling. The temperature and humidity in Westminster at the start of each of the five sampling bouts were also recorded using the iPhone weather application (2020).

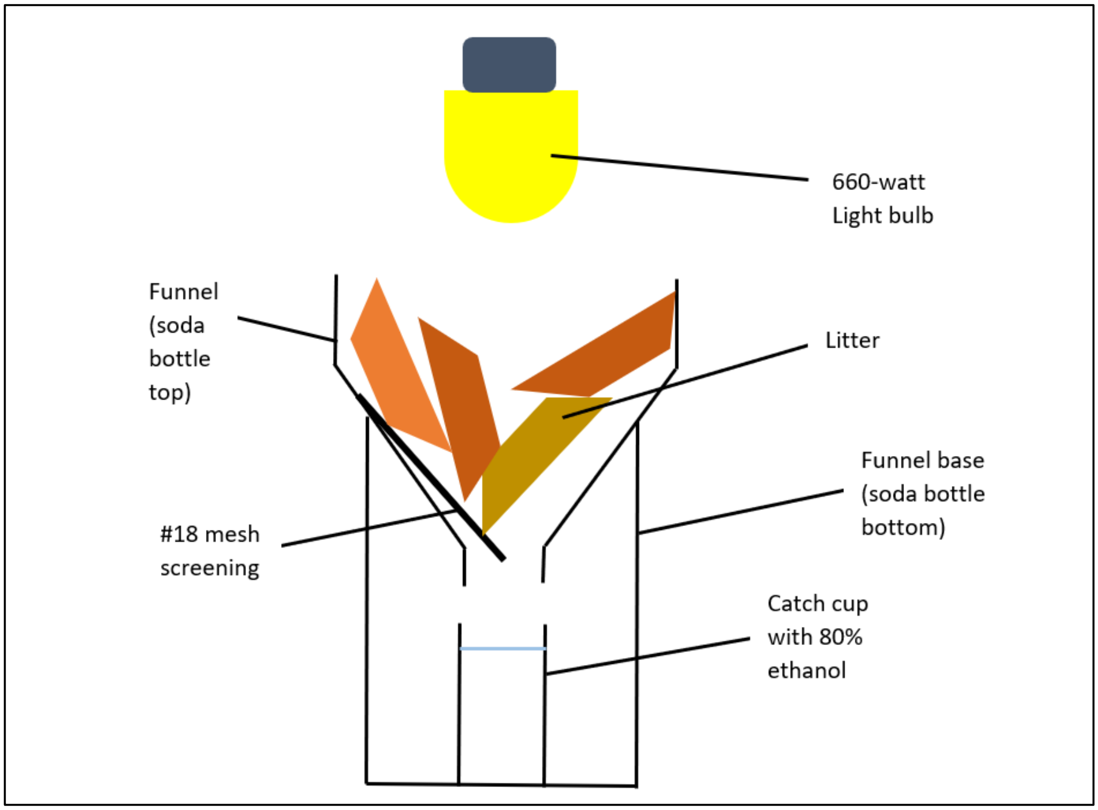

Figure 2 – Diagram of a Berlese funnels. Detritus or mulch samples from each tree well were placed in a funnel for one week in order to sort out the invertebrates inside.

After the detritus or mulch samples were collected, they were placed in Berlese funnels for the purpose of sorting out any mites inside (Figure 2). Each funnel was constructed using a two-liter plastic soda bottle that was cut in half so that the top half formed a funnel and the bottom formed a container for the funnel. A small (approximately 6.35 x 5.08 cm) piece of #18 mesh screening was placed in the tapered end of the top half of the bottle for the purpose of preventing any soil material from falling through (note that the screening was not used as a filter, but was placed in such a way as to leave part of the funnel's opening unobstructed). The top half of the bottle was then put inside the bottom half with the tapered end facing down. A sample of detritus or mulch was placed inside the funnel and was left to sit for seven days with a 660 W lightbulb shining on it to dry out the soil material, forcing any invertebrates inside to move downwards. In the bottom half of the bottle, a small container of 80% ethanol was placed beneath the funnel in order to catch and preserve any invertebrates that dropped down from the sample.

The invertebrates filtered from the detritus or mulch samples were stored in 80% ethanol until they could be processed. The mites in each sample were identified and counted by hand, using a Nikon SMZ645 dissecting microscope. Mites were defined for the purpose of this study as any microarthropod with four pairs of legs, indistinct body segments, and no spinnerets (Dunlop and Alberti 2008; Srivastava Lab 2012). The mite count from one well was not included in the study due to a malfunction with the funnel being used to sort the sample.

Statistical Analysis

Once all the data had been collected, a series of exploratory correlation tests were performed on the relationships between each of the major variables (area, isolation, soil lead concentrations) and mite abundance, as well as between mite abundance and weather data (temperature, humidity) from the dates when the invertebrate samples were collected. A two-sample t-test was also performed on the relationship between dominant substrate type and mite abundance. Because only two bare soil dominated wells were sampled, only detritus (n = 8 wells) and mulch (n = 4) were considered. These tests, along with all other statistical tests in this study, were performed using RStudio and R (version 1.1.463, R Core Team 2018).

Soil lead concentration, dominant substrate type, and weather conditions did not relate significantly to mite abundance (see Results) and were therefore not included in the more complex statistical models, which instead focused on well area, isolation, and the influence of wind channelization effects. Biogeographical theory emphasizes the interaction between area and isolation, so five linear regression models of the impacts of well area, isolation, and their interaction on mite abundance were compared for fit with the data collected using the lm() function in R (see Supplementary Files for full data set and R code used). Due to a lack of time and resources, data on local wind conditions at the Westminster study site could not be collected. Therefore, the possible influence of wind channelization effects was tested in four of the models by including the isolation of each well relative to its closest neighbor in *only one direction*. This was done under the assumption that mite distribution, if it is influenced by wind channelization effects, would be biased in the direction in which these effects most frequently funnel air (Figure 3). To wit, Model 1 (n = 10 wells) assumed that a well's area and the distance to its nearest southern (for Pennsylvania Avenue) or southeastern (for West Main Street) neighbor interact to affect mite abundance. Model 2 (n = 10) assumed that a well's area and the distance to its nearest northern (for Pennsylvania Avenue) or northwestern (for West Main Street) neighbor interact to affect mite abundance. Model 3 (n = 11) assumed that a well's area and the distance to its nearest southern neighbor on Pennsylvania Avenue and its nearest northwestern neighbor on West Main Street interact to affect mite abundance, while Model 4 (n = 9) assumed that a well's area and distance to its nearest northern neighbor on Pennsylvania Avenue and its nearest southeastern neighbor on West Main Street interact to affect mite abundance. Model 5 (n = 14) served as a control and assumed that a well's area and the distance to its nearest neighbor, regardless of direction, interact to affect mite abundance without the influence of a wind channelization effect. Simple slopes analyses were then performed using the sim_slopes() function in the R interactions package (Long 2021) on any models which were found to significantly explain the data. This was done in order to determine the nature of the interaction between area and isolation in their effect on mite abundance.

Finally, due to the small sample sizes used in this study, a post hoc, fixed model, R^2 deviation from zero power analysis and a post hoc, fixed model, R^2 increase power analysis were performed on each model using the program G* Power 3.1 (Faul et al. 2007) in order to evaluate the likelihood of Type II errors.

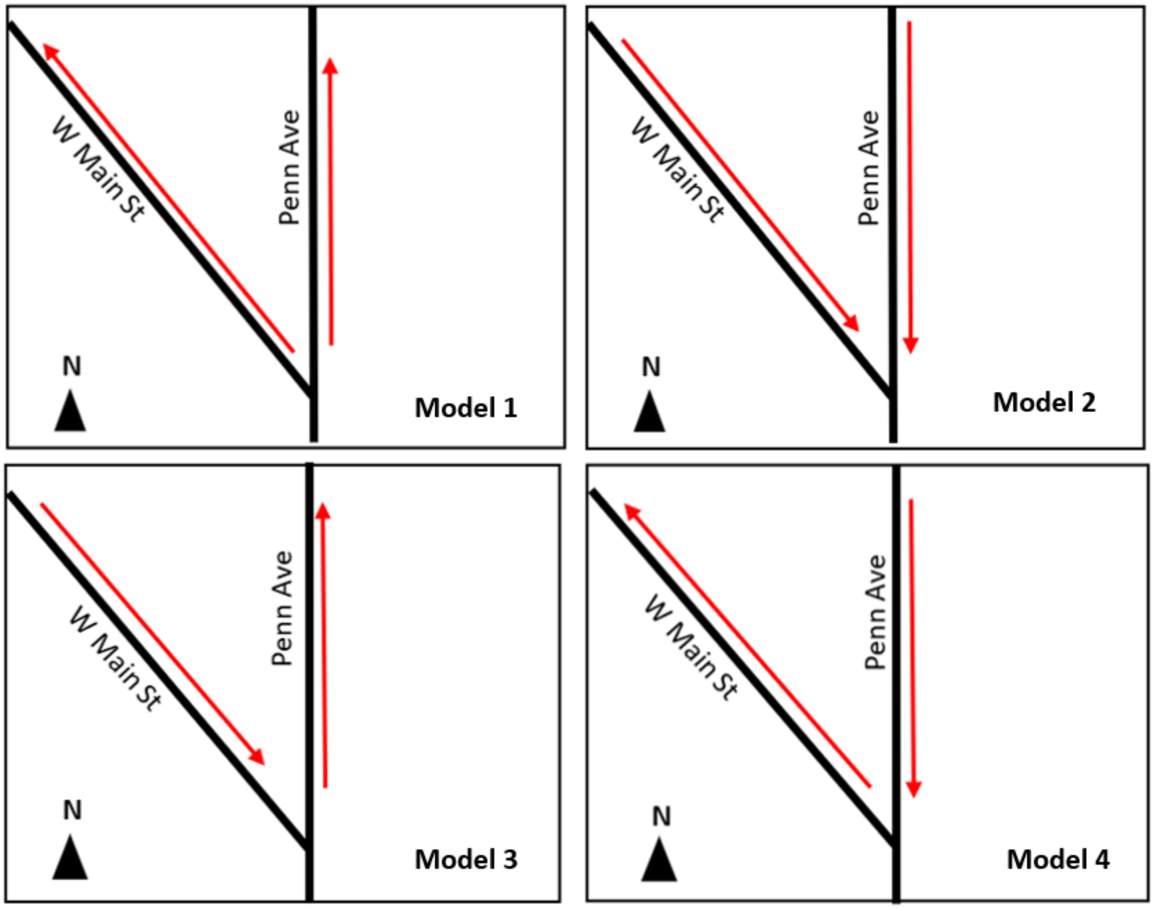

Figure 3 – Diagrams of the biogeographical models, where the red arrows represent the direction in which the wind channelization effect is funneling air. Mites colonizing any given well are assumed to have dispersed from that well's nearest neighbor in the direction that wind is primarily flowing *from*. As such, it is assumed in Model 1, for example, that well area and distance to the nearest southern (for Pennsylvania Avenue) or southeastern (for West Main Street) well interact to affect mite abundance. See Supplementary Files for full data set and R Code used for the five models.

RESULTS

Soil invertebrate samples for this study were collected and processed from 14 tree wells in downtown Westminster, Maryland. The samples contained a total of 1,051 mites, along with a number of other invertebrate taxa, including sowbugs, springtails, termites, and beetle larva.

Neither the dominant substrate type (t = 1.717, df = 9, p = 0.060), nor the soil lead concentration (r[12] = 0.13, p = 0.666) were found to significantly affect mite abundance in tree wells. The temperature (r[12] = -0.49, p = 0.0741) and humidity (r[12] = 0.09, p = 0.769) on the date of collection for the invertebrate samples were also found to be non-significant.

Of the three biogeographical models, the variance in mite abundance was not explained significantly by Model 2 ($F_{3,6}$ = 2.99, p = 0.118), Model 3 ($F_{3,7}$ = 3.10, p = 0.098), Model 4 ($F_{3,5}$

= 2.04, p = 0.227), or Model 5 ($F_{3,10}$ = 1.77, p = 0.217). Instead, mite abundance was best explained by Model 1, which incorporated well area, distance to a well's closest southern (Pennsylvania Avenue) or southeastern (West Main Street) neighbor, and their interaction (model R^2 = 0.76 [adjusted R^2 = 0.64], $F_{3,6}$ = 6.324, p = 0.027). Model 1 found no significant main effect for area (b = 0.002, SE = 0.002, t = -0.89, p = 0.408), but did find a significant main effect for distance to a well's nearest southern or southeastern neighbor (b = -0.284f, SE = 0.106, t = -2.67, p = 0.037). This was qualified, however, by a significant interaction between area and isolation (significant interactive effect: p = 0.0436). As shown in Figure 4a, simple slopes analysis revealed a negative relationship between mite abundance and distance to the nearest upwind well for tree wells with smaller areas (b = -0.14, t = -2.66, p = 0.04), but a non-significant relationship for tree wells with larger areas (b = -0.03, t = -1.16, p = 0.29).

The post-hoc fixed model, R^2 deviation from zero power analysis of each model returned a power (1-β) of less than 0.80 for a large effect size (f = 0.35) and error size of 0.05, indicating that the power of each model was insufficient to rule out Type II errors for large, medium, and small effects (Cohen 1988). This was the case for Model 1 (n = 10; number of predictors = 3; 1-β = 0.19), Model 2 (n = 10; number of predictors = 3; 1-β = 0.19), Model 3 (n = 11; number of predictors = 3; 1-β = 0.22), Model 4 (n = 9; number of predictors = 3; 1-β = 0.16), and Model 5 (n = 14: number of predictors = 3; 1-β = 0.31). The post-hoc fixed model, R^2 increase power analysis also failed to return a power (1-β) of less than 0.80 for a large effect size (f = 0.35) and error size of 0.05 for Model 1 (n = 10; number of tested predictors = 1; number of predictors = 3; 1-β = 0.35), Model 2 (n = 10; number of tested predictors = 1; number of predictors = 3; 1-β = 0.35), Model 3 (n = 11; number of tested predictors = 1; number of predictors = 3; 1-β = 0.40), Model 4 (n = 9; number of tested predictors = 1; number of predictors = 3; 1-β = 0.30), and Model 5 (n = 14; number of tested predictors = 1; number of predictors = 3; 1-β = 0.26).

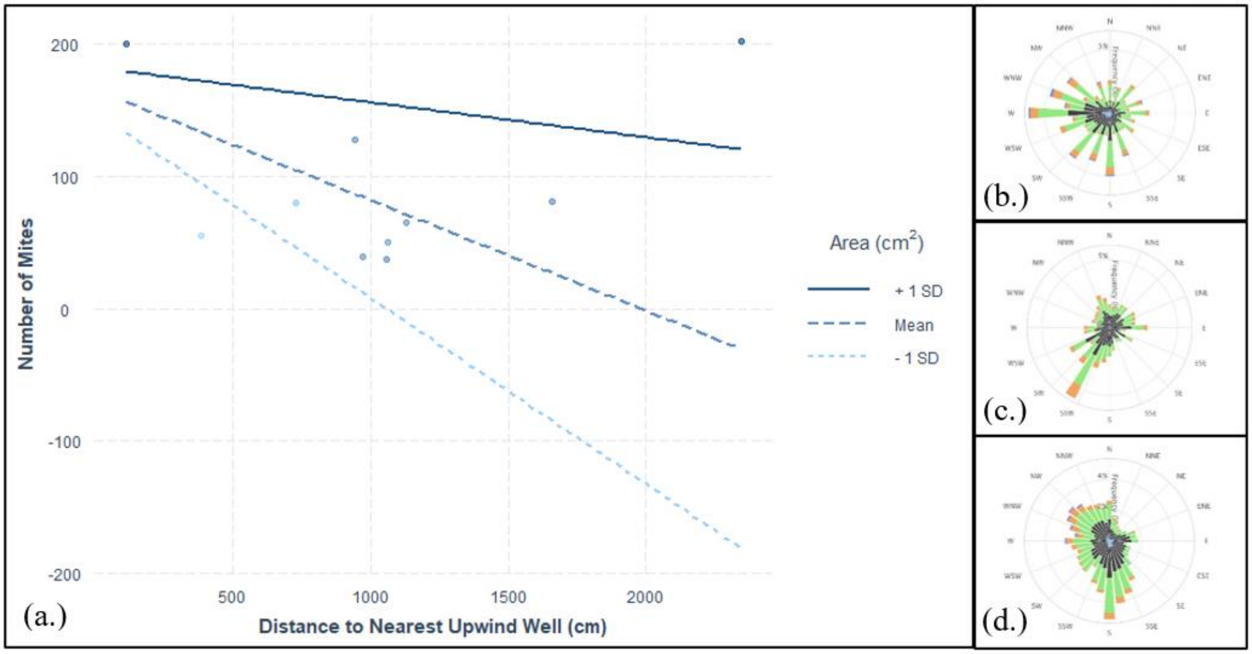

Figure 4 – This interaction plot (a.) shows the results of Model 1 in more detail. The dark blue dotted line in the center represents the relationship between mite abundance and distance to a well's closest neighbor to the south or southeast (depending on which street the well is located on), assuming that the wells area is equal to the mean area of all the well's sampled in the study. The two lines above and below represent this same relationship assuming that the well's area is equal to one standard deviation above or below the mean. Although wind data could not be obtained for Westminster, data from surrounding counties shows that winds often blow from the south or southwest during the summer months when mites are most active (Midwestern Regional Climate Center 2020). In this figure, (b.) shows the average wind direction in Ann Arundel County, Maryland, from May through September, 1945-2020, (c.) shows May through September wind direction in Harford County from 1977-2016, and (d.) shows May through September wind direction in Washington County from 1973-2020. The length of each spoke in the wind roses refer to the average amount of time the wind is blowing from that compass direction.

DISCUSSION

The results of this study provide some intriguing, though largely inconclusive, evidence that wind channelization effects may play a role in shaping the population structure of soil mites in urban street tree wells. Of the four biogeographical models that included wind direction as a factor, only one (Model 1) showed a statistically significant relationship between mite abundance and the interaction between a well's area and the distance to its closest neighbor. One would expect this to be the case if wind channelization effects are indeed having an impact on mite dispersal, as the direction of funneled air would most frequently match that of the regional prevailing winds, perhaps biasing mite distribution in that direction. Model 1 assumed that wind channelization effects tend to funnel air from the south more than from the north on Pennsylvania Avenue and from the southeast more than from the northwest on West Main Street.

Since specific data on local wind patterns in Westminster, Maryland could not be obtained, it is unclear whether this is actually the case. However, data from three surrounding counties indicate that prevailing winds during the summer (when mites tend to be most active) do tend to blow from the south or southwest in the region (Midwestern Regional Climate Center

2020; Figure 4b-d), offering at least some support for this interpretation of the Pennsylvania Avenue data. While a directional variable appears to be playing a role in mite abundance in tree wells, this study only provides circumstantial evidence to link this variable to wind direction, and future studies of the impacts of channelization effects on urban biogeography should either be performed in cities where there is existing data on prevailing wind directions or, preferably, include the collection of this data in the studies' designs. They would also likely benefit from including more direct measures of mite wind dispersal in their methods (such as those described by Zhao and Amrine, 1997) in order to better confirm its influence on observed abundances.

The results of this study also appear to support the use of island biogeographical theory as a tool for modeling the distribution of soil invertebrates in tree wells and perhaps other small urban habitat patches as well. In conventional island biogeographical theory, both the area and isolation of a habitat patch play a part in determining the structure of populations and communities within that patch through their influence on colonization and extinction (McArthur and Wilson 1967). In this study, mite abundance was indeed best explained by a model which assumes an interaction between area and isolation. In addition, simple slopes analysis performed on Model 1 found that the negative impact of the isolation of a tree well on mite abundance becomes larger as the size of the well decreases (Figure 4a). As such, my results suggest that tree well area has a positive effect on mite abundance, while isolation has a negative effect – results which are again in line with the predictions of island biogeographical theory. Future studies might expand on these results by examining the relationship between tree well area and isolation and other population and community variables, such as species richness and diversity.

While both of these conclusions – that wind channelization effects and the interaction between area and isolation may have an impact on mite abundance in tree wells – are interesting, they should be treated with caution in light of certain important limitations with the design of this study. Due to limited time and resources, a very small number of wells were sampled and, as shown by the power analysis performed on the five models, this leaves open the possibility of Type II errors occurring during statistical analysis. Because the design of this study relies heavily on there being no significant effect detected in all but one of the models for the strength of its conclusions about the impacts of wind on mite abundance, the weak power of the models requires that the above interpretation of the results be treated as highly speculatory. On the other hand, Model 1 does appear to explain an unusually high amount of the observed variance in mite abundance – its R^2 value of 0.76 (adjusted R^2 = 0.64) is much higher than the average of between .025 and .054 reported by Møller and Jennions (2002) for ecological studies. In general, an accumulation of type II errors will result in an artificially low R^2 value, meaning that this result should be unaffected by Model 1's low power (Colton and Bower 2002). This, along with the model's agreement with better established relationships between area, isolation, and population structure, suggest the possibility that wind may still be an important variable impacting mite abundance, even if the relationship is not as simplistic as suggested by only one model returning a significant effect. At the very least, these results suggest that further investigation of the relationship between urban wind affects and the abundance of wind dispersing mites in isolated tree wells may be worthwhile. In addition to being better positioned to find more conclusive evidence for or against the existence of this relationship, future studies with a larger sample size may also help to confirm the role of temperature and dominant substrate type in determining tree well mite abundance, since both variables were found to be nearly, but not quite significant in this study. Including additional habitat variables may also help in producing a picture of mite distribution which is almost certainly shaped by more complex mechanisms than a simple interaction between area, isolation, and wind (Fox and Fox 2000; Kallimanis et al. 2008; Triantis and Sfenthourakis 2012).

Overall, the results of this study, while inconclusive, do seem to support the potential fruitfulness of future biogeographical research into small urban habitat patches, as well as the role of wind effects in the distribution of urban organisms. As pointed out by Goddard et al. (2010), many of the small patches which make up much of the available habitat for urban wildlife are too small to support viable populations of important species on their own, meaning that they must be managed collectively. Knowledge of how mechanisms of colonization and extinction impact species distribution and the population and community structures of habitat patches will be vital for effectively designing such management strategies. While wind patterns associated with urban and roadside areas have been implicated in the distribution of urban lichens via their impact on air pollution (Neurohr Bustamante 2011) and in the distribution of invasive plant species (Kowarik and Von der Lippe 2011), this sort of research is still rare and, indeed, this study appears to be among the first to examine the impact of wind on the distribution of an urban invertebrate. Wind is used by a substantial number of other organisms, including many invasive species, helpful natives, and agricultural pests (Li and Margolies 1993; Flores-Moreno et al. 2013), as a means of dispersal. As such, future interdisciplinary research that combines the skills and knowledge of ecologists and fluid engineers studying urban wind patterns may very well unearth useful information that can be used to design and manage the matrix of urban habitat patches in ways that strengthen the health and diversity of urban ecosystems.

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