Urban greenspaces benefit both human utility and biodiversity

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Abstract

Urban greenspaces are essential for both human well-being and biodiversity, with their importance continually growing in the face of increasing urbanization. The dual role of these spaces raises questions about how their planning and management can best serve the diverse needs of both people and biodiversity. Our goal was to quantify the synergies and tradeoffs between human utility and biodiversity benefits in urban greenspaces. Through a detailed inventory, we mapped 639 urban greenspaces throughout Broward County, Florida — one of the most populous counties in the United States. We identified and categorized various physical attributes contributing to human utility, including playgrounds, athletic facilities, and picnic areas. Concurrently, we assessed biodiversity by estimating species richness within an urban greenspace. We found little relationship between overall human utility and biodiversity. More specifically, we found a positive correlation between human utility attributes such as playgrounds, bodies of water, and nature preserves with biodiversity, indicating potential synergies rather than tradeoffs. This alignment between human utility and biodiversity benefits suggests that urban parks can effectively serve multiple values without necessarily sacrificing one for the other. Both human utility and biodiversity correlate with greenspace size, emphasizing the significance of larger greenspaces in accommodating diverse values. Our results offer insights for optimizing planning and management of urban greenspaces to simultaneously benefit local communities and ecosystems, highlighting the potential for harmonizing human and biodiversity needs to foster sustainable cities.

Keywords: urban greenspace; biodiversity; human use; human-natural systems; urbanization; recreation

Introduction

By 2050, the urban population is projected to increase from 55% to 68% (United Nations, 2018). This rapid growth in urbanization — a process characterized by a significant shift of a population from rural to urban areas and associated land use changes (Trivedi et al., 2008) — has led to a growing importance of quantifying the impact of urbanization on both human and environmental systems. One component of cities that is critical to both humans and the environment are urban greenspaces. Urban greenspaces (i.e., broadly defined as open-space areas within cities for parks and recreational purposes) play a pivotal role in urban environments due to their role in providing essential habitats to various forms of life and sustaining vital urban ecosystem services (Tzoulas et al., 2007; Li et al. 2019). The range of ecosystem services urban greenspaces can provide is substantial, encompassing air and water purification, climate regulation, carbon sequestration, landscape aesthetics and recreational benefits, and the creation of habitats and resources for wildlife (United Nations, 2005; Mexia et al., 2018). Moreover, urban greenspaces contribute significant amenity values, derived from an array of public facilities, aiming to enhance human utility and therefore human well-being.

Ecological planning — urban design that is conscious of biodiversity and nature (Steiner & Brooks, 1981) — provides broad frameworks and tactics to consider the impact on biodiversity when designing urban environments. Strategies developed in the context of urban greenspaces include increasing tree canopy with native species (Shackleton et al., 2015), expanding greenspaces near one another to increase connectivity (Beninde et al., 2015), and restoring habitats where diverse species can thrive (Blaustein, 2013). Human preference for the planning of greenspaces has shown to be driven by their ability to maximize experiential and health benefits (Veen et al., 2020). Preferences for attributes in greenspaces include experiencing and interacting with nature (Lafrenz, 2022), athletic and sport facilities (Mahmoudi Farahani & Maller, 2018), and play zones (Almanza et al., 2012). However, such urban greenspace planning strategies tend to favor human health benefits with a focus on maximizing the user experience (Clayton, 2007). As a result, common greenspace management techniques are not always strategically and explicitly aimed at enhancing biodiversity. Standard management procedures, such as turf grass lawns, pesticide and herbicide usage, and the introduction of non-native plant species, could endanger urban biodiversity (Aronson et al., 2017).

Understanding how urban greenspaces impact both biodiversity and human utility across different greenspaces is thus a critical question that remains poorly understood. Biodiversity benefits and human utility represent the functions of urban greenspace that could potentially lie at opposite end of the social-ecological spectrum. The Millennium Ecosystem Assessment distinguishes cultural ecosystem services as the “insubstantial benefits” derived from nature (2005). These benefits constitute the convergence of the human-nature dynamic and have the prospect to shape the presence and diversity of nature in an urban environment (Mexia et al., 2018). The design and planning of urban greenspaces differ based on human preferences for how users interact with, and perceive, a greenspace (Mahmoudi Farahani & Maller, 2018). In some instances, a greenspace can be designed with ‘biodiversity benefits’ in mind, for example, a greenspace can be created and designed to duplicate a natural system (e.g., a nature preserve or urban restoration project). In contrast, an urban greenspace can be designed with ‘human benefits’ in mind, and organized primarily to serve human activities (e.g., athletic facilities, playgrounds, walking paths), driven primarily by public health and community engagement benefits (Lafrenz, 2022; Veen et al., 2020). Such focus on the planning of urban greenspaces for societal benefits lacks in considering how these preferences may influence biodiversity, leading to potential tradeoffs, with potentially little opportunity to achieve synergies of a greenspace for benefiting both human utility and biodiversity. For example, light installations, installed for safety purposes after dark, can benefit safety while also leading to light pollution, negatively impacting nocturnal insects (Eisenbeis et al., 2009). Or, frequent mowing, to meet human aesthetic preferences can have negative impacts on native pollinator diversity (Proske et al., 2022). Acknowledging the dual significance of both ecological and human services highlights the need for a better understanding of the dynamic between human and biodiversity utility in urban greenspaces.

Data to produce a comprehensive understanding of biodiversity and human utility among urban greenspaces are scarce, and traditional fieldwork-intensive methods can be difficult to scale up, posing a challenge to an empirical understanding of the human-biodiversity dynamic in urban greenspaces. Leveraging "big data" platforms, such as iNaturalist, can expedite the collection of ecological data, providing biodiversity data and offering a scalable solution for understanding biodiversity patterns on a broader scale (Callaghan et al., 2021). Additionally, incorporating the physical attributes of a greenspace, remains critical in providing an understanding of how greenspace attributes can influence biodiversity. Our overall objective in this study was to assess human utility (defined as the sum of eight identified physical attributes), and its relationship with biodiversity, within and among urban greenspaces. Specifically, we first quantified and summarized the distribution of human utility among urban greenspaces. We then assessed the relationship between human utility and biodiversity across a range of distinct urban greenspaces and how these correlated with greenspace size. Lastly, we quantified the relationship between biodiversity and specific physical attributes.

Methods

Study area

Our research was conducted throughout Broward County, Florida, United States. Broward County is Florida's second most populated county and ranked among the top 20 largest counties in the U.S. with roughly 1.9 million residents (U.S. Census Bureau, 2021). The majority of Broward County's expanse is the Everglades Wildlife Management Area that extends to the western border, but with a sharp demarcation that delineates the urban boundary within the county (Figure 1). The county encompasses a total area of 1,323 square miles, with 8.5% of the total area consisting of water. Broward county contains 31 municipalities, with urbanized areas occupying 427.8 square miles of land (U.S. Census Bureau, 2021). The Broward County Parks and Recreation division consists of nearly 6,500 acres of land (Broward.org, 2021). Our selection of Broward County was based on the following reasons: (1) its representation of highly urbanized landscapes, part of one of the largest conurbations in the world; (2) where urban greenspaces are much needed but also face threats from ongoing development; and (3) it represents a subtropical and tropical urban system that remain less understood in the literature but has the potential to harbor substantial levels of urban biodiversity.

Defining and delineating urban greenspaces

In this study, our focus was on defining "urban greenspace" predominantly in the context of urban parks and similar green areas within urbanized regions. Urban greenspace refers to green zones predominantly surrounded by urban development, distinct from contiguous natural vegetation, and generally accessible to the public (Taylor and Hochuli, 2017). These spaces exhibit qualitative disparities from adjoining green areas, emphasizing their unique character within an urban landscape. We adapted the definition by Callaghan et. al (2020) in that urban greenspace data in our study meet the criteria of specific areas within Broward County municipalities that are 'managed and designated' as parks or recreational spaces accessible to the community. A key guiding principle in our definition was that a given urban greenspace had a high likelihood of being a contingent management unit, therefore neglecting vacant lots and other similar types of green areas that are less likely to have management interventions.

Based on the above definition, we stratified our delineation of urban greenspaces throughout Broward County by municipality. Broward County consists of 31 municipalities, however, two of them (Village of Lazy Lake and Village of Sea Ranch Lakes) did not contain any greenspaces based on the definition we are using in this study. To map urban greenspaces, each municipality's official Parks and Recreation website was reviewed to compile a list of urban parks and greenspaces. OpenStreet maps and Google Maps were used to create, verify, and delineate the boundaries of each identified greenspaces, individually in GEOJSON format. OpenStreet maps was utilized for their open source, user contributed, up-to-date geographic information, which allowed for precise identification and mapping of greenspaces, and was accessed through geojson.io. Additionally, Broward County managed parks were mapped separately as its own municipality, rather than incorporating them into their respective municipality based on location. Exclusions were made for types of parks that did not qualify as a greenspace for the purpose of this study, such as marinas or small beach areas, standalone indoor recreation centers, and greenways (i.e., long contiguous strips of vegetation). We also excluded cemeteries and golf courses due to their infrequency, specificity, and lack of range in human utility characteristics. In total, we mapped 639 urban greenspaces which all were used in our final analyses (Figure 1).

Quantifying human utility

The characteristics of greenspaces used in this analysis were adapted from prior studies that investigate the human perception of value in a greenspace that groups greenspace usage into four broad categories: utilitarian, recreation, sport, and play (Jasmani et al., 2017). Ives et al. (2017) created a final typology of values including nature, activity/physical exercise, and social interaction. Building upon these conceptual frameworks, we generated and defined a list of eight distinct physical attributes that represent common forms of human utility (see Table 1). These attributes were chosen to balance ease of annotation and generalizability to be relatively employable throughout all urban greenspaces, following some exploratory analyses of individually searching each urban greenspace for different types of physical attributes. For example, while some urban greenspaces have additional types of characteristics that can serve human utility (e.g., disc golf course), these were excluded because they do not broadly represent multiple human utilities of urban greenspaces based on our literature review and were often uncommon, only appearing in a handful of urban greenspaces during our preliminary scoping analyses. We determined the presence or absence of each type of physical human attribute per individual greenspace (i.e., binary annotation). To assign the presence or absence of each type, we used a combination of aerial imagery, visitor generated content from Google Reviews, and the municipality's parks and recreation website as sources to gather the data. Table 1 provides a detailed overview of each characteristic and their corresponding definition. After we annotated each urban greenspace with the physical attributes, we calculated a human utility index. To do this, we counted the number of physical attributes for each greenspace and scaled the count between 0 to 1 using the "rescale" function in the R package Scales (Wickham and Seidel 2022). This provided a relative index of human utility to compare among greenspaces and to biodiversity utility (see next section).

Quantifying biodiversity utility

To quantify the use of greenspaces for biodiversity benefits, we calculated a standardized species richness value for each greenspace that served as a proxy for biodiversity utility. To obtain species richness values, we used citizen science data from the platform iNaturalist (www.inaturalist.org), an online social network for sharing observations of organisms and obtaining crowdsourced species identifications (Callaghan et al. 2022). In Broward County alone, there are approximately 140,000 observations from more than 9,000 users on iNaturalist (iNaturalist 2023), indicating the potential robustness of available data to quantify biodiversity. Citizen science data are prevalent in urban areas, even more so than professionally collected biodiversity data, making this data source ideal for quantifying biodiversity utility in urban greenspaces (Li et al. 2019). We downloaded all iNaturalist data from Florida, United States directly from the iNaturalist website so we could obtain all non-research grade and research grade observations (i.e., observations with two thirds agreement on species identification) while increasing the sample size of the dataset (iNaturalist Community 2023). We included non-research grade observations in our analysis because our focus was not on the absolute species richness value (i.e., how many species per urban greenspace), but rather a relative measure of biodiversity across different urban greenspaces. However, we did remove observations of captive organisms, which are occasionally shared with iNaturalist for “casual” documentation but are not appropriate for biodiversity calculation.

We found many greenspaces in Broward County are small and have no iNaturalist data (N=355) to predict species richness directly. For these greenspaces, we considered the number of observations, number of observers, and species richness data to be unavailable. Therefore, we developed a random forest model to predict a standardized value of species richness (i.e., focused on relative levels of species richness prediction and not on an absolute measure of species richness). A random forest was used as we were only interested in prediction, and not inherently interested in understanding patterns of what influences species richness. This approach was applied to all urban greenspaces, where the observations from the sampled urban greenspaces were used as training data for the random forest and predictions were made using remotely-sensed landcover within urban greenspaces. Full details on our methodology to calculate species richness as a proxy for biodiversity utility can be found in Appendix S1. We tested the predictive ability of this analysis using a leave-one-out cross validation analysis and found a positive association between predicted and observed values ($R^2 = 0.93$), providing robustness to our methodological choices. Lastly, we similarly scaled the predicted species richness values to between 0 and 1 using the “rescale” function in the R package Scales (Wickham and Seidel 2022) to obtain a relative measure of biodiversity that is comparable to human utility.

Statistical analyses

We first empirically summarized the correlations between human utility attributes by calculating correlation coefficients and visualizing the data as a correlogram using the "corrplot" function in R package corrplot (Wei and Simko 2021). To quantify the relationships between human utility and biodiversity we first ran a generalized linear model using the "glm" function in R with a Gaussian error distribution. This model included scaled biodiversity as the response variable and scaled human utility as a predictor variable. In addition, because greenspace size was positively correlated with human utility and biodiversity utility (Figure S1), we also included log10-transformed greenspace size (m^2), due to the positively skewed distribution, as a predictor variable. We ran three models, one with human utility and greenspace area as the predictor variables, one with just human utility as the predictor variable, and one with just greenspace area as the predictor variable. We did this to account for all combinations of variables and compared models using the Akaike Information Criterion (AIC). To assess whether specific physical attributes (i.e., Table 1) were related to biodiversity, we used a linear model with biodiversity as the response variable and a binary categorical variable for each of the eight physical attributes as the predictor variables. For all models (N=8), we examined the relationship between residuals and fitted values and the QQ plot to ensure model assumptions were met.

Data analysis and availability

Unless otherwise stated, all analyses were conducted in R statistical software (R Core Team 2023). We report statistical significance following the convention suggested by Muff et al. (2022), where *p*-values between 0.1 – 1 indicate little or no evidence, 0.05 – 1 indicate weak evidence, 0.01 – 0.05 indicate moderate evidence, 0.001 – 0.01 indicate strong evidence, and less than 0.001 indicate very strong evidence of a relationship between variables of interest. Data from iNaturalist are openly available (see inaturalist.org), but summarized versions as well as our data on human utility are available at this GitHub repository (https://github.com/coreytcallaghan/greenspaces_broward) and will be archived in Zenodo following acceptance.

Results

We analyzed 639 greenspaces in Broward County ranging from 0.03 to 376 ha in size (Figure 1). The average greenspace size was 8.0 ha. On average, there were about 22 greenspaces included per municipality. The number of physical attributes in urban greenspaces is approximately normally distributed (Figure 2a), with the median number of 3 attributes per urban greenspace, few having 1 physical attribute and few having 7 (the maximum observed). The most frequent physical attributes were pavilion/picnic area (23.08%), followed by kid's playground (21.72%), jogging/walking path (18.50%), athletic facility (16.06%), indoor/outdoor fitness center (6.67%), body of water (8.48%), dog park (2.94%), and nature preserve (2.54%) as illustrated by Figure 2b.

When assessing the relationships between physical attributes in urban greenspaces we found a mix of positive and negative associations (Figure S1). Predominant positive pairs, defined as $r > 0.25$, include pavilion/picnic area and kid's playground ($r = 0.36$), kid's playground and athletic facility ($r = 0.44$). There was a strong correlation ($p < 0.001$) between nature preserve and body of water ($r = 0.09$); pavilion/picnic area and body of water ($r = 0.12$); athletic facility and pavilion/picnic area ($r = 0.21$); jog/walk path and body of water ($r = 0.21$), nature preserve ($r = 0.17$), and pavilion/picnic area ($r = 0.22$); and indoor/outdoor fitness center and pavilion/picnic area (r = 0.15), kid's playground (r = 0.21), athletic facility (r = 0.22), dog park (r = 0.11), and jog/walk path (r = 0.25). There is a slight positive correlation between nature preserve and picnic area ($p < 0.001$, r = 0.02), and positive correlation between dog park and pavilion/picnic area ($p = 0.041$, r = 0.08). Conversely, strong evidence ($p < 0.001$) points to a negative correlation between kid's playground and body of water (r = -0.14), kid's playground and nature preserve (r = -0.21), athletic facility and body of water (r = -0.14), and athletic facility and nature preserve (r = -0.18).

Association between human utility and biodiversity

We found very strong evidence of a positive, logarithmic relationship between biodiversity and greenspace size ($p < 0.001$) and human utility and greenspace size ($p < 0.001$; Table 2; Figure S2). However, at the aggregated level, we found no evidence of a relationship between biodiversity and human utility ($p = 0.546$; Table 2; Figure 3). Our generalized linear model with just greenspace size as the predictor variable performed slightly better than the full model (ΔAIC = 1.633). However, for the different physical attributes, we did find significant relationships between certain physical attributes and biodiversity (Figure 3). There was moderate evidence of a positive relationship between the presence of kid's playground and biodiversity ($p = 0.019$); strong evidence of a positive relationship between the presence of dog park and biodiversity ($p = 0.006$); and very strong evidence of a positive relationship between presence of body of water ($p < 0.001$), jog/walk path ($p < 0.001$), and nature preserve ($p < 0.001$) on biodiversity. We found little to no evidence of a relationship between the presence of pavilion/picnic area ($p = 0.494$), athletic facility ($p =0.188$), and indoor/outdoor fitness center ($p = 0.507$) on biodiversity.

Discussion

By mapping more than 600 urban greenspaces and quantifying human utility we found that human utility is approximately normally distributed among greenspaces and that there was no evidence of tradeoffs in overall human utility and biodiversity benefits at the aggregated level. Our findings suggest that there are notable synergies between certain physical attributes and biodiversity in urban greenspaces, illustrating the potential of urban greenspaces to be designed and managed to simultaneously benefit both human populations and local biodiversity (van Leeuwen et al. 2010; Connop et al. 2016). The positive associations between certain physical attributes — such as kid's playgrounds, dog parks, bodies of water, jogging/walking paths, and nature preserves — and biodiversity underscore the potential of thoughtful urban greenspace design (Daniels et al. 2018) to foster biodiversity alongside recreational and social activities.

The absence of a direct trade-off between human utility and biodiversity in our analysis challenges a commonly held assumption that urban development inevitably leads to minimizing ecological integrity (Balfors et al. 2016). Benefits derived from urban greenspaces for human populations does not necessarily conflict with the maintenance of biodiversity. Our results suggest that with careful planning and consideration of ecological principles, urban greenspaces can be optimized to serve dual purposes effectively. This outcome is particularly relevant in the context of rapid urbanization and the increasing need for spaces that support human well-being while preserving and enhancing urban biodiversity (Tzoulas et al. 2007). However, overall greenspace size appears to be an important factor in urban greenspace utility, positively influencing both human utility and biodiversity. This makes sense as larger greenspaces accommodate a larger range of human activities and provide more varied habitats for biodiversity (Callaghan et al. 2018), backing the idea that size matters in optimizing the multifunctionality potential of urban greenspaces. One thing we did not account for is the number of visitors that are attracted to an urban greenspace — another potential measure of human utility that could be explored in future work.

From an urban planning perspective, our findings highlight the importance of considering multiple benefits derived from both humans and biodiversity, challenging the division between prioritizing human utility or biodiversity utility solely. Our results extend the literature of understanding the contributions of biodiversity to ecosystem services (Haines-Young and Potschin 2010; Le Provost et al. 2023; Mitchell et al. 2024) to the actual use and benefits of urban greenspaces to humans' welfare. For instance, the specific design and management of greenspaces — such as the maintenance of native plant species, the provision of water features, and the limitation of light pollution — are critical factors that can encourage park visitation and influence the biodiversity utility of these areas (Song et al. 2022; Threlfall et al. 2017). Additionally, although dog parks and kid's playgrounds cater more towards 'human benefit,' we found that they also increase biodiversity utility. This is likely due to these features encouraging park visitation and use of other features, such as walking trails, which are valued by both dog owners and children (Lee et al. 2009; Song et al. 2022; Veitch et al. 2020). Contrarily, some features such as athletic facilities, fitness centers, and pavilion areas, do not tend to significantly increase or decrease biodiversity utility likely due to their limited impact on long-term park visitation (Song et al. 2022).

Our analysis illustrates the importance of integrating biodiversity and human utility, but nevertheless takes a macroecological scale approach, looking across many urban greenspaces at once. While we performed a comprehensive search of all urban greenspaces throughout Broward County, it is possible that not every urban greenspace is included as some gated communities, for example, have privately managed greenspaces, or municipality websites could be out-of-date. Nevertheless, our methodologies, specifically the use of "big data" platforms like iNaturalist for biodiversity analysis, provide a scalable solution to understand urban biodiversity patterns. Additionally, big data and AI can be leveraged to obtain human utility data on a larger scale to provide further information on the human experience of greenspaces through online reviews and aerial imagery. Future research should explore incorporating other big data platforms for a more refined understanding of human utility, incorporating online reviews, social media, and citizen engagement for broader and more nuanced insights of the human and biodiversity dynamics (e.g., actual human uses of greenspaces). This contrasts with the laborious task of searching through each individual urban greenspace manually to annotate physical attributes (see Methods). We also did not assess individual management actions, for example, our approach estimates biodiversity from a holistic perspective. However, within an urban greenspace, management actions can have a significant influence (positively or negatively) on biodiversity, either for individual taxa or at aggregated levels, as well as on extent to which greenspaces can better serve human needs and utilities (Threlfall et al. 2017). And further from this, staff, funding levels, and the population that an urban greenspace serves could all be informative avenues to explore in future work. Understanding the effects of scale and urban greenspace management (Borgstrom et al. 2006), for example how actions within one urban greenspace correlate and correspond with actions among all urban greenspaces, remains an important avenue for future research.

While there are many calls to integrate urban biodiversity and human utilization within urban planning (e.g., Sadler et al. 2010), we have provided empirical data showing that indeed, there is no evidence of tradeoffs between biodiversity and human utility, at least at a macroecological scale. Our results also illustrated multiple synergies between urban biodiversity and certain human utility attributes, highlighting the potential to achieve ‘win-win’ outcomes from sustainable urban greenspace management. As urbanization continues, and cities continue to grow, our study highlights the importance of considering multifunctional benefits in urban greenspaces. Urban greenspaces are important components of cities for both people and nature.

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Figures

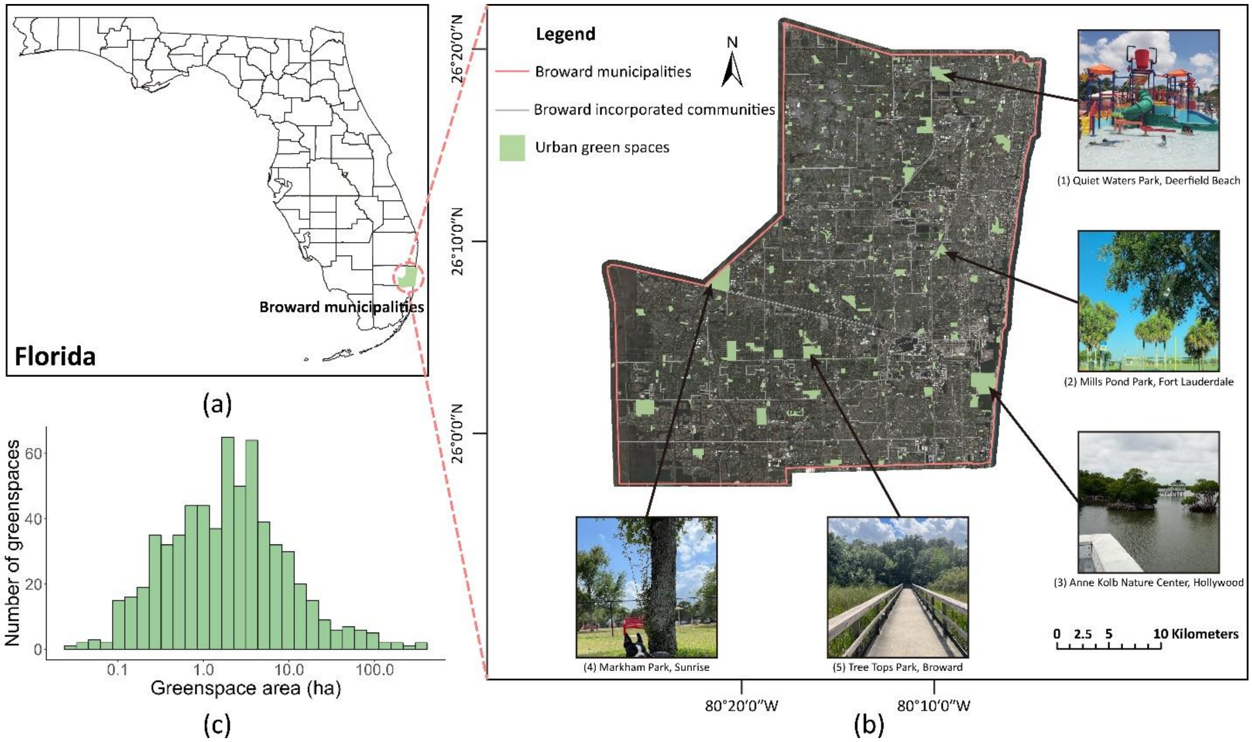

Figure 1. (a) Location of Broward County, Florida, USA. (b) Map of study area and the 646 delineated urban greenspaces. (c) The histogram displays the distribution of greenspace area on the log10 scale for ease of interpretation.

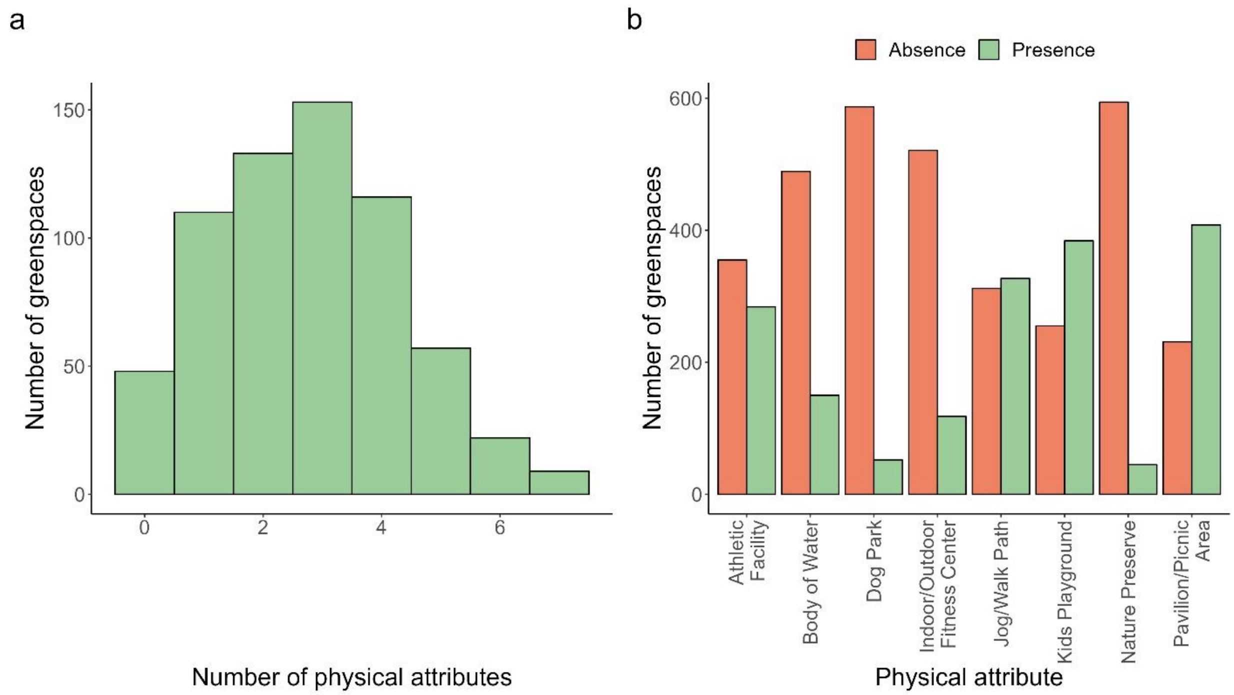

Figure 2. The (a) distribution of number of physical attributes per greenspace and (b) the count of presence and absence of each physical attribute for all greenspaces.

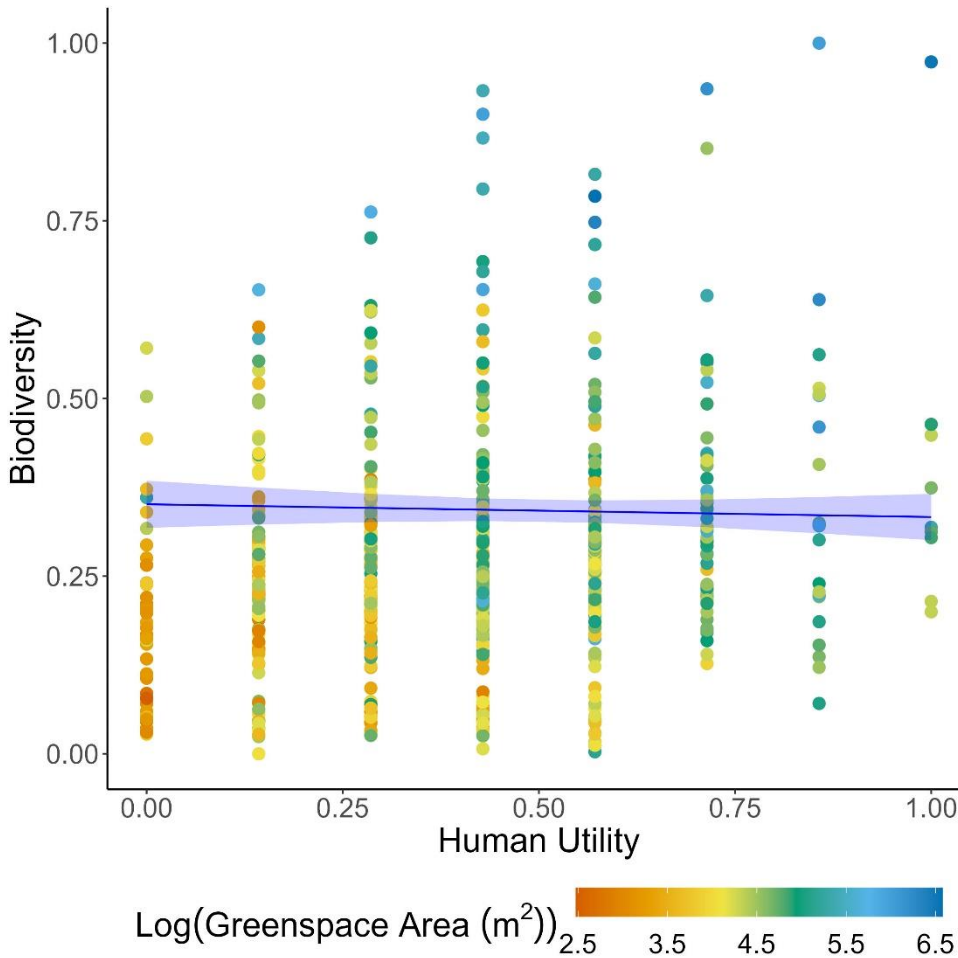

Figure 3. Comparison of human utility and biodiversity utility value by log transformed greenspace area. The blue slope line and 95% confidence interval is from a generalized linear model that compared biodiversity to human utility and greenspace area (see Table 2).

Figure 4. Linear model predictions of human utility attributes by bio-use value. The linear model included scaled bio-use values as the response variable and each human utility attribute as a binary predictor variable. **p*-value <0.05 and ≥ 0.001 ***p*-value < 0.001

Tables

Table 1. Human utility characteristics found in greenspaces and definitions.

Attribute type	**Definition**	**Uses**	**Examples**
Pavilion/Picnic Area	A sheltered area within a park that provides seating and tables.	Outdoor dining, special events, socializing.	Benches, picnic tables, pavilions, gazebos.
Kids Playground	An area specifically designed with play equipment and features tailored to children.	Physical exercise, playing, and social interaction among children.	Slides, swings, climbing structures, splash pads, water parks.
Body of water	A natural or man-made water feature within or surrounding a park.	Boating, fishing, swimming, water view.	Ponds, rivers, lakes, canals, beaches.
Jog/Walk Path	A designated route or trail typically paved or surfaced with materials suitable for foot traffic. May be marked with signage or directional indicators.	Walking, jogging, running activities.	Nature trail, exercise path.
Athletic Facility	An area designed with infrastructure and amenities for various organized sports.	Soccer, basketball, tennis, volleyball, swimming, etc.	Sports fields, courts, tracks, swimming pools.
Nature Preserve	A designated area that is actively managed and protected to serve natural ecosystems and biodiversity.	Bird watching, scientific research, education, nature-based recreation.	Contain native plants, animal species, and preserved natural features.
Dog Park	An area or open field that provides a controlled environment for dogs to exercise and play off leash.	Recreational activities for dogs and dog owners.	Fenced boundaries, waste disposal stations, water stations, agility equipment.
Indoor/Outdoor Fitness Center	An enclosed or open air space with equipment to promote physical fitness through exercise.	Individual or group fitness, yoga, calisthenics, strength training.	Exercise machines, weights, cardio equipment, allocated spaces for physical activities.

Table 2. Generalized additive models (glm) and a linear model (lm) to compare the relationship between (1 – 3) scaled biodiversity to scaled human utility values and log transformed greenspace area (m^2), (4) scaled human utility values to greenspace area, and (5) scaled bio-use values to eight physical attributes. The human utility attributes are binary, and the model estimates are for attribute presence.

Model specification	**Estimate**	**SE**	**t value**	**p-value**
glm(biodiversity ~ human_utility + log(area))				
Human Utility	-0.018	0.030	-0.604	0.546
Area	0.050	0.004	11.766	<0.001
glm(biodiversity ~ human_utility)				
Human Utility	0.168	0.028	6.069	<0.001
glm(biodiversity ~ log(area))				
Area	0.048	0.004	13.530	<0.001
glm(human_utility ~ log(area))				
Area	0.076	0.005	15.885	<0.001
lm(biodiversity ~ pp + kp + w + path + af + np + dp + fc)				
Pavilion/Picnic Area (pp)	-0.009	0.014	-0.685	0.494
Kids Playground (kp)	0.034	0.015	2.355	0.019
Body of Water (w)	0.054	0.015	3.636	<0.001
Jog/Walk Path (path)	0.057	0.013	4.363	<0.001
Athletic Facility (af)	-0.018	0.014	-1.317	0.188
Nature Preserve (np)	0.168	0.024	6.870	<0.001
Dog Park (dp)	0.061	0.022	2.763	0.006
Indoor/Outdoor Fitness Center (fc)	0.011	0.016	0.664	0.507

Supporting information for:

Assessing multifunctional utility of urban greenspaces - exploring synergies and tradeoffs between human utility and biodiversity utility

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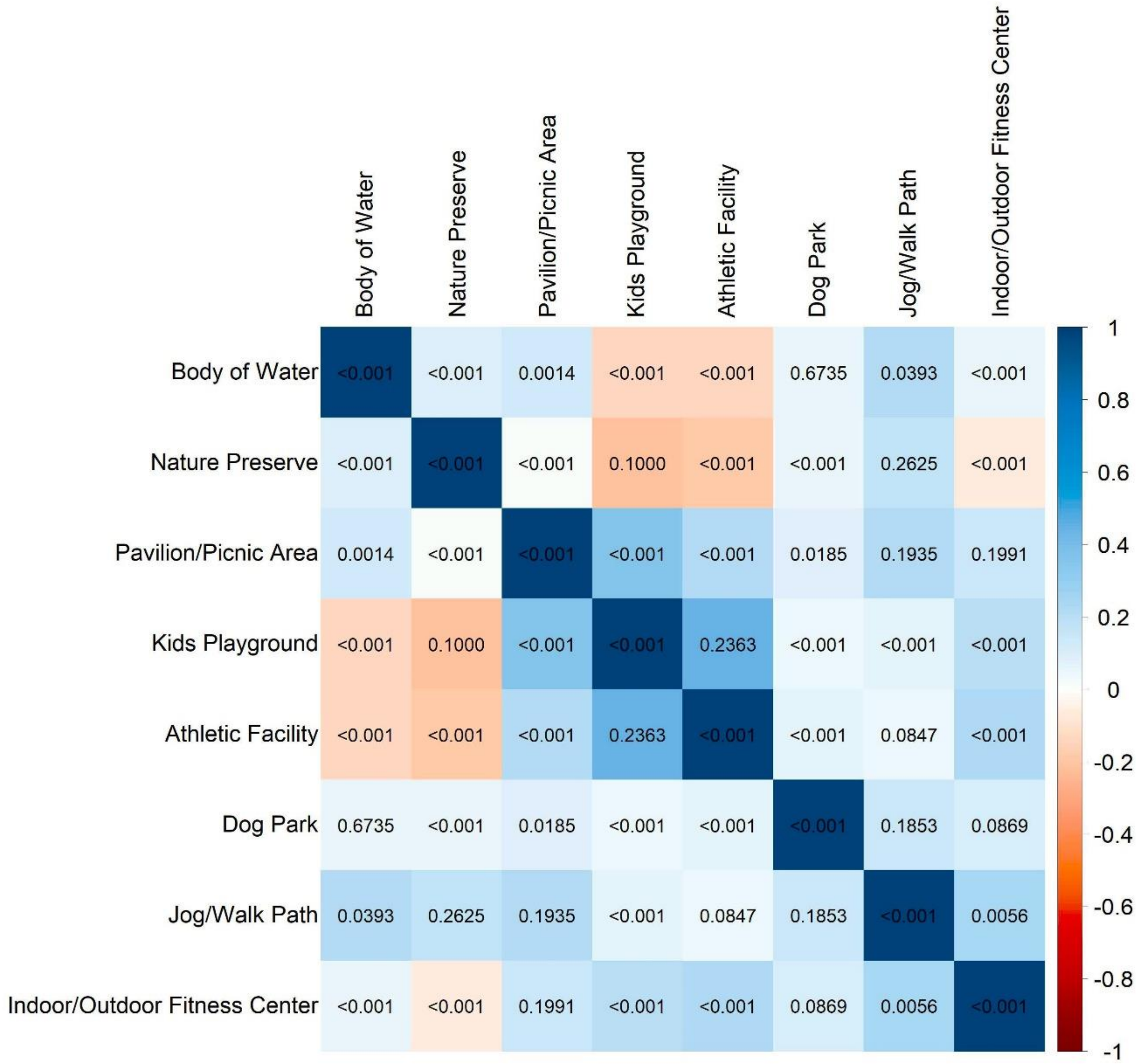
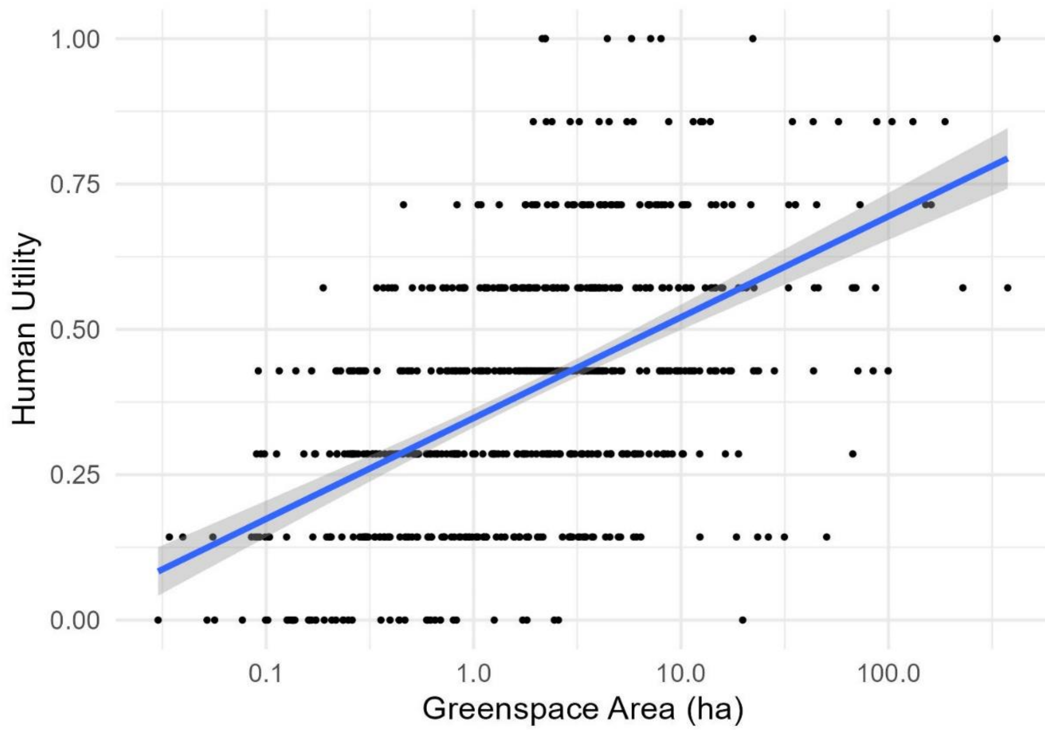


Figure S1. Correlogram of physical attributes, displayed as clusters from hierarchical clustering. Colors represent the correlation coefficient and values in the boxes represent *p*-values.



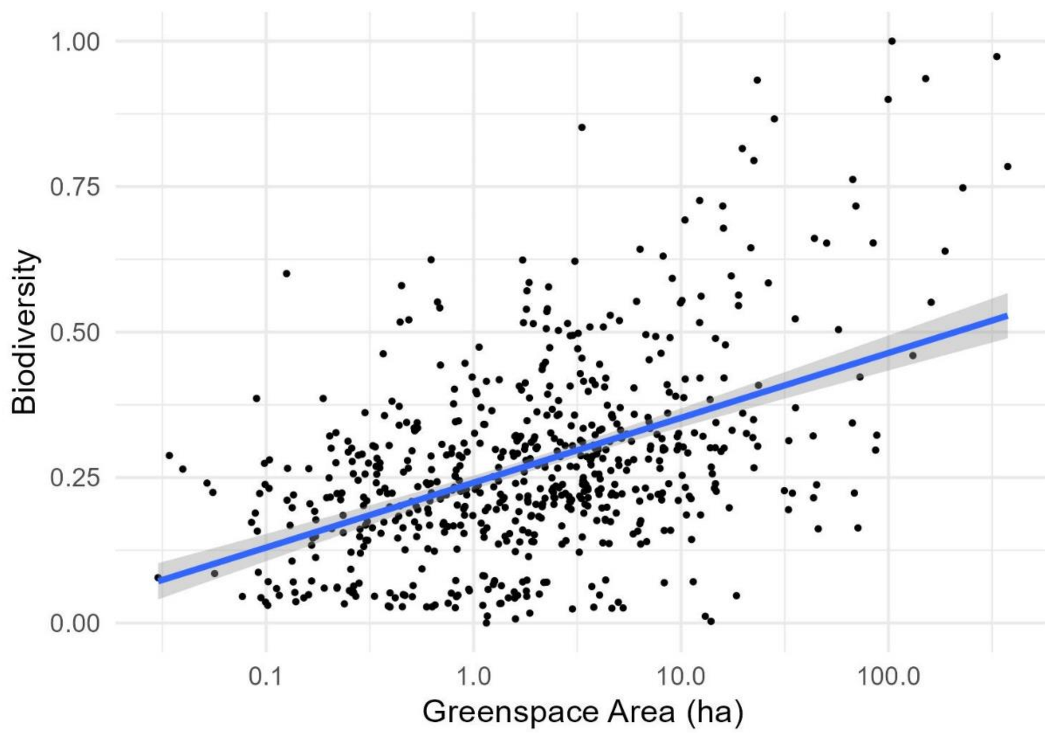


Figure S2. The relationship between human utility value and greenspace area (top) and biodiversity utility and greenspace area (bottom). The x-axis is displayed on the log10-scale. The blue line represents the linear model trend line using geom_smooth() and the grey shading is the 95% confidence interval.

Appendix S1. Details on our random forest approach to classify and quantify biodiversity utility used in our main analyses (i.e., standardized species richness).

Here we detail our methods for predicting species richness values to obtain a relative scale of biodiversity utility for all greenspaces. To predict species richness for the greenspaces with no iNaturalist data, we first obtained habitat data for all greenspaces. The habitat variables were obtained from raster data on percentage of tree cover (DiMinceli et al. 2017), non-tree vegetation (DiMinceli et al. 2017), water (Global Inland Water 2015), and impervious surface coverage (Dewitz and US. Geological Survey 2021), accessed from within the Google Earth Engine Data Catalog. From the raster files, we calculated average percentage of tree cover per 250 m^2 (resolution of raster), average percentage of non-tree vegetation cover per 250 m^2 (resolution of raster), the percentage of area that contained water (at 30 m resolution), and average percentage of impervious surface cover per 30 m^2 (minimum resolution of raster).

To understand the relationship between species richness and our predictor variables, we used a random forest analysis to model species richness in greenspaces with iNaturalist data using the randomForest R package (Liaw and Wiener 2002). We chose this methodology due to our small and nonparametric dataset and because we were only interested in prediction, and not inherently interested in understanding patterns of what influences species richness. The model included log10 transformed species richness (number of observed species) as the response variable and number of iNaturalist observations, number of iNaturalist users, average percentage of tree cover (%), water cover area (%), average percentage of impervious surface (%), and average percentage of non-tree vegetation cover (%) as the predictor variables.

To test the predictive ability of the random forest analysis from our dataset, we created a model from a training dataset (80% of data) and used it to calculate species richness values from a test dataset (20% of the data). We found a linear association between the predicted richness and observed richness in the test dataset ($R^2 = 0.99$), meaning the random forest model is reliable for predicting richness. Next, we ran the random forest model for the entire dataset, and found this model explained 96.34% of variance in the data.

To make species richness comparable across greenspaces, we chose a constant value for number of observations and used this to predict species richness for each park. We chose a constant value of 1,000 to allow for trends in the data, and subsequently scaled the number of observers (number of observers * (1000/number of observations)) based on this value. The other predictor variables are percentage of habitat coverage for each park, so these values were not scaled. From this new dataset, we used the predict function in the randomForest package (Liaw and Wiener 2002) to predict species richness for the scaled values based on the previously calculated random forest model.

Finally, to calculate species richness values for greenspaces with no iNaturalist data, we used a random forest imputation algorithm from the R package missForest (Stekhoven 2022). For the greenspaces with missing iNaturalist data, we set the total number of observations to 1,000. We combined the data with with the predicted species richness, scaled covariates, and habitat variables dataset calculated previously, and ran the random forest imputation to fill in missing values. To test the predictive ability of this analysis, we conducted a leave-one-out cross validation analysis and found a linear association between predicted and observed values ($R2$ = 0.94), meaning this method is valid for predicting species richness. Lastly, we scaled the predicted bio-use to values between 0 to 1 using the "rescale" function in the R package Scales (Wickham and Seidel 2022) to get a relative measure of biodiversity utility that is comparable to human utility.

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