Winged Witnesses: Gentrification's Impacts on Bird Biodiversity in San Francisco

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ABSTRACT

Gentrification, an increase in a neighborhood's affluence, cost-of-living, and amenities leading to displacement of those of lower socioeconomic status, poses challenges for both human communities and urban wildlife, such as birds. Birds play crucial roles as urban predators, prey, pest controllers, pollinators, and ecosystem engineers. However, the relationship between gentrification and bird biodiversity in San Francisco remains uncertain. San Francisco, with its rapidly gentrifying neighborhoods, serves as an important case study for understanding this phenomenon. Leveraging eBird citizen science data (2015 – 2019) and the Urban Displacement Project's SF Bay Area Gentrification Map (2018), this study investigates the impact of gentrification on reported bird observations and bird biodiversity via species richness and Shannon diversity. I also explore differential impacts on generalists versus non-generalists. I found that neither gentrification nor change in time significantly affected the overall number of observations. However, gentrification did have an impact on bird species richness and diversity. Moreover, I found that for species richness, NDVI is a stronger predictor of species richness compared to gentrification, whereas the opposite pattern was found for Shannon diversity. Finally, gentrification decreases species richness solely in generalist species, whereas it impacts Shannon diversity in both generalist and non-generalist species. These results underscore the importance of prioritizing conservation efforts safeguarding vulnerable bird populations in gentrified areas by incorporating gentrification as a non-ecological metric in these efforts. Policymakers are urged to integrate such wildlife biodiversity considerations into urban planning processes that could result in gentrification to ensure sustainable development supporting human and ecological well-being.

KEYWORDS

citizen science, land-use change, socio-environmental interactions, urbanization, urban wildlife

INTRODUCTION

Cities are dynamic environments shaped by a myriad of social and ecological factors (Collins et al. 2000, Collins et al. 2001, Ramalho and Hobbs 2012, Des Roches et al. 2021), exerting pressures on wildlife ecology, including species distribution, abundance, and behavior (Ouyang et al. 2018). For example, urbanization can alter habitats, human-wildlife interactions, and access to resources through novel stressors such as disturbances in the built environment, changes in green spaces, pollution, noise, and artificial lighting, disrupting wildlife prevalence and behavior (McKinney 2002, Longcore and Rich 2004, Gaston et al. 2014, Moll et al. 2019, Wilkinson et al. 2023). Social factors like population density, income inequality, and land-use policies can underpin the spatial distribution of urban development, subsequently impacting habitat degradation and fragmentation (Luck et al. 2004, Seto et al. 2012). For instance, systemic racism has led to ecological heterogeneity due to socioeconomic disparities and neighborhood segregation (Schell et al. 2020). Therefore, urban ecosystems exhibit spatial heterogeneity as a result of systemic racism in terms of habitat type, vegetation distribution, and land-use intensities, resulting in equally heterogeneous biodiversity in urban landscapes (Smith et al. 2018, Pearsall et al. 2020, Schell et al. 2020).

Previous research on urban impacts on biodiversity has shown an intricate relationship between vegetation and faunal diversity (Leong et al. 2018, Chamberlain et al. 2019). Namely, affluent neighborhoods tend to have higher biodiversity due to increased investment in green infrastructure and landscaping, a phenomenon known as the "luxury effect" (Gaston et al. 2017, Leong et al. 2018, Chamberlain et al. 2019). Specifically, Gaston et al. observed the luxury effect in areas of low urbanization where species richness increased as income level increased (2017). On the contrary, in areas of high urbanization, species richness is negatively correlated with income level, exemplifying the complex relationship between urbanization, socioeconomic status, and biodiversity (Gaston et al. 2017). Additionally, historical factors such as redlining, have also played an important role in shaping biodiversity by reinforcing wealth disparities and influencing land-use decisions (Schell et al 2020). Recent work has shown lower species richness and community composition in historically redlined neighborhoods (Estien et al. 2023, Wood et al. 2023). While previous work has acknowledged the influence of these historical legacies, contemporary variables like gentrification may override their effects and reshape urban biodiversity dynamics.

Gentrification, characterized by the rapid demographic shift in urban neighborhoods, involves the influx of wealthier residents into previously marginalized communities, often leading to significant socioeconomic and environmental transformations in a neighborhood (Cole et al. 2017, Schinasi et al. 2021). Factors such as land use change and development can have far-reaching consequences for human communities and wildlife populations (Hubbard and Brooks 2021). Although gentrification can result in resource and infrastructure improvements in an area, vulnerable populations face displacement due to the rising housing costs and may not reap these benefits (Cole et al. 2017). One key form of gentrification is green gentrification, the process of developing green spaces in previously neglected areas, attracting affluent residents, and driving further urban development (Anguelovski et al. 2019). However, these changes can have unintended consequences for wildlife through habitat degradation or development, particularly birds, which play crucial roles in urban ecosystems (Jongsomjit et al. 2013).

Birds are essential for maintaining ecological balance, acting as pest controllers, prey, and pollinators, as well as ecosystem engineers, and are typically dependent on vegetation and green space (Whelan et al. 2015). As neighborhoods undergo gentrification, changes in land use and habitat availability can disrupt bird populations, leading to shifts in biodiversity as recently found in mammal populations in the United States (Fidino et al. 2024). While gentrified areas may benefit from increased resources for wildlife and potentially greater land management, they may also experience habitat loss and fragmentation, exacerbating the challenges faced by bird species (Fidino et al. 2020). Certain species, often those considered colorful or charismatic, may be favored in the gentrification process due to human interest in them, leading to an increase in bird feeders and microhabitats to attract these birds (Gaston et al. 2017). In contrast, other species, such as pigeons and other perceived "pests," may face increased pressure and displacement as urban areas undergo redevelopment with more financial incentives, leading to a decrease in species richness and diversity (Hubbard and Brooks 2021, Hung et al. 2021). Therefore, shifts in green spaces and habitat availability resulting from gentrification can profoundly and disproportionately affect bird populations and biodiversity, as well as eBird observations.

Contributory science platforms like eBird offer significant advantages for ecological research, through the collective efforts of citizen scientists generating large-scale datasets with a widespread spatial and temporal distribution of birds across cities (Kelling et al. 2019, Veech et al. 2021, Carlen et al. 2023). Despite potential biases in such data, including variation in observer skill and effort, non-uniform sampling, and selection bias based on neighborhood income levels and ethnicity, the comprehensive coverage provided by eBird enables researchers to detect patterns in species occurrence and biodiversity on fine and coarse scales (Sullivan et al. 2009, Tang et al. 2021, Grade et al. 2022). This plethora of observational data, unlike traditional methods such as point counts limited by spatial and temporal constraints, is less limited by spatial and temporal constraints, allowing for more thorough analyses (Sullivan et al. 2014). Ecological studies at broader scales provide important insights into how species respond to environmental changes over time for developing strategic conservation methods (Johnston et al. 2019). Although biases in the dataset could lead to differential numbers of observations recorded in neighborhoods of different socioeconomic status, it still provides extensive data suitable for this study.

Despite the growing recognition of gentrification's impacts on urban ecosystems, research on its effects on wildlife remains limited (Fidino et al 2024). San Francisco was an ideal case study to investigate how gentrification influences wildlife biodiversity as it is one of the most gentrified U.S. cities (Kwak 2018). This study used 2015 – 2019 eBird data in San Francisco to answer the question: *How does gentrification influence bird biodiversity and biodiversity data?* Additionally, I used the Urban Displacement Project's (UDP) 2018 SF Bay Area Gentrification and Displacement Map to perform analyses with the eBird data to understand the differences in bird biodiversity between various levels of gentrification. This study sought to answer the following four sub-questions: (1) *How does the number of reported bird observations differ between gentrified and non-gentrified neighborhoods? How do reported observations change over time as a result of gentrification?* (2) *How does overall bird species richness vary with gentrification?* (3) *How does bird diversity vary with gentrification?* And (4) *Are non-generalist species impacted differently by gentrification than generalist species of birds?* First, I hypothesized that the number of bird observations would increase as gentrification increases due to demographic changes in the people living in a neighborhood. Second, I hypothesized that bird species richness and diversity would decrease as a function of gentrification in SF, due to the shifts in green spaces and urban infrastructure disrupting populations and habitats (Jongsomjit et al. 2013). Further, I expected that generalist species would be more positively impacted by gentrification due to their ability to adapt to and benefit from green gentrification (Chamberlain et al. 2019). Understanding the intricate relationship between gentrification and bird biodiversity is essential for informing wildlife policy and management practices in gentrifying neighborhoods (Hubbard and Brooks 2021). By quantifying the impacts of gentrification on bird populations, this study aimed to fill a crucial gap in research and contribute to the development of sustainable urban planning strategies that support both human and ecological well-being. To understand the effects of gentrification on bird populations in San Francisco, I followed a quantitative approach comparing a gentrification score and gentrification binary to bird observations, species richness, and Shannon diversity to answer my study questions.

METHODS

Study site

The study site is the city of San Francisco (37.7749° N, 122.4194° W), with a size of 46.91 square miles and a population of 808,437 people. San Francisco is 43.4% white, 5.2% African or African American, 0.5% Indigenous American, 34.4% Asian, 0.4% Native Hawaiian/Pacific Islander, and 15.4% Hispanic or Latinx (U.S. Census Bureau 2022). The median household income is $126,187, and 10.3% of people are under the poverty level (U.S. Census Bureau 2022). As for land use, most regions of the city are residential, with northeastern San Francisco having the most land-use diversity (Adepeju 2017). The UDP classifies gentrification across nine different gentrification levels (Figure 1; Chapple et al. 2021). In San Francisco, 46.7% of census tracts are classified by UDP as at risk of or experiencing advanced stages of gentrification and displacement, with the most gentrified areas being in northeastern San Francisco (Figure 1; Mujahid et al. 2019, Chapple et al. 2021). To coincide with the UDP's dataset, I'm using eBird data from the years 2015 to 2019 (Chapple et al. 2021).

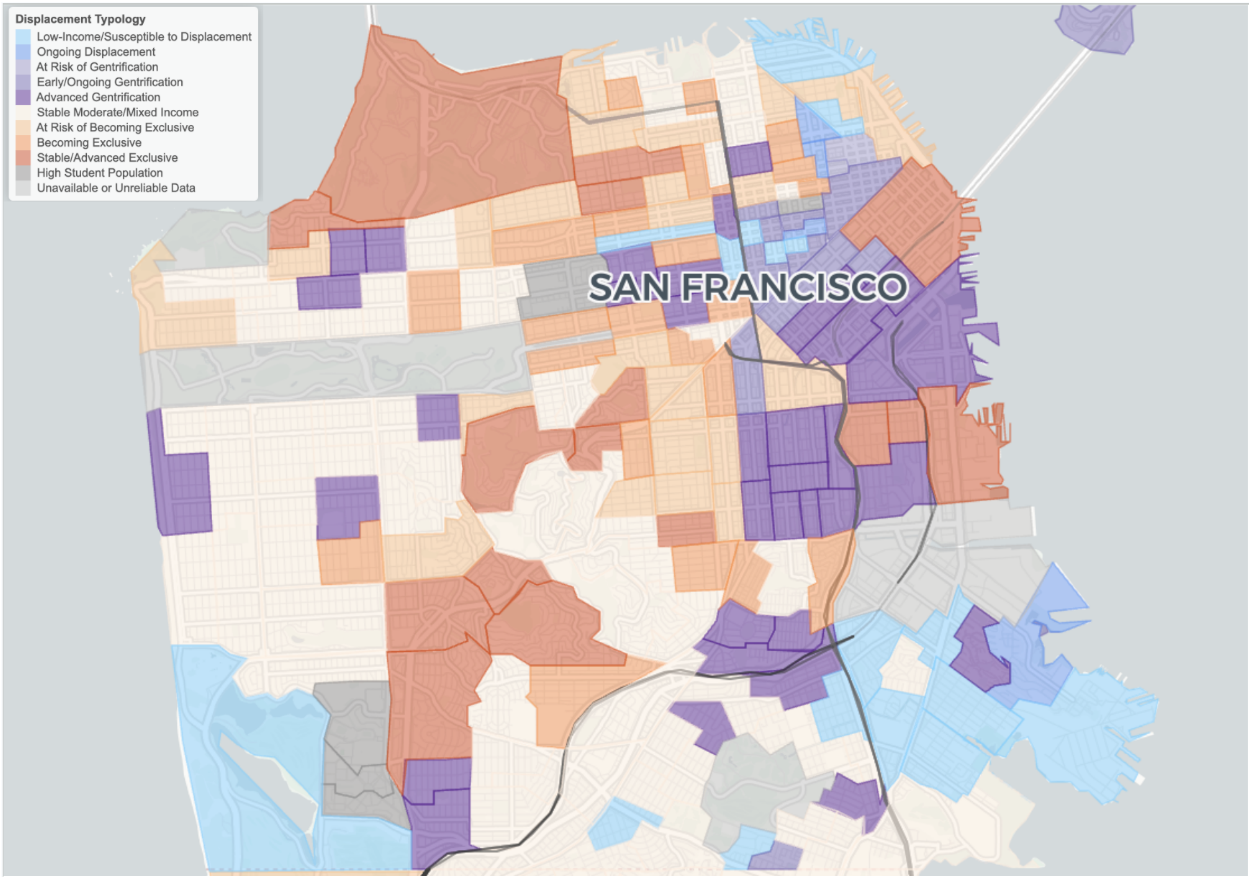

Figure 1. Gentrification levels of San Francisco's census tracts in 2018 (Chapple et al. 2021).

Gentrification data collection

I used the UDP's' 2018 SF Bay Area Gentrification Map, created as a way to understand exclusion, gentrification, and displacement in the city of San Francisco (Chapple et al. 2021). UDP aggregated its collected data to develop nine ordinal categories of gentrification, ranging from low-income/susceptible to displacement to stable/advanced exclusive (Figure 2). I analyzed gentrification in two forms: categorically (i.e., gentrified vs non-gentrified) and continuously. For my categorical analyses, I created a gentrification binary with early/ongoing gentrification, advanced gentrification, and becoming exclusive being considered as gentrified, and low-income/susceptible to displacement, ongoing displacement of low-income households, at risk of gentrification, stable moderate/mixed-income, at risk of becoming exclusive, and stable/advanced exclusive as non-gentrified).

MODIFIED TYPES	CRITERIA
LOW-INCOME/SUSCEPTIBLE TO DISPLACEMENT	• Low or mixed low-income tract in 2018
ONGOING DISPLACEMENT OF LOW-INCOME HOUSEHOLDS	• Low or mixed low-income tract in 2018 • Absolute loss of low-income households, 2000-2018
AT RISK OF GENTRIFICATION	• Low-income or mixed low-income tract in 2018 • Housing affordable to low or mixed low-income households in 2018 • Didn't gentrify 1990-2000 OR 2000-2018 • Marginal change in housing costs OR Zillow home or rental value increases in the 90th percentile between 2012-2018 • Local and nearby increases in rent were greater than the regional median between 2012-2018 OR the 2018 rent gap is greater than the regional median rent gap
EARLY/ONGOING GENTRIFICATION	• Low-income or mixed low-income tract in 2018 • Housing affordable to moderate or mixed moderate-income households in 2018 • Increase or rapid increase in housing costs OR above regional median change in Zillow home or rental values between 2012-2018 • Gentrified in 1990-2000 or 2000-2018
ADVANCED GENTRIFICATION	• Moderate, mixed moderate, mixed high, or high-income tract in 2018 • Housing affordable to middle, high, mixed moderate, and mixed high-income households in 2018 • Marginal change, increase, or rapid increase in housing costs • Gentrified in 1990-2000 or 2000-2018
STABLE MODERATE/MIXED INCOME	• Moderate, mixed moderate, mixed high, or high-income tract in 2018
AT RISK OF BECOMING EXCLUSIVE	• Moderate, mixed moderate, mixed high, or high-income tract in 2018 • Housing affordable to middle, high, mixed moderate, and mixed high-income households in 2018 • Marginal change or increase in housing costs
BECOMING EXCLUSIVE	• Moderate, mixed moderate, mixed high, or high-income tract in 2018 • Housing affordable to middle, high, mixed moderate, and mixed high-income households in 2018 • Rapid increase in housing costs • Absolute loss of low-income households, 2000-2018 • Declining low-income in-migration rate, 2012-2018 • Median income higher in 2018 than in 2000
STABLE/ADVANCED EXCLUSIVE	• High-income tract in 2000 and 2018 • Affordable to high or mixed high-income households in 2018 • Marginal change, increase, or rapid increase in housing costs

Figure 2. UDP's nine gentrification levels in San Francisco and their respective criteria (Chapple et al. 2021).

For my continuous analysis, I used UDP's code alongside methodology from Fidino et al. (2024) to select seven metrics of equal weights to create a continuous scale of gentrification in San

Francisco for a more nuanced approach. To weigh each metric equally, I calculated the percentile of each of the tracts' metrics divided by ten, and I then added these individual scores and assigned a continuous score of 0 - 100 to each tract for comparison against bird populations in RStudio. The metrics are as follows:

1. change in median income from 2000 to 2018
2. 2018 median income
3. change in housing or rent prices from 2012 to 2018
4. 2018 housing or rent price
5. change in the number of low-income households from 2000 to 2018
6. change in the proportion of college-educated residents from 2000 to 2018
7. change in the proportion of non-hispanic white residents from 2000 to 2018

Bird species data collection

I obtained data from eBird, a repository of citizen science bird observations, spanning from 2015 to 2019 for the region of San Francisco (GBIF 2024). I included all species observations for my initial analyses and separated them by generalists and non-generalists for my subsequent analyses to understand varying gentrification impacts on the two categories of species. To determine which birds were generalist and non-generalist I used the AVONET dataset to determine which species belonged with which group and classified the eBird observations accordingly (OTN 2022).

Analysis

Gentrification versus observations

I used RStudio (v 2024.04.0+735; R Core Team, 2024) for all statistical analyses and data visualization. To understand how bird observations changed over time as a function of gentrification, I plotted a time series to understand how data uploads to eBird have changed over time from 2015 to 2019 in gentrified and non-gentrified census tracts with local polynomial regression fitting lines-of-best-fit using the *loess* function in the *stats* package, and I calculated a Pearson's correlation coefficient using the *stat_cor* function in the *ggpubr* package. Then, I created boxplots to compare gentrified and non-gentrified tracts' number of eBird observations. To determine if there is a significant difference between the two groups, I used the *leveneTest* function in the *car* package and *shapiro.test* function in the *stats* package to see if assumptions of homogeneity of variance and normal distribution are met for a t-test, and subsequently used the *wilcox.test* function in the *stats* package to perform non-parametric Wilcoxon rank-sum tests. Next, I wanted to see the relationship between the number of eBird observations and the continuous gentrification score, so I created a scatterplot with a line-of-best-fit similar to that of the time series.

Lastly, I created four generalized linear mixed models (GLMMs) to understand which factors associated with urbanization — gentrification and normalized difference vegetation index (NDVI) — are the best predictors of the number of eBird observations recorded in a census tract using the *glmmTMB* function in the *glmmTMB* package. The area of a census tract was used as a log-offset variable to control for neighborhood size. In the four models, the fixed effects are as follows: (1) gentrification; (2) NDVI; (3) gentrification and NDVI; (4) a null model, where gentrification and NDVI were omitted. Then, I used the *AIC* function in the *stats* package to perform an Akaike information criterion (AIC) comparison and the *compare_performance* function in the *performance* package to determine the best-performing model for predicting eBird observations. I used this modeling approach for the continuous metric of gentrification.

Gentrification versus species richness

I next wanted to understand differences in bird species richness based on gentrification. I assigned each bird observation to its corresponding census tract and calculated species richness by adding the number of unique species recorded for each tract.

Similarly to my methods for eBird observation analysis, I plotted a time series to understand how bird species richness has changed over time from 2015 to 2019 in gentrified and non-gentrified census tracts with local polynomial regression fitting lines-of-best-fit developed, and I calculated a Pearson's correlation coefficient. Then, I created boxplots to compare gentrified and non-gentrified tracts' species richness. To determine if there is a significant difference between the two groups, I tested t-test assumptions of homogeneity of variance and a normal distribution, and I subsequently used the *t.test* function in the *stats* package to perform a t-test and performed non-parametric Wilcoxon rank-sum tests. Next, I wanted to see the relationship between species richness and the continuous gentrification score, so I created a scatterplot with a line-of-best-fit similar to that of the time series.

Lastly, I followed the same modeling approach for eBird observations to understand which factors associated with urbanization — gentrification and normalized difference vegetation index (NDVI) — are the best predictors of bird species richness recorded in a census tract (see above). Finally, I plotted and calculated a Pearson's correlation coefficient to see how NDVI correlates with species richness.

Gentrification versus Shannon diversity

To understand differences in bird Shannon diversity based on gentrification, I calculated Shannon diversity, which measures species abundance and evenness, for each census tract using the *diversity* function in the *vegan* package.

Once again, I plotted a time series to understand how bird Shannon diversity has changed over time from 2015 to 2019 in gentrified and non-gentrified census tracts with local polynomial regression fitting lines-of-best-fit developed, and I calculated a Pearson's correlation coefficient. Then, I created boxplots to compare gentrified and non-gentrified tracts' Shannon diversity. To determine if there is a significant difference between the two groups, I tested t-test assumptions of homogeneity of variance and a normal distribution, and I subsequently performed a t-test and non-parametric Wilcoxon rank-sum tests. Next, I wanted to see the relationship between Shannon diversity and the gentrification score, so I created a scatterplot with a line-of-best-fit similar to that of the time series.

Lastly, I followed the same modeling approach as for eBird observations to understand which factors associated with urbanization — gentrification and normalized difference vegetation index (NDVI) — are the best predictors of bird species richness recorded in a census tract. Finally, I plotted and calculated a Pearson's correlation coefficient to see how NDVI correlates with Shannon diversity. I repeated the above steps for the number of eBird observations, species, richness, and Shannon diversity in generalists and non-generalists to understand how gentrification may be differentially impacting these bird types in San Francisco.

RESULTS

Gentrification versus observations

I did detect a significant relationship between gentrification and the number of eBird observations. An AIC comparison of the four generalized linear mixed models showed both gentrification (β = -0.083, P = 0.008) and NDVI (β = -16.052, P = 0.212) as predictors of the number of eBird observations in a census tract (Table 1). Although the global model was the best-performing model, only gentrification had a significant impact (Table 1). A performance comparison of the models corroborated these results.

Table 1. AIC model selection results for the effects of gentrification on the number of eBird observations, total richness, and total diversity. The global model was the best predictor for observations, NDVI was the best predictor for total richness, and gentrification was the best predictor for total diversity.

Response variable	Variables (s)	LL	AIC	ΔAIC
Observations	Gentrification	-986500	1972932	642402
	NDVI	-678000	1355940	25410
	Gentrification + NDVI	**-665300**	**1330530**	**0**
	NULL	-1134000	2268196	937666
Total richness	Gentrification	-861.4	1728.874	60.102
	NDVI	**-831.4**	**1668.772**	**0**
	Gentrification +	-831.3	1670.662	1.89

	NDVI			
	NULL	-861.7	1727.488	58.716
Total diversity	**Gentrification**	**-225.3**	**456.691**	**0**
	NDVI	-233.4	472.881	16.190
	Gentrification + NDVI	-224.4	456.861	0.170
	NULL	-233.9	471.882	15.191

Between 2015 and 2019, there was a slight decrease in the number of eBird observations over time in gentrified tracts (Pearson's correlation, R = -0.018, P = 0.430) and no change in non-gentrified tracts (Pearson's correlation, R = -0.001, P = 0.860), though neither trend was significant (Figure 2A). In gentrified tracts, there was a greater decrease where the numbers of observations converged towards the end of 2019 (Figure 2A). Additionally, gentrified (M = 5089.444, SD = 25791.970) and non-gentrified (M = 3471.684, SD = 25146.050) tracts did not have a significantly different number of observations (Figure 2B, Table 2; Wilcoxon rank-sum test, W = 2248, P = 0.070), while Figure 2C shows a negative correlation between observations and gentrification score (Pearson's correlation, R = -0.120, P = 0.100).

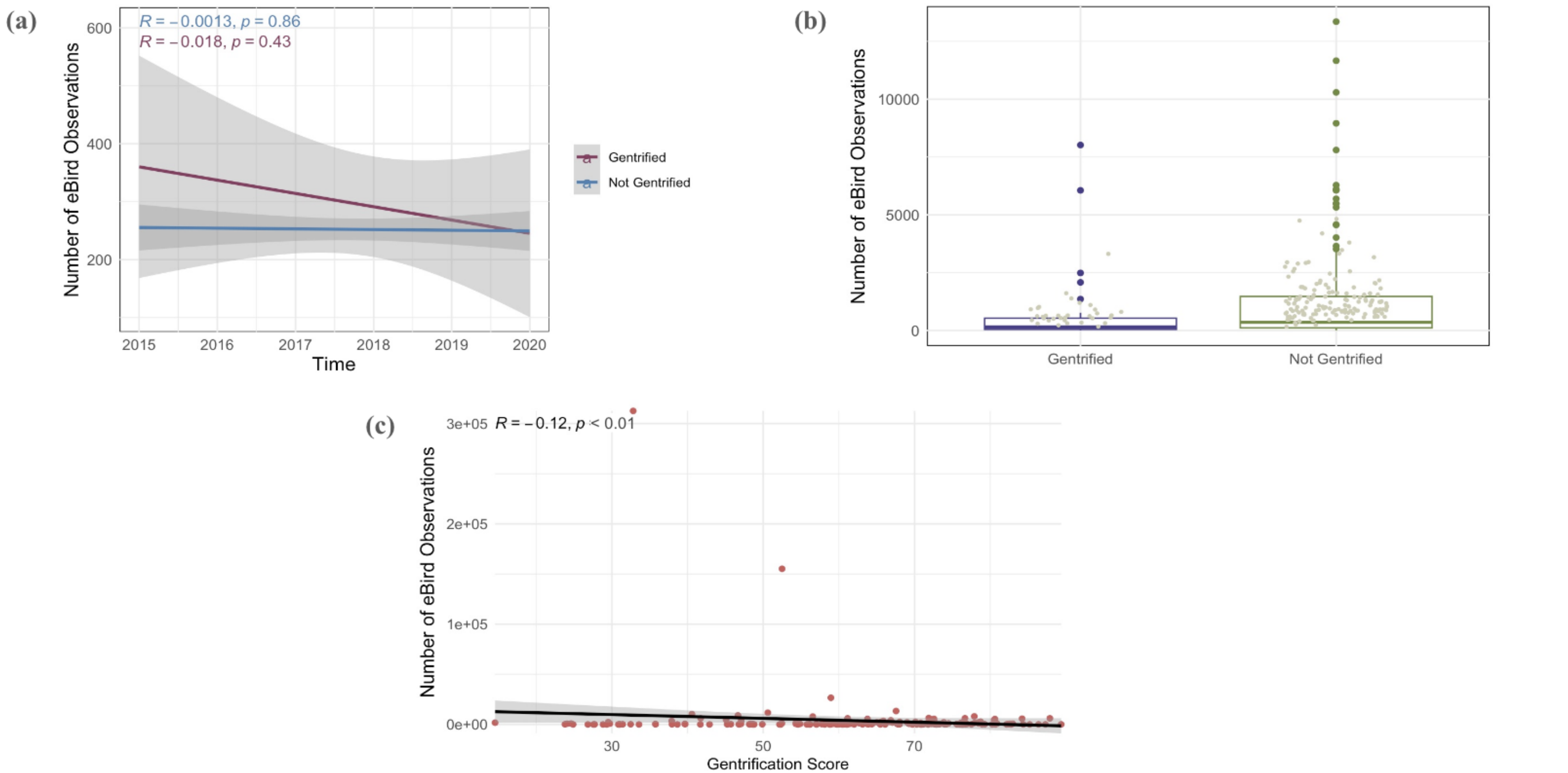

Figure 3. Plots for gentrification versus number of eBird observations. (a) Change in number of eBird observations from 2015 to 2019. The time series is stratified with lines-of-best-fit by gentrified (Pearson's correlation, R = -0.001, P = 0.860) versus not gentrified (Pearson's correlation, R = -0.018, P = 0.430) groups. (b) Number of eBird observations versus gentrification level. The box-and-whisker plots are stratified by gentrified versus not gentrified groups. The points plotted are from a zero-inflated Poisson regression. The two groups are not significantly different (Wilcoxon rank-sum test, W = 2248, P = 0.070). (c) Number of eBird observations versus gentrification score. The scatterplot with a line-of-best-fit shows a negative correlation between the two variables (Pearson's correlation, R = -0.120; GLMM, $P < 0.01$). R is found from a Pearson's correlation test, while the p-value is from the GLMM model.

Table 2. Means and standard deviations for all sub-groups in the study. Results for the number of eBird observations, bird species richness, and bird diversity are stratified by gentrified and non-gentrified. These results are further stratified by niche.

Variable	Census-tract type	Niche	Mean	Standard deviation
Observations	Gentrified	ALL	5089	25792
		Generalist	N/A	N/A
		Non-Generalist	N/A	N/A
	Non-gentrified	ALL	3472	25146
		Generalist	N/A	N/A
		Non-generalist	N/A	N/A
Richness	Gentrified	ALL	28.556	27.403
		Generalist	5.485	4.810
		Non-Generalist	11.697	8.538
	Non-gentrified	ALL	38.090	30.940
		Generalist	7.326	4.615
		Non-generalist	13.028	6.933
Diversity	Gentrified	ALL	2.031	0.824
		Generalist	0.888	0.670
		Non-Generalist	1.409	0.599
	Non-gentrified	ALL	2.336	0.899
		Generalist	1.243	0.582
		Non-Generalist	1.665	0.502

Gentrification versus species richness

I did not detect that bird species richness was significantly impacted by gentrification. An AIC comparison of the four generalized linear mixed model results showed NDVI (β = 447.015, P < 0.001) as a better predictor than gentrification of bird species richness in a census tract (Table 1). A performance comparison of the models corroborated these results. Consequently, when stratified by gentrification, the relationship between NDVI and species richness was similar in both strata (Figure 3D).

Between 2015 and 2019, there was no correlation in species richness over time in gentrified tracts (Pearson's correlation, R = 0.038, P = 0.09) and no correlation in non-gentrified tracts (Figure 3A; Pearson's correlation, R = -0.0086, P = 0.23), with neither trend being significant. I found that gentrified (M = 28.556, SD = 27.403) and non-gentrified (M = 38.090, SD = 30.940) tracts did have significantly different species richness (Wilcoxon rank-sum test, W = 2177.5, P = 0.041), with gentrified tracts having lower species richness (Figure 3B, Table 2). More precisely, Figure 3C shows a slight increase in species richness as gentrification increases, but at very high gentrification scores, there is a dip in species richness (Pearson's correlation, R = 0.054, P = 0.47).

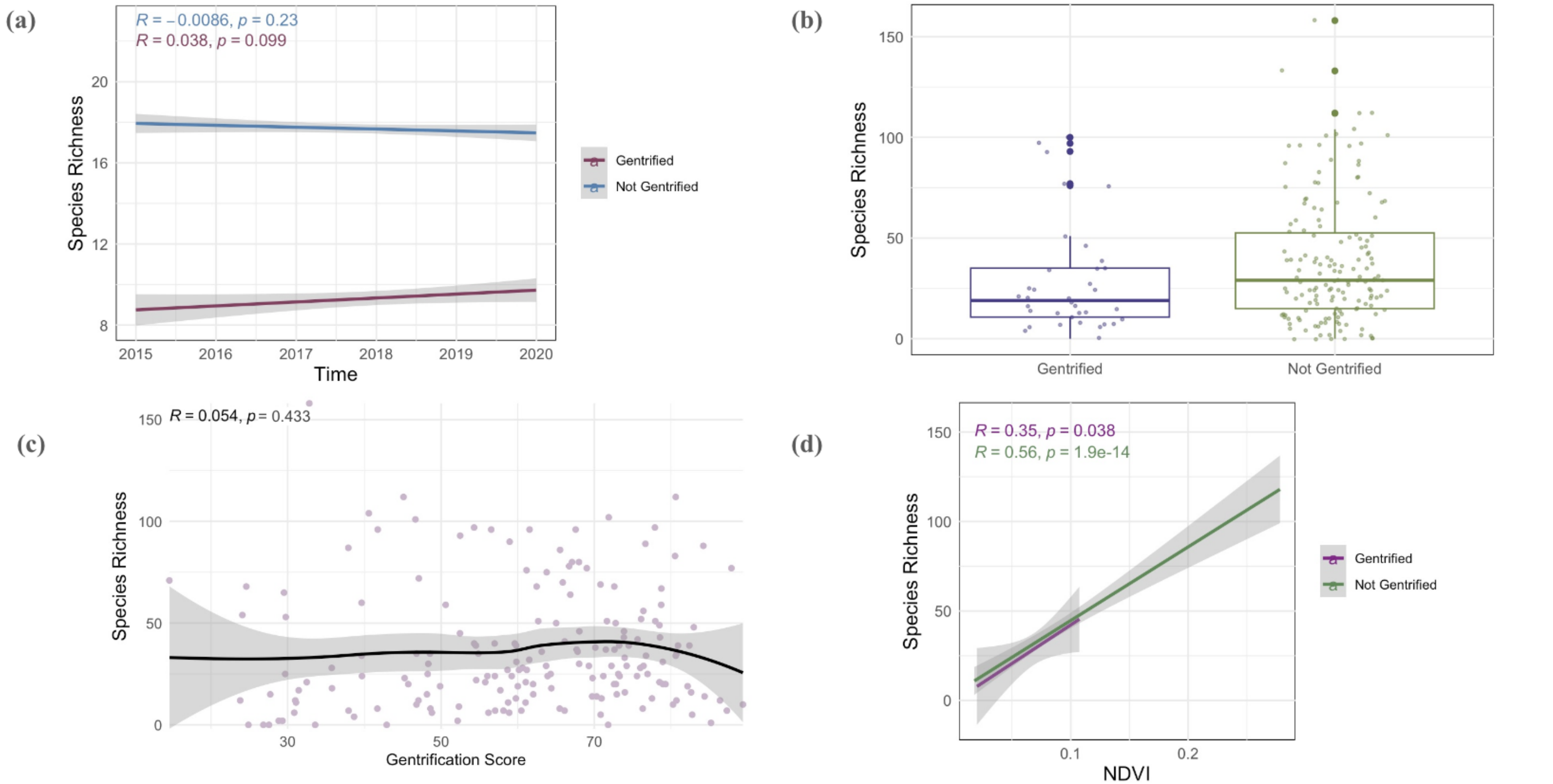

Figure 4. Plots for gentrification versus bird species richness. (a) Change in species richness from 2015 to 2019. The time series is stratified with lines-of-best-fit by gentrified (Pearson's correlation, R = -0.009, P = 0.230) versus not gentrified (Pearson's correlation, R = -0.038, P = 0.099) groups. (b) Species richness versus gentrification level. The box-and-whisker plots are stratified by gentrified versus not gentrified groups. The two groups are significantly different (Wilcoxon rank-sum test, W = 2177.5, $P < 0.05$). (c) Species richness versus gentrification score. The scatterplot with a curve-of-best-fit shows no correlation between the two variables (Pearson's correlation, R = 0.054; GLMM, P = 0.433). (d) Bird species richness versus NDVI. Lines-of-best-fit are stratified by gentrified (Pearson's correlation, R = 0.350, P = 0.038) versus not gentrified (Pearson's correlation, R = 0.560, $P < 0.001$).

Gentrification versus Shannon diversity

Bird diversity was significantly impacted by gentrification. An AIC comparison of the four generalized linear mixed model results showed gentrification ($\beta = 0.016$, $P < 0.001$) as a better predictor than NDVI of bird species richness in a census tract (Table 1). A performance comparison of the models corroborated these results. Consequently, when stratified by gentrification, the relationships between NDVI and Shannon diversity had different slopes in the two groups (Figure 4D).

Between 2015 and 2019, there was a significant decrease in diversity over time in gentrified tracts (Pearson's correlation, $R = -0.025$, $P < 0.001$), but not in non-gentrified tracts (Figure 4A; Pearson's correlation, $R = -0.023$, $P = 0.320$). Additionally, gentrified ($M = 2.031$, $SD = 0.824$) and non-gentrified ($M = 2.336$, $SD = 0.899$) tracts significantly differed in diversity (Wilcoxon rank-sum test, $W = 2177.5$, $P = 0.041$), where more gentrified tracts had lower Shannon diversity (Figure 4B, Table 2). More precisely, Figure 4C shows a slight increase in Shannon diversity as gentrification increases, but at very high gentrification scores, there is a dip in Shannon diversity (Pearson's correlation, $R = 0.054$, $P = 0.47$).

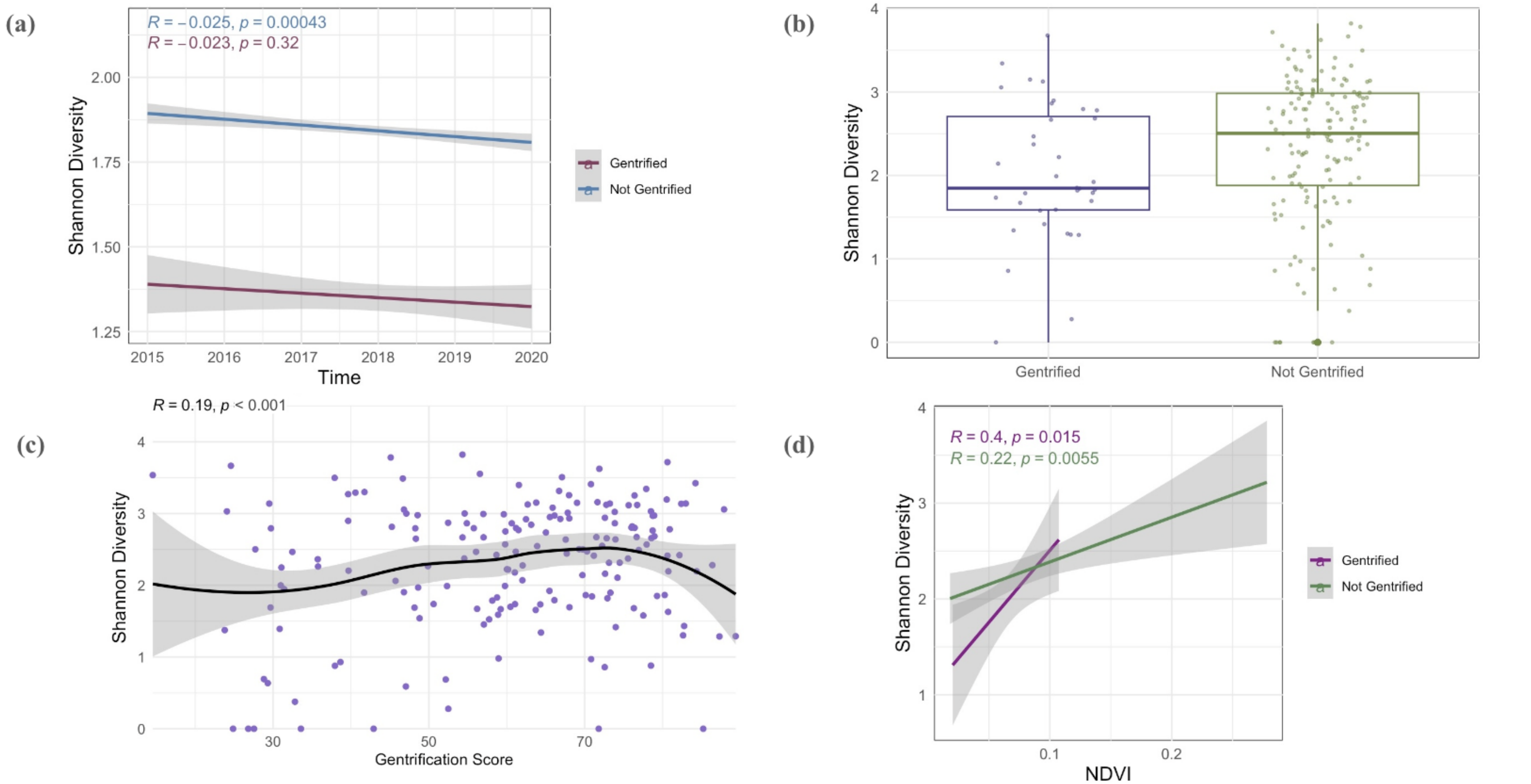

Figure 5. Plots for gentrification versus bird species diversity. (a) Change in bird Shannon diversity from 2015 to 2019. The time series is stratified with lines-of-best-fit by gentrified (Pearson's correlation, R = -0.025, P < 0.001) versus not gentrified (Pearson's correlation, R = -0.023, P = 0.320) groups. (b) Bird Shannon diversity versus gentrification level. The box-and-whisker plots are stratified by gentrified versus not gentrified groups. The two groups are significantly different (Wilcoxon rank-sum test, W = 2088.5, P < 0.05). (c) Bird Shannon diversity versus gentrification score. The scatterplot with a curve-of-best-fit shows a positive correlation between the two variables (Pearson's correlation, R = 0.190; GLMM, P < 0.001). (d) Bird Shannon diversity versus NDVI. Lines-of-best-fit are stratified by gentrified (Pearson's correlation, R = 0.400, P < 0.05) versus not gentrified (Pearson's correlation, R = 0.220, P < 0.01).

Gentrification's impacts on generalists versus non-generalists

Species richness

Bird species richness was significantly impacted by gentrification. An AIC comparison of the four generalized linear mixed model results showed NDVI as a better predictor than gentrification of both generalist ($\beta = 51.538$, $P < 0.001$) and non-generalist ($\beta = 0.016$, $P < 0.001$) bird species richness in a census tract (Table 3). A performance comparison of the models corroborated these results.

Table 3. AIC model selection results stratified by niche for the effects of gentrification on the number of eBird observations, total richness, and total diversity. NDVI was the best predictor for generalist and non-generalist richness. Gentrification was the best predictor of generalist diversity, but the global model of gentrification and NDVI was the best predictor of non-generalist diversity.

Response variable	Variables(s)	LL	AIC	ΔAIC
Generalist richness	Gentrification	-482.5	971.050	33.713
	NDVI	**-465.7**	**937.337**	**0**
	Gentrification + NDVI	-465.7	939.304	1.967
	NULL	-482.7	969.315	31.978
Non-generalist richness	Gentrification	-556.0	1118.078	7.252
	NDVI	**-552.4**	**1110.826**	**0**
	Gentrification + NDVI	-552.4	1112.780	1.954
	NULL	-556.1	1116.222	5.396
Generalist diversity	**Gentrification**	**-161.7**	**329.308**	**0**
	NDVI	-166.6	339.246	9.938

	Gentrification + NDVI	-161.2	330.405	1.098
	NULL	-166.9	337.761	8.453
Non-generalist diversity	Gentrification	-165.5	336.993	7.843
	NDVI	-163.4	332.878	3.727
	Gentrification + NDVI	**-160.6**	**329.151**	**0**
	NULL	-167.8	339.567	10.417

There is a general difference between generalist and non-generalist species richness in San Francisco. Generalists and non-generalists have significantly different species richness in both gentrified (Wilcoxon rank-sum test, $W = 271$, $P < 0.001$) and non-gentrified (Wilcoxon rank-sum test, $W = 5211$, $P < 0.001$) census tracts (Figure 5A). More specifically, non-generalists have generally higher species richness, and there are dips in species richness in both generalists and non-generalists at very high levels of gentrification (Figure 5B). Additionally, generalists seem to be more impacted than non-generalists by gentrification with respect to species richness. Generalist species richness is significantly lower in gentrified tracts ($M = 5.485$, $SD = 4.810$) than in non-gentrified tracts ($M = 7.326$, $SD = 4.615$; Wilcoxon rank-sum test, $W = 1759$, $P < 0.01$), while non-generalists do not significantly differ in species richness in gentrified ($M = 11.697$, $SD = 8.538$) and non-gentrified tracts ($M = 13.028$, $SD = 6.933$; t-test, $t(42) = -0.835$, $P = 0.409$). This indicates that the presence or absence of gentrification influences the species richness differently for generalist and non-generalist species, where the latter is less impacted (Figure 5B, Table 2).

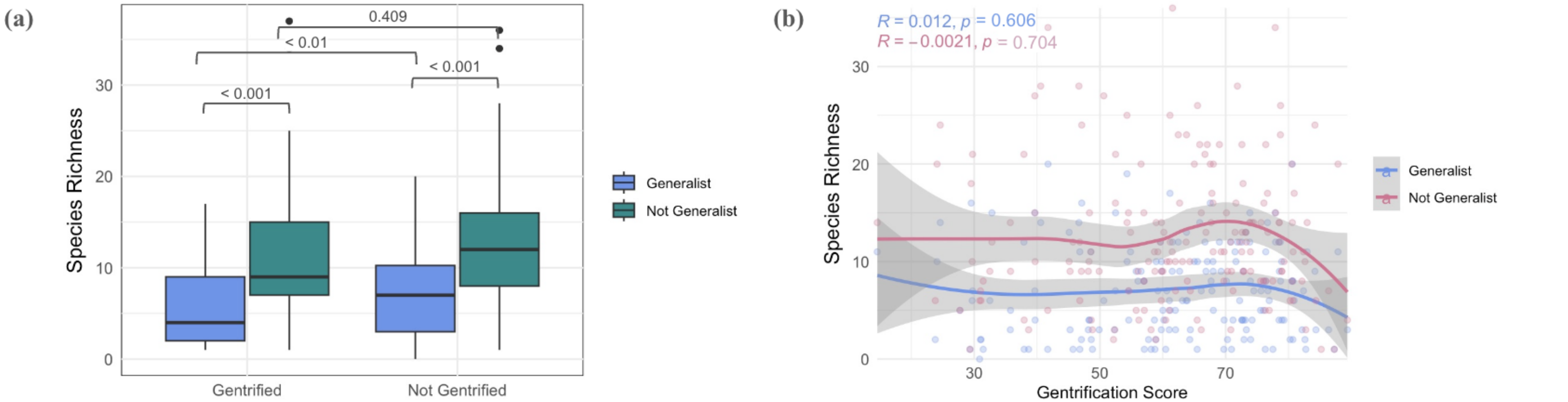

Figure 6. Plots for gentrification versus bird species richness in generalists and non-generalists. (a) Boxplots of gentrified and non-gentrified tracts' species richness stratified by generalist versus non-generalist. While generalist and non-generalist species richness seems to generally differ across strata, generalist species richness is significantly impacted by gentrification, while non-generalist species richness is not. (b) Curves-of-best-fit for bird species richness versus gentrification score stratified by bird niche. Neither generalists (Pearson's correlation, R = 0.012; GLMM, P = 0.606) nor non-generalists (Pearson's correlation, R = -0.002, GLMM, P = 0.704) saw a correlation between gentrification and richness.

Shannon diversity

Bird species richness was significantly impacted by gentrification. An AIC comparison of the four generalized linear mixed model results showed NDVI as a better predictor than gentrification of both generalist ($\beta = 51.538$, $P < 0.001$) and non-generalist ($\beta = 0.016$, $P < 0.001$) bird species richness in a census tract (Table 3). A performance comparison of the models corroborated these results.

There is a general difference between generalist and non-generalist Shannon diversity in San Francisco. Generalists and non-generalists have significantly different species diversity in both gentrified (Wilcoxon rank-sum test, $W = 315$, $P < 0.01$) and non-gentrified (Wilcoxon rank-sum test, $W = 6170$, $P < 0.001$) census tracts (Figure 6A). More specifically, non-generalists have generally higher diversity, and there are dips in diversity in both generalists and non-generalists at very high levels of gentrification (Figure 6B). Additionally, generalists seem to be more impacted than non-generalists by gentrification with respect to species diversity. Both generalists (gentrified tracts: $M = 0.888$, $SD = 0.670$, non-gentrified tracts: $M = 1.243$, $SD = 0.582$; Wilcoxon rank-sum test, $W = 1647.5$, $P = 0.006057$) and non-generalists (gentrified tracts: $M = 1.409$, $SD = 0.599$, non-gentrified tracts: $M = 1.665$, $SD = 0.502$; t-test, $t(42) = -2.2739$, $P = 0.02804$) are significantly impacted by gentrification in terms of diversity, indicating that the presence or absence of gentrification influences diversity in both groups of species (Figure 6B, Table 2).

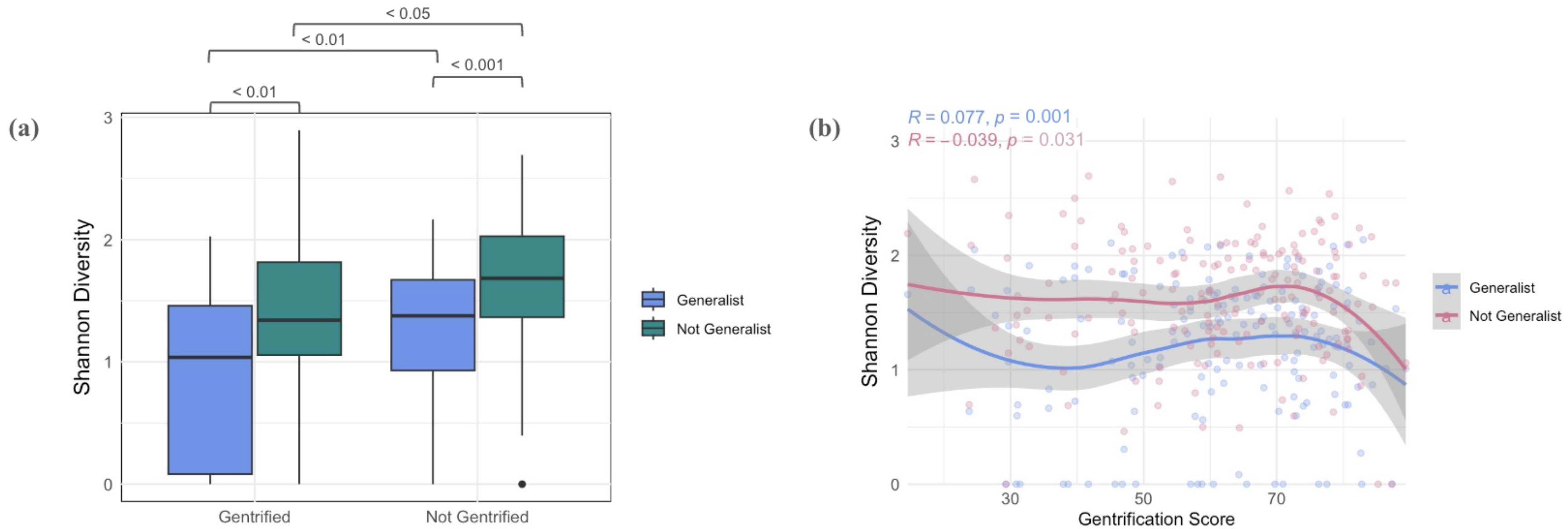

Figure 7. Plots for gentrification versus bird species diversity in generalists and non-generalists. (a) Boxplots of gentrified and non-gentrified tracts' Shannon diversity stratified by generalist versus non-generalist. Generalist and non-generalist Shannon diversity seem to generally differ across strata, and both groups' diversity is significantly impacted by gentrification. (b) Curves-of-best-fit for bird species diversity versus gentrification score stratified by bird niche. Neither generalists (Pearson's correlation, R = 0.077; GLMM, P = 0.001) nor non-generalists (Pearson's correlation, R = -0.039; GLMM, P = 0.031) saw a correlation between gentrification and diversity.

DISCUSSION

The results of the study indicate that while there is not a significant relationship between gentrification and the number of eBird observations in San Francisco, there are observable trends in bird species richness and Shannon diversity. Bird species richness does not appear to be significantly impacted by gentrification over time, as shown with mammalian species richness in the Bay Area in response to gentrification (Fidino et al 2024), though slight fluctuations are observed. However, there is a noticeable difference in species richness between gentrified and non-gentrified tracts, with more gentrified areas generally exhibiting lower species richness. On the other hand, Shannon diversity shows a significant decrease over time in both gentrified and non-gentrified tracts, with gentrified tracts typically having lower Shannon diversity. Interestingly, the analysis also reveals differences in the impact of gentrification on generalist and non-generalist species, with generalists generally experiencing more significant declines in species richness and Shannon diversity compared to non-generalists. The findings of this study shed light on the complex relationship between gentrification and bird biodiversity in urban environments, particularly in San Francisco. The results reveal nuanced impacts of gentrification on bird observations, species richness, and Shannon diversity, highlighting the importance of considering socio-economic dynamics in urban wildlife conservation efforts.

Gentrification versus observations

The lack of a significant relationship between gentrification and the number of eBird observations, contrary to my hypothesis, may be influenced by several contradicting factors. Firstly, it's essential to consider the dynamics of eBird participation itself. While eBird provides valuable citizen science data, participation rates can vary spatially and temporally due to factors such as observer distribution, accessibility of birding sites, and individual observer behavior (Sullivan et al. 2009, Johnston et al. 2020; Carlen et al 2024). In gentrified areas, where demographic shifts may occur rapidly, changes in resident populations could affect the availability and interest of individuals in contributing to eBird. While more affluent individuals may indeed be more inclined to participate in citizen science due to factors such as higher education levels and access to technology (Dickinson et al. 2010, Crall et al. 2011), the distribution of these observers within census tracts may not necessarily align with the spatial patterns of gentrification. Research has shown that citizen science participation tends to be higher in urban areas with greater socioeconomic advantage (Trouille et al. 2017). However, affluent residents may also have more opportunities and resources to travel outside their immediate neighborhoods in search of bird observation sites, potentially leading to a lower density of observations within their own tracts (Crall et al. 2011). This behavior could result in a skewed representation of bird observations within gentrified versus non-gentrified tracts, impacting the observed relationship between gentrification and eBird observations. While gentrification may not directly influence eBird observations in some cases, its interaction with other socioeconomic and environmental variables has the potential to influence citizen science outcomes, though more research is needed

Gentrification versus species richness

Gentrification often involves extensive redevelopment and urban renewal projects, leading to changes in land use patterns and built environments (Anguelovski et al. 2019). In gentrified tracts, these transformations could result in the loss or degradation of natural habitats, such as green spaces and street trees, which are essential for supporting diverse bird communities (Colding et al. 2009). The decline in species richness in gentrified tracts may thus reflect habitat loss or fragmentation caused by gentrification-related urban development (Aronson et al. 2014). The significant difference in species richness between gentrified and non-gentrified tracts further reflects the influence of socioeconomic and environmental factors on urban biodiversity. Gentrified areas, characterized by rising property values and demographic shifts, may experience heightened development pressures and land use changes that disproportionately impact remnant natural habitats in SF's densely built environment (Chapple and Zuk 2015). Conversely, non-gentrified areas may retain more intact or undeveloped habitats due to reduced redevelopment, potentially supporting higher species richness despite other urbanization pressures and disturbances. Additionally, the observed association between vegetation and bird species richness suggests that vegetation cover and quality play a crucial role in shaping bird biodiversity patterns in urban environments. NDVI, which quantifies the density and health of vegetation based on satellite imagery, can serve as a proxy for habitat suitability and resource availability for birds (Pettorelli et al. 2005). Higher NDVI values indicate more favorable habitat conditions, including greater vegetation density and diversity, which can support a greater variety of bird species (Goddard et al. 2010). The stronger predictive power of NDVI compared to gentrification in explaining bird species richness highlights the importance of green infrastructure and habitat quality in biodiversity conservation efforts (Ernstson et al. 2008). While gentrification may contribute to habitat loss or degradation in urban landscapes, other urbanization pressures and environmental variables, such as vegetation cover and quality, also play significant roles in shaping bird communities. Further interdisciplinary research is needed to disentangle these complex relationships and inform sustainable urban planning strategies that promote both human well-being and ecological resilience in rapidly changing urban environments.

Gentrification versus Shannon diversity

The slight decreases in Shannon diversity over time in both gentrified and non-gentrified tracts suggest that broader urbanization processes may exert significant pressures on bird communities, leading to reduced diversity across the landscape. The reduced diversity may be due to habitat loss and the homogenization of landscapes associated with general trends of urbanization seen throughout the city (Aronson et al. 2014). The observed differences in Shannon diversity between gentrified and non-gentrified tracts highlight the differential impacts of socioeconomic processes on urban biodiversity. Gentrified tracts may experience intensified urbanization pressures and habitat loss, leading to disproportionately lower Shannon diversity compared to non-gentrified areas (Chapple and Zuk 2015). Conversely, non-gentrified tracts may retain more intact or less disturbed habitats, thereby supporting higher diversity despite other urbanization pressures. The slight increase in Shannon diversity with increasing levels of gentrification, followed by a dip at very high gentrification scores, suggests nonlinear relationships between socioeconomic factors and biodiversity patterns. This pattern may reflect the initial investments in green infrastructure and urban greening efforts associated with gentrification, which could temporarily enhance habitat quality and diversity in newly developed or revitalized areas (Anguelovski et al. 2019). However, as gentrification intensifies and urbanization pressures mount, these gains may be outweighed by habitat loss and degradation, resulting in declines in Shannon diversity. The stronger predictive power of gentrification compared to NDVI in explaining Shannon diversity emphasizes the complex socioeconomic drivers of biodiversity patterns in urban environments. In summary, while gentrification may initially enhance habitat quality and diversity, its long-term impacts on biodiversity may be contingent on the scale, intensity, and duration of urbanization processes.

Gentrification's impacts on generalists versus non-generalists

The significant differences in species richness between generalist species in gentrified and non-gentrified tracts, coupled with the non-significant differences in species richness among non-generalist species in these areas, suggest that generalists may be more susceptible to the disturbances associated with gentrification (Lerman and Warren 2011). Meanwhile, the significant impacts of gentrification on Shannon diversity in both generalist and non-generalist species indicate that the complex social processes of gentrification can influence community structure and composition irrespective of species' ecological traits (McKinney 2006). The observed differences in species richness and Shannon diversity between generalist and non-generalist bird species in San Francisco are further elucidated by considering the ecological preferences and habitat associations of these avian groups. Generalist species, such as the black-billed gull (*Larus bulleri*), which are adapted to living in urban environments, tend to inhabit areas characterized by high levels of human activity and urbanization, possibly making them more likely to occur in neighborhoods susceptible to gentrification and displacement (Blair 2001). In contrast, non-generalist species, such as the gray-bellied hawk (*Accipiter poliogaster*), often exhibit habitat preferences for areas with greater habitat complexity and vegetation cover, which may buffer them from the direct impacts of urban redevelopment and gentrification pressures (Jokimäki et al. 2018). As gentrification intensifies in urban neighborhoods, generalist species that rely on human-modified environments for resources and nesting sites may experience displacement, leading to declines in species richness and diversity (Lerman and Warren 2011; Hubbard and Brooks 2021). Meanwhile, non-generalist species occupying less urbanized areas may be less affected by gentrification-related habitat transformations, resulting in relatively stable or higher levels of species richness and Shannon diversity in these habitats (McKinney 2006). The differential responses of generalist and non-generalist bird species to gentrification point to the importance of considering species-specific ecological traits and habitat associations in urban biodiversity conservation and management efforts. The observed dips in species richness and Shannon diversity in both generalist and non-generalist species at very high levels of gentrification suggest that extreme urbanization processes may have different negative impacts on bird biodiversity depending on their ecological niches. As gentrification intensifies and urban landscapes undergo extensive redevelopment and infrastructural changes, habitat quality and ecological connectivity may deteriorate, leading to declines in species richness and diversity even among non-generalist species adapted to specific non-urban habitats (Grimm et al. 2008, Anguelovski et al. 2019). Ecological niches should therefore be considered when doing such studies due to their differential interactions with and impacts caused by urban landscape factors.

Conclusions

Conservation efforts should focus on preserving non-generalist bird populations in gentrified neighborhoods in San Francisco, as well as all bird populations in highly gentrified tracts. These birds are being disproportionately impacted by gentrification, and are essential for sustaining pest control, pollination, and biodiversity of San Francisco's ecosystem. Current bird conservation efforts do not take gentrification into account as a major effect of urbanization due to a lack of studies done on this topic, which is not suitable for a city such as San Francisco with high levels of gentrification. Taking gentrification into consideration in the field of conservation is essential to understanding its role in exacerbating urbanization’s impacts on San Francisco's birds. Additionally, construction projects and land-use changes should only be approved after accounting for biodiversity impacts on urban wildlife.

Some of the limitations of this study include the eBird dataset used to identify bird populations in various San Francisco neighborhoods. Since the data was collected through citizen science, there could be bias with reporting based on gentrification level (Carlen et al 2024); perhaps, neighborhoods with higher income levels would include people with more interest in bird watching and inputting data to eBird, leading to a skewed set of data (Eubanks Jr et al. 2009, Rosenblatt et al. 2022). Future research could develop and analyze a gentrification score for more recent years in San Francisco, as well as expand to other cities that have highly prevalent or emerging gentrification trends, such as Seattle or New Orleans. Since San Francisco is a densely populated coastal city, the results of this study may not be as generalizable to other cities or countries. Complementary studies should be done by collecting standardized data in the field from all the census tracts in San Francisco (e.g., point counts), rather than using citizen science to have data that better represents the landscape (Perkins 2020). Since birds are migratory and able to relocate faster than other animals, future studies should seek to understand gentrification's impacts on species with less mobility or smaller home ranges, such as mammals or plants.

In addition to the human and social implications of gentrification, cities should consider wildlife implications when approving land use changes and housing projects. If these trends of increasing gentrification and decreasing biodiversity continue, San Francisco ecosystems and human populations will be negatively impacted due to birds' vital role in pollination and pest control. Zoning laws should reflect the interests of birds and other wildlife, not just humans and corporations, particularly in regions of the city where endangered wildlife reside. Additionally, these considerations can expand to other important species in the future, such as pollinating insects.

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