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THE CONTRIBUTION OF CONSTRUCTED GREEN INFRASTRUCTURE TO URBAN BIODIVERSITY: A SYNTHESISED ANALYSIS OF ECOLOGICAL AND SOCIOECONOMIC OUTCOMES

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Abstract

This study examines how constructed green infrastructure green roofs, bioswales and rain gardens, pocket parks, and constructed wetlands contributes to urban biodiversity and neighborhood social outcomes, and integrates a narrative review of 50 peer-reviewed studies to ground the framework. The purpose is to quantify links between designed vegetated systems, site-level biodiversity, and perceptions of well-being, safety, satisfaction, place attachment, and usage. Design is quantitative, cross-sectional, and case-based. The sample comprises 180 CGI sites across diverse urban contexts with standardized pedestrian catchments, alongside 5,220 intercept-survey responses. Key variables include CGI extent, quality and maintenance, and connectivity; biodiversity indices (species richness, abundance, Shannon's H', Simpson's 1–D); and social outcomes measured on 5-point Likert scales, with covariates for NDVI, density, land-use mix, transit access, street connectivity, and neighborhood deprivation. The analysis plan specifies descriptives, Pearson or Spearman correlations, and multivariable models: negative binomial for counts, OLS with HC3 errors for continuous outcomes, ordinal logit for usage, plus bootstrapped mediation and prespecified moderation by typology, maintenance, and SES. Headline findings show CGI quality is the strongest ecological predictor, connectivity adds smaller but consistent benefits, and extent is positive yet modest; biodiversity is positively associated with well-being and satisfaction and, to a lesser extent, safety and attachment. Mediation tests indicate 20 to 35 percent of the quality effect on well-being and satisfaction is transmitted through biodiversity. Returns are larger where maintenance is higher, somewhat smaller on access-limited roofs, and stronger for safety in lower-SES catchments. Implications include prioritizing native-rich, vertically structured plantings, funding visible maintenance as a performance multiplier, completing green networks, and adopting a lean site-level dashboard that jointly tracks biodiversity and social outcomes.

Keywords

Constructed Green Infrastructure; Urban Biodiversity; Shannon Diversity; Perceived Well-Being; Neighborhood Safety;

INTRODUCTION

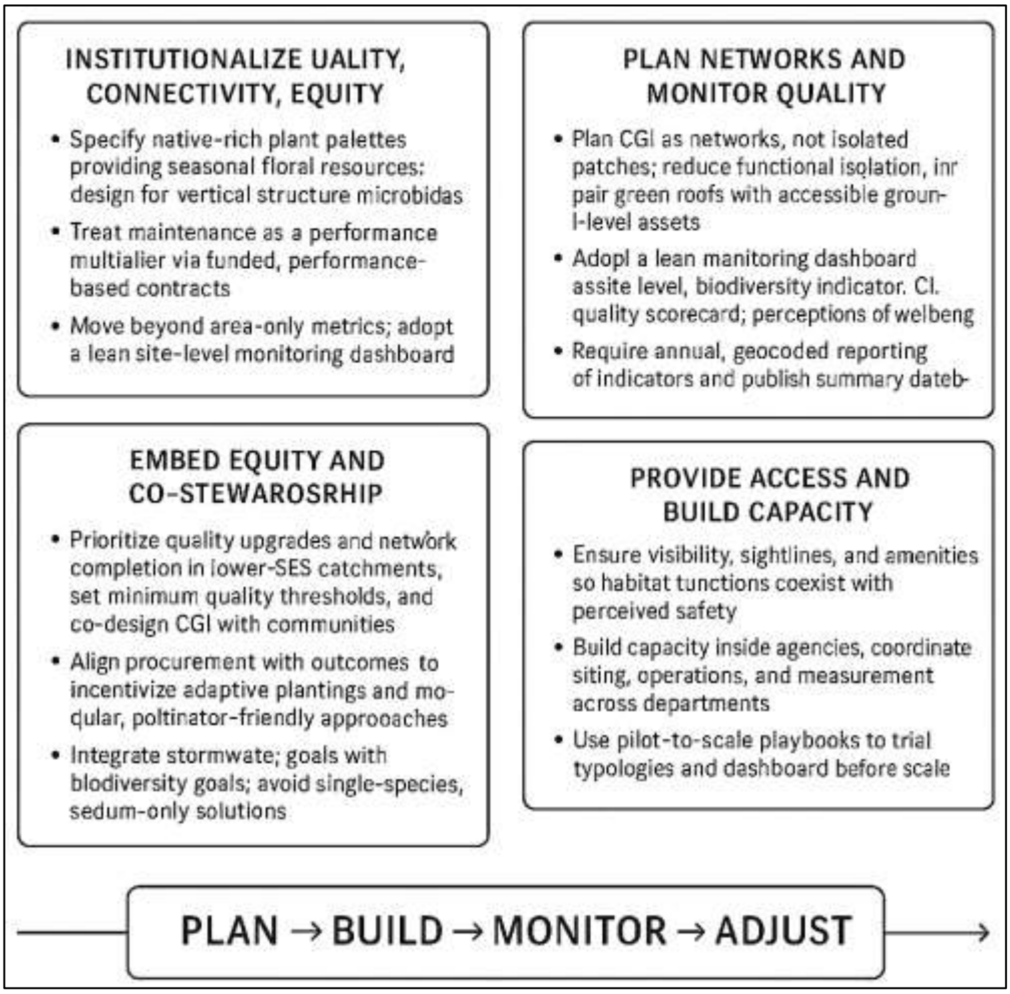
Green infrastructure (GI) refers to strategically planned and managed networks of natural and semi-natural areas, designed and implemented to deliver a wide range of ecosystem services and ecological benefits within urban and peri-urban landscapes (Threlfall et al., 2016). Within this umbrella, constructed green infrastructure (CGI) including green roofs, rain gardens/bioretention basins, bioswales, pocket parks, and constructed wetlands encompasses intentionally engineered vegetated systems embedded in the built environment to enhance ecological functioning and provide social co-benefits (Goddard et al., 2010; Oberndorfer et al., 2007). As rapid urbanization continues globally, cities have emerged as critical arenas for biodiversity conservation and human well-being, making the strategic deployment of CGI a matter of international importance (Seto et al., 2012). Conceptually, GI and CGI frameworks align with ecosystem-services thinking by emphasizing regulating, supporting, cultural, and, in certain cases, provisioning services that are co-produced by biophysical structures and human institutions (Bolund & Hunhammar, 1999; Gill et al., 2007). At neighborhood scales, CGI may increase habitat heterogeneity and connectivity, thereby affecting species richness and functional diversity (Elmqvist et al., 2013; Goddard et al., 2010). At the same time, CGI is frequently justified on public-health and social grounds urban heat mitigation, stormwater management, and restorative experiences positioning it as an integrated policy lever across environment, planning, and health sectors (Hartig et al., 2014; Twohig-Bennett & Jones, 2018). Despite these claims, empirical syntheses that quantifiably link the ecological outcomes of CGI (e.g., site-level biodiversity indices) to socioeconomic outcomes (e.g., perceived well-being, safety, satisfaction, and economic vitality) across multiple cases remain comparatively limited and methodologically diverse (Kabisch et al., 2016). This study is designed to address that evidence gap by operationalizing CGI characteristics and biodiversity metrics alongside socio-psychological indicators in a cross-sectional, multi-site framework.

Constructed GI systems differ in structure, substrate, plant community composition, and hydrologic function, and these differences are hypothesized to generate measurable ecological outcomes relevant to urban biodiversity (Oberndorfer et al., 2007). Green roofs extensive or intensive have been shown to provide urban habitat for plants, arthropods, and birds, though their conservation value depends on substrate depth, native species use, and habitat structure (Williams et al., 2014). Bioswales and rain gardens integrate vegetation and engineered soils to intercept, infiltrate, and evapotranspire stormwater, potentially creating small, moisture-rich habitat patches and foraging resources in otherwise hostile streetscapes (Gill et al., 2007). Pocket parks and micro-greenspaces can function as "stepping-stones" that enhance local connectivity, enabling species movement across fragmented urban matrices (Goddard et al., 2010). In combination, these CGI typologies may influence not only species richness, abundance, and diversity indices (e.g., Shannon, Simpson) but also the functional traits and network structure of urban biotic communities (Magurran, 2013). The degree to which CGI contributes to biodiversity, however, is expected to vary with patch size, quality (e.g., proportion of native flora, vertical structure), and landscape context (e.g., surrounding greenness, proximity to other habitat patches), all of which can be measured and modeled quantitatively in cross-sectional designs (Ahern, 2007). These typologies also intersect with human use patterns; well-designed pocket parks, for example, may generate frequent visitation and perceived safety benefits that co-occur with ecological improvements suggesting coupled human–nature dynamics amenable to integrated measurement.

Urban biodiversity exhibits complex, taxon-specific responses to land-use change. Large cross-city syntheses indicate that urbanization typically reduces native species richness and increases biotic homogenization, yet many cities still harbor substantial numbers of native and even endemic species (Aronson et al., 2014). Fine-scale studies in greenspaces show that perceived and actual biodiversity can be linked, with higher plant and bird richness sometimes corresponding to greater reported psychological benefits among users (Fuller et al., 2007), though findings vary by taxon and context (Dallimer et al., 2012). For pollinators, evidence from multi-city and landscape studies suggests that urban mosaics can support abundant and diverse pollinator assemblages, and targeted interventions flower-rich plantings, continuous bloom periods, structural diversity can enhance community robustness (Baldock et al., 2015). CGI elements such as biodiverse green roofs and rain gardens provide nectar, nesting substrates, and microclimatic refugia, potentially elevating site-level Shannon or

Simpson diversity under appropriate design and maintenance regimes (Oberndorfer et al., 2007). Connectivity metrics (e.g., distance to nearest green patch, patch density) and local quality metrics (e.g., native species share, vegetation strata) are therefore plausible predictors of biodiversity outcomes in regression modeling, with expected positive associations after accounting for urban form, NDVI, and socioeconomic covariates (Donovan & Butry, 2010).

Figure 1: Framework for Quality in Constructed Green Infrastructure



Accumulating public-health evidence links greenspace exposure with lower all-cause mortality, improved mental health, and better self-reported well-being, situating neighborhood green interventions as salient for population health (Donovan & Butry, 2010; Hartig et al., 2014). Randomized and quasi-experimental studies of urban lot greening indicate reductions in crime and improvements in perceived safety and mental health among nearby residents, suggesting that visible, well-maintained vegetated lots can modulate social disorder and stress pathways (Branas et al., 2011). Economic studies similarly document capitalization of street-tree and greenspace amenities into property values, indicating revealed preferences for green neighborhood attributes (Donovan & Butry, 2010). However, distributional and environmental-justice research reveals that access to high-quality green amenities is uneven across race and income, and parks or flagship ecology projects can catalyze displacement pressures if not designed with equity safeguards (Rigolon, 2016; Wolch et al., 2014). In sum, the socioeconomic portfolio of CGI includes perceived well-being, safety, local vitality, and equity considerations dimensions that can be measured via validated Likert-scale items and secondary indicators. Integrating these outcomes with biodiversity metrics enables empirical testing of whether and how ecological gains associate with social benefits at the site scale.

Despite conceptual alignment between ecosystem services and urban planning, empirical studies often remain siloed, focusing either on biodiversity or on social outcomes. Integrative models posit both direct effects of CGI on socioeconomic outcomes (e.g., improved aesthetics and visibility correlating with safety perceptions) and indirect effects mediated by biodiversity (e.g., richer, more functionally diverse communities enhancing restorative experiences) (Hartig et al., 2014). Urban ecological theory suggests that structural habitat attributes (patch size, vertical complexity, native flora) and landscape connectivity should increase richness and diversity measurable via Shannon or Simpson indices while social-environmental theories of place attachment and perceived safety anticipate improved Likert-scale scores where care and maintenance are evident. A cross-sectional, multi-case design can therefore formalize Model A (CGI → Biodiversity), Model B (Biodiversity + CGI → Socioeconomic outcomes), and Mediation (CGI → Biodiversity → Socioeconomic), with covariate control for density, NDVI, land-use mix, transit access, and neighborhood deprivation (Goddard et al., 2010; Kabisch et al., 2016). Prior syntheses provide the basis for directional hypotheses but call for standardized measures across sites to improve comparability and transferability to policy practice (Garvin et al., 2013; Kabisch et al., 2015). This study answers that call by specifying operational variables for CGI quality/extent/connectivity, biodiversity indices, and socio-psych scales, enabling the use of descriptive statistics, correlation analysis, and regression modeling to estimate effect sizes with adequate power.

The overarching objective of this study is to quantify the contribution of constructed green infrastructure (CGI) including green roofs, bioswales, rain gardens, pocket parks, and constructed wetlands to urban biodiversity and to evaluate how resultant ecological conditions are associated with socioeconomic outcomes at the neighborhood scale. Specifically, the study seeks to: (1) systematically characterize CGI at multiple sites across diverse urban contexts using standardized indicators of extent (e.g., vegetated area and cover), quality (e.g., native species share, vegetation strata, and maintenance frequency), and connectivity (e.g., proximity to other green patches and local patch density); (2) measure site-level biodiversity through comparable ecological audits yielding species richness, abundance counts, and diversity indices, with a focus on plants, birds, and pollinators as tractable urban taxa; (3) assess residents' or users' perceptions of well-being, safety, place attachment, usage frequency, and satisfaction with CGI using a 5-point Likert scale instrument, and complement these with available administrative or environmental indicators relevant to the local social environment; (4) describe the distributions and central tendencies of all ecological, social, and contextual variables, and examine their bivariate relationships through appropriate correlation analyses; (5) estimate multivariable regression models that test the predictive effects of CGI characteristics on biodiversity (Model A) and the combined effects of biodiversity and CGI on socioeconomic outcomes while adjusting for demographic, environmental, and urban-form covariates (Model B); (6) evaluate a mediation pathway in which CGI affects socioeconomic outcomes indirectly through biodiversity, using a pre-specified analytic framework with bootstrapped confidence intervals for indirect effects (Model C); (7) investigate moderation by CGI typology, neighborhood socioeconomic status, and maintenance regime through interaction terms and stratified analyses; (8) conduct a-priori power checks and apply robustness and diagnostic procedures addressing distributional assumptions, multicollinearity, and spatial dependence to strengthen internal consistency of estimates; and (9) deliver a reproducible, case-comparable dataset and reporting template that allow clear interpretation of effect sizes relevant to urban planning and site management. Collectively, these objectives define a coherent empirical program that aligns measurement, design, and analysis so that the independent roles of CGI attributes, the ecological conditions they support, and their associations with human-centered outcomes can be tested within a single, quantitative, cross-sectional, multi–case framework.

LITERATURE REVIEW

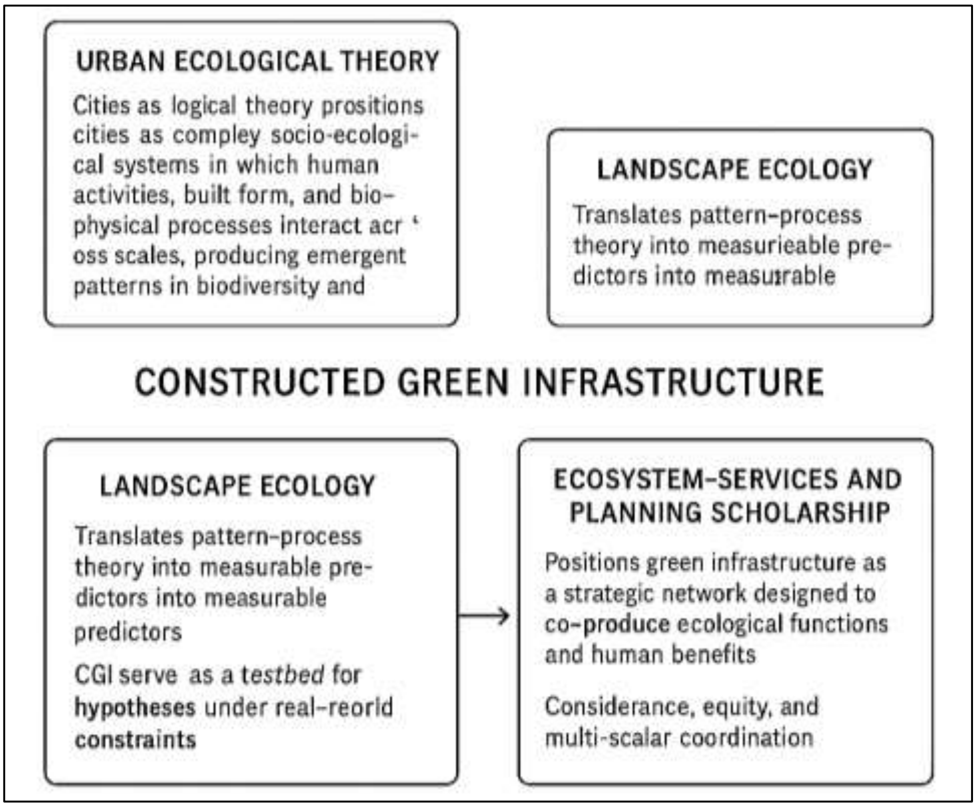
The literature on constructed green infrastructure (CGI) sits at the intersection of urban ecology, landscape planning, and environmental public health, yet it has often evolved in disciplinary silos that address either ecological performance or human outcomes rather than their interdependence. Foundational work defines green infrastructure broadly as strategically planned networks of natural and semi-natural features embedded within the built environment, while more recent strands focus on intentionally engineered systems green roofs, rain gardens, bioswales, pocket parks, and constructed wetlands designed to deliver targeted ecosystem services. Across these strands, three thematic pillars recur. First, studies of ecological functioning examine how site-level attributes extent, substrate depth, vegetation composition (particularly the use of native species), vertical structure, and maintenance regimes shape habitat quality, species richness, abundance, and diversity indices for plants, birds, and pollinators. Second, research on spatial context emphasizes landscape connectivity, neighborhood greenness, and surrounding land-use mosaics as determinants of community assembly and movement, calling for metrics that capture both patch quality and configuration. Third, social-science perspectives investigate socioeconomic outcomes associated with neighborhood green interventions, including perceived well-being and safety, site satisfaction and usage, place attachment, and indicators of local vitality; this body of work also interrogates equity in access and distribution of benefits. A growing integrative literature proposes models in which CGI influences socioeconomic outcomes both directly (e.g., through aesthetics, microclimate, and visibility) and indirectly via biodiversity, yet operational and methodological heterogeneity differences in typologies, sampling protocols, taxonomic focus, outcome scales, and covariate control limits cross-study comparability. For a synthesized, quantitative analysis, the literature points to the importance of standardized measures spanning exposures (extent, quality, connectivity), ecological responses (richness, abundance, Shannon/Simpson indices), and social outcomes (validated multi-item Likert scales), analyzed within a framework that controls for salient urban form and socioeconomic covariates. This review therefore organizes prior evidence around typologies and performance of CGI, biodiversity responses across key taxa, socioeconomic outcomes and equity considerations, and integrative models linking ecological and social domains. It culminates in a concise analytic framework and measurement strategy that resolve definitional ambiguities and support robust, cross-sectional, multi-case testing of associations between CGI, urban biodiversity, and neighborhood-scale socioeconomic conditions.

Theoretical Foundations

Urban ecological theory positions cities as complex socio-ecological systems in which human activities, built form, and biophysical processes interact across scales, producing emergent patterns in biodiversity and ecosystem service delivery. Rather than treating urbanization as purely degradative, contemporary frameworks emphasize that urban mosaics can host novel assemblages and processes, provided that heterogeneity, habitat resources, and connectivity are intentionally structured and maintained. This perspective builds on early syntheses that argued for integrating social drivers, infrastructure, and ecological dynamics to understand urban patterns and processes, highlighting feedbacks between human decision-making and ecological outcomes. It underscores that ecological functions such as primary production, nutrient cycling, microclimate regulation, and trophic interactions are not absent in cities but are redistributed and reconfigured by land-use intensity, impervious cover, and management regimes (Grimm et al., 2008; Niemelä, 1999). Accordingly, the theoretical baseline for constructed green infrastructure (CGI) treats engineered vegetated systems as levers that can shift urban system states by altering the availability and spatial arrangement of resources and refugia. Framed this way, CGI is not merely amenity landscape but an intervention into coupled human–nature dynamics, where design choices embed hypotheses about how structure yields function. This systems lens motivates measurement that captures both biophysical variation and human experience, enabling explicit tests of how CGI features relate to biodiversity and to neighborhood-scale social outcomes within a common analytic scaffold (Grimm et al., 2008; Niemelä, 1999).

Landscape ecology provides the pattern–process logic that links the spatial configuration of green elements to ecological mechanisms relevant for urban biodiversity. Classic landscape-scale principles posit that patch size, shape, quality, edge, and isolation jointly influence colonization, extinction, and movement, thereby shaping species richness, abundance, and functional composition. In fragmented urban matrices, small vegetated patches can act as stepping-stones if their quality and arrangement reduce effective resistance to movement; conversely, poorly connected or low-quality patches exacerbate isolation effects and biotic homogenization. The CGI paradigm operationalizes these principles through controllable design variables substrate depth, native plant palettes, vertical structure, hydrologic regime, and maintenance that modulate resource availability and microclimates. From a modeling standpoint, indices of extent (area, cover), quality (native share, strata diversity), and connectivity (proximity, patch density) translate pattern–process theory into measurable predictors that can be related to biodiversity outcomes via correlation and regression (Turner, 1989). This translation is crucial in cross-sectional, multi-case designs, where spatial heterogeneity is high and confounding must be managed statistically. By grounding the selection of exposures and covariates in landscape ecological mechanisms, the study improves interpretability of coefficients and supports generalization across typologies and neighborhoods. Put differently, CGI becomes a testbed for pattern–process hypotheses under real-world constraints, with site-level diversity indices serving as integrative response variables that reflect both local habitat conditions and landscape context (Turner, 1989).

Figure 2: Theoretical Foundations Linking to Constructed Green Infrastructure

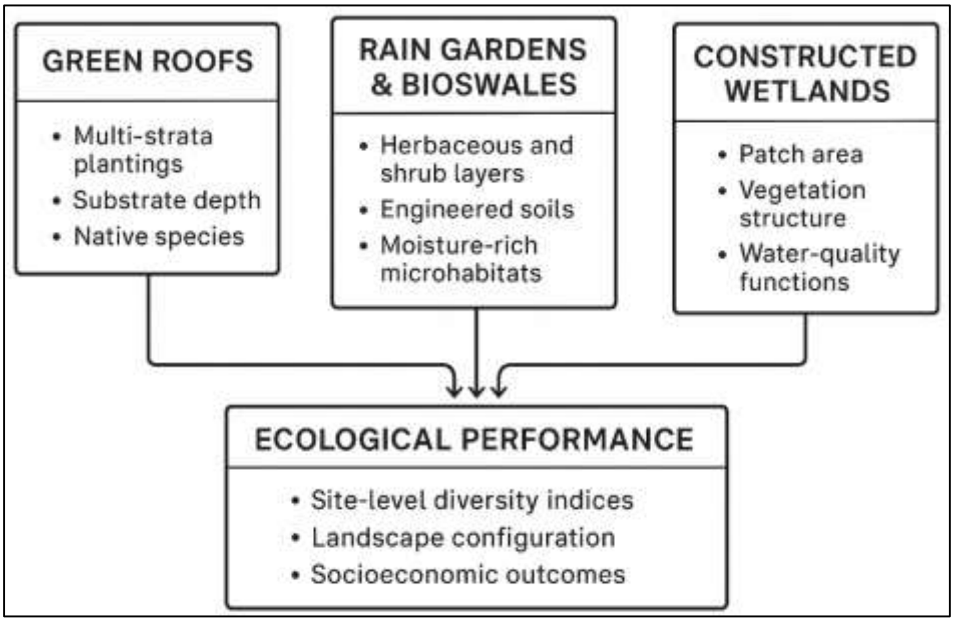


A complementary theoretical strand comes from ecosystem-services and planning scholarship, which frames green infrastructure as a strategic network designed to co-produce ecological functions and human benefits. Within this strand, biodiversity is not only an outcome of habitat provisioning but also a contributor to service stability and quality, especially for regulating and cultural services germane to dense urban neighborhoods (Niemelä, 1999). Conceptual models therefore position biodiversity as both a response to CGI design and a mediator of social outcomes such as perceived well-being, safety, and place attachment. Importantly, this framing requires attention to governance, equity, and multi-scalar coordination so that benefits are distributed and maintained across diverse communities and land tenures. European green-infrastructure policy work, for example, emphasizes multifunctionality, connectivity, and evidence-based planning standards, offering a vocabulary for aligning site-scale interventions with district and city strategies. For empirical research, these ideas imply standardized metrics that tie CGI structure to biodiversity and to human-centric endpoints, with spatial configuration and management embedded as first-order design considerations. They also imply that robust inference must separate direct social effects of visible, well-maintained greenery from indirect effects transmitted through ecological conditions, a distinction that guides the study's mediation and moderation tests. In sum, the theoretical foundations integrate urban systems thinking, landscape pattern–process theory, and ecosystem-services planning into an operational framework that justifies the study's variables, modeling choices, and cross-site comparability (Mace et al., 2012; Pauleit et al., 2017).

Constructed Green Infrastructure Typologies and Ecological Performance

Constructed green infrastructure (CGI) encompasses a family of intentionally engineered, vegetated systems most prominently green roofs, bioretention/rain gardens and bioswales, and constructed wetlands whose structural attributes can be tuned to influence urban biodiversity. Among these, green roofs provide a clear example of how design translates into ecological function: multi-strata plantings with deeper substrates and added structural complexity tend to support richer and more abundant arthropod communities than shallow, sedum-dominated installations. Large, multi-site studies have demonstrated that roof vegetation structure is a primary driver of arthropod richness and abundance, with shrub- and meadow-layer configurations outperforming moss/sedum roofs; similarly, large-scale plant surveys show substantial colonization by native flora when substrate depth and habitat heterogeneity are adequate (Hatt et al., 2009a; Madre et al., 2013). These findings position substrate depth, vertical stratification, and native plant palettes as measurable levers for enhancing site-level diversity indices design choices that are directly mappable to our exposure variables (extent, quality, connectivity). Intra-urban context remains important, but evidence suggests local roof design can meaningfully shape communities even amid heterogeneous city matrices. For a cross-sectional, multi-case study, such typology-specific insights justify modeling biodiversity outcomes as a function of roof structural complexity while controlling for surrounding greenness and building context. (Hatt et al., 2009a; Madre et al., 2013).

Figure 3: Constructed Green Infrastructure Typologies and Their Ecological Performance Pathways



Street-level CGI bioretention cells (rain gardens), bioswales, and "green streets" adds another mechanism set by marrying engineered soils with diverse herbaceous and shrub layers. These systems create moisture-rich microhabitats, nectar and pollen resources, and structural refuge along rights-of-way, with invertebrate richness and diversity often exceeding that of typical lawn or gardenbed comparators in the same streetscapes (Kazemi et al., 2011; Madre et al., 2014). At the same time, field-scale hydrologic and water-quality studies show that biofilters attenuate peaks and improve water quality across a range of pollutants, underscoring that vegetation strata and media composition drive both ecological and hydraulic performance. For biodiversity-focused analyses, the implication is that mid-strata vegetation cover, flowering plant diversity, and hydrologic regime (e.g., antecedent moisture, drawdown) are plausible predictors of site-level richness and Shannon/Simpson indices. In regression terms, these features operationalize the "quality" dimension, while linear corridors of bioswales can contribute to local "connectivity" by acting as stepping-stone habitat along streets. Integrating such street-scale mechanisms into our models helps test whether design-controlled habitat structure retains predictive power after accounting for neighborhood form and vegetation background

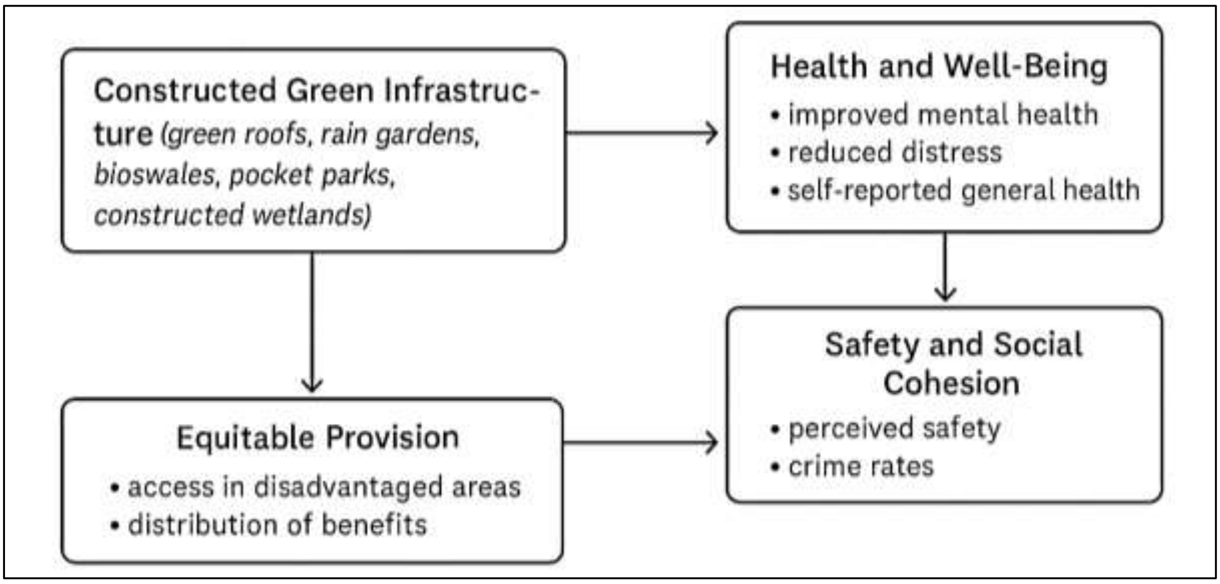
(Kazemi et al., 2011; Madre et al., 2014). Finally, CGI must be situated within broader urban biodiversity theory: patch area, vegetation structure, and corridor presence are consistently among the strongest correlates of intra-urban biodiversity across taxa (Hatt et al., 2009b). This means local design (e.g., roof strata, rain garden plant palettes) should be interpreted alongside landscape configuration how many patches are nearby, how large they are, and how they are arranged when explaining variation in richness and community composition. Synthesis work on "biodiversity in the city" emphasizes that urban green spaces can support meaningful biodiversity when size, quality, and configuration are addressed together, offering a conceptual rationale for including extent (area/cover), quality (native share, strata), and connectivity (proximity/patch density) in a unified exposure set. For constructed wetlands specifically, well-designed systems can contribute habitat while delivering water-quality functions; although created primarily for treatment, they often diversify urban aquatic habitat, reinforcing the need to treat them as part of multifunctional CGI networks. Collectively, these strands support a typology-aware but integrative modeling strategy: estimate how CGI structure and landscape pattern jointly predict biodiversity, and then test whether those ecological conditions are associated with the socioeconomic outcomes measured in our Likert instrument. (Beninde et al., 2015; Lepczyk et al., 2017).

Socioeconomic Outcomes and Equity

Urban green interventions such as constructed green infrastructure (CGI) green roofs, rain gardens, bioswales, pocket parks, and constructed wetlands are increasingly evaluated not only for their ecological merits but also for their contributions to population health and neighborhood quality of life. A substantial body of epidemiological research links everyday access to greenery with better self-reported health, reduced psychological distress, and improved mental well-being, suggesting that local vegetated environments can buffer the stresses of dense urban living. Early population-level evidence demonstrated that residents living in greener neighborhoods reported better general health even after accounting for urbanity and socio-demographic factors, indicating that the association is robust across different settlement patterns and social strata (Maas et al., 2006). Longitudinal quasi-experimental findings extend this cross-sectional picture: individuals who move to areas with more greenery show sustained improvements in mental health relative to those moving to less green neighborhoods, implying that environmental context functions as an ongoing exposure rather than a one-time amenity (Alcock et al., 2014). At a systems level, conceptual work has clarified plausible causal pathways through which local vegetation influences health by promoting physical activity and social cohesion, reducing exposure to air/noise pollution and heat, and supporting psychological restoration offering a structured basis for selecting social outcome measures in empirical CGI studies (Markevych et al., 2017). Importantly for equity, access to restorative greenery appears to narrow health gaps: analyses at large scales show that contact with natural environments attenuates socioeconomic gradients in health outcomes, reinforcing the idea that neighborhood-scale green interventions may disproportionately benefit more deprived populations when provision is equitable (Mitchell & Popham, 2008). Together, these strands situate CGI within a socio-ecological framework in which localized vegetated features contribute to measurable health benefits through multiple, interacting mechanisms that are relevant at the block and neighborhood scales (Nesbitt et al., 2019).

Beyond health, scholars have examined relationships between neighborhood vegetation and perceived safety or recorded crime, domains directly relevant to residents' day-to-day experience and willingness to use local public spaces. Pioneering inner-city research linked vegetated residential surroundings with lower rates of aggression and property crime, advancing the hypothesis that maintained greenery supports informal social control and attention restoration, thereby reducing incivilities and opportunities for crime (Kuo & Sullivan, 2001). Subsequent landscape-scale analyses across urban–rural gradients reported negative associations between tree canopy and several crime categories, while noting that the strength and direction of relationships varied with land-use context and sociodemographic composition, which must therefore be explicitly modeled to avoid spurious inference (Mitchell & Popham, 2008). Synthesizing these insights for CGI, street-level bioretention corridors and pocket parks potentially enhance territorial functioning, visibility, and pedestrian presence mechanisms that may, in turn, influence fear of crime and actual victimization risk. From a measurement standpoint, these studies underscore the value of integrating perceptual outcomes (e.g., Likert-scale safety and disorder perceptions) with administrative indicators (e.g., incident counts) and of controlling for confounders such as density, income, housing stock, and baseline greenness. They also suggest moderation analyses, as the social effects of vegetated features can depend on maintenance regimes and contextual cues: well-kept plantings may signal investment and collective efficacy, whereas neglected sites could carry ambiguous signals. In the context of multi-case, cross-sectional designs, this literature supports modeling CGI quality (native share, strata, maintenance) alongside landscape configuration (extent, connectivity) to test whether site-specific vegetated elements contribute to safer, more socially cohesive street environments after accounting for neighborhood structure (Kuo & Sullivan, 2001; Troy et al., 2012).

Figure 4: Socioeconomic Outcomes of Constructed Green Infrastructure

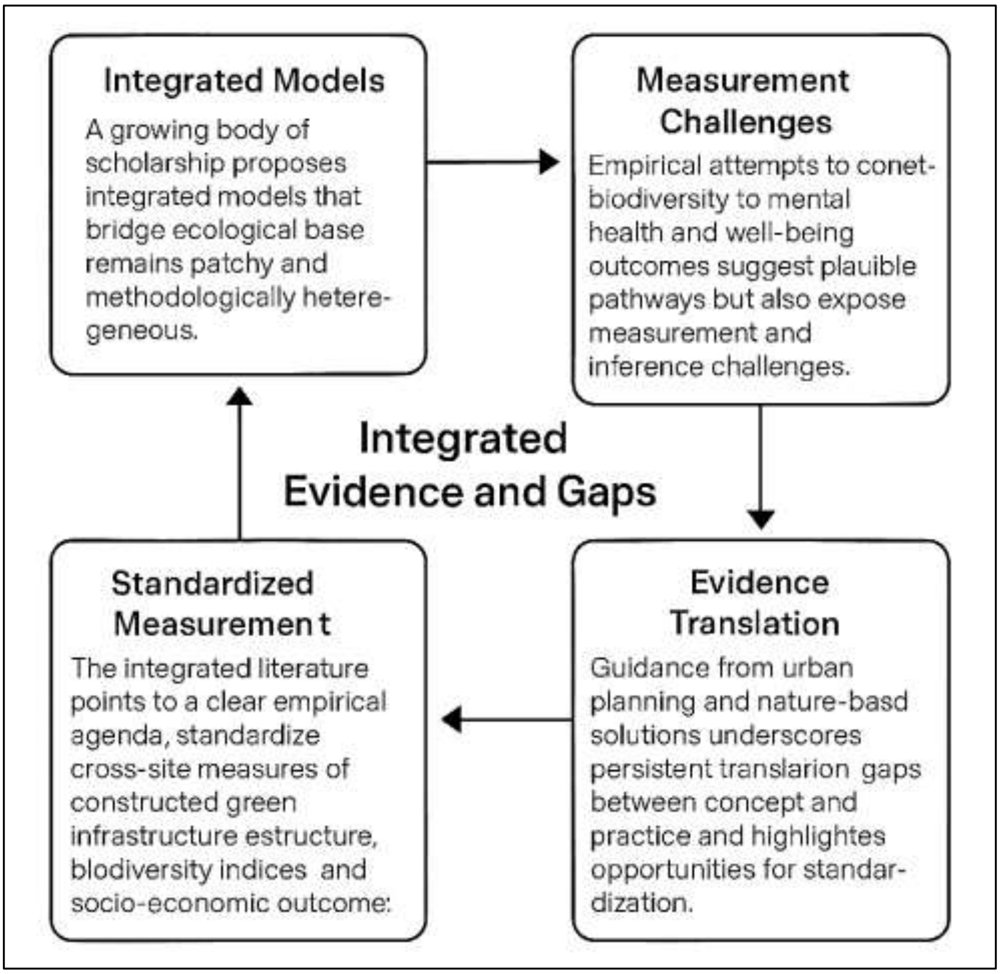


Equity is a central concern when linking CGI to socioeconomic outcomes, because the benefits of neighborhood greenery are rarely distributed evenly within cities. Health-gradient research indicates that greener local environments can mitigate disparities, but only when access is widespread and not contingent on ability to pay or residential sorting (Maas et al., 2006; Markevych et al., 2017). Empirical distributional studies document pronounced inequalities in urban tree canopy and park quality across income and racial lines, implying that the ecological services and psychosocial benefits conferred by vegetation accrue disproportionately to already advantaged communities (Nesbitt et al., 2019). For CGI evaluation, this raises two operational imperatives. First, exposure must be measured at the scales that residents actually experience frontages, blocks, and micro-greenspaces so that fine-grained inequities are visible in the data. Second, analyses should incorporate deprivation indices and other covariates that capture structural drivers of green access, enabling assessment of whether associations between CGI and social outcomes vary across socioeconomic strata. Integrating these equity lenses with the multi-pathway health framework helps clarify whether observed benefits reflect direct social effects of well-maintained vegetated settings, indirect effects mediated by ecological conditions (e.g., richer biodiversity contributing to restorative experiences), or both (Markevych et al., 2017). For policy-relevant research, the key question is not merely whether CGI correlates with better outcomes, but where, for whom, and under what maintenance regimes those correlations are strongest. Consequently, the proposed measurement strategy combining standardized CGI quality/extent/connectivity metrics, biodiversity indices, and validated social scales within a single modeling framework provides a basis for testing distributive patterns and for quantifying the extent to which equitable provision of CGI could contribute to narrowing observed health and safety differentials across neighborhoods (Nesbitt et al., 2019).

Integrated Evidence

A growing body of scholarship proposes integrated models that bridge ecological performance and human outcomes, yet the empirical base remains patchy and methodologically heterogeneous. Synthesis work on biodiversity–ecosystem functioning demonstrates that species loss can erode multiple ecosystem processes with implications for the stability and magnitude of services people value, providing conceptual footing for linking biodiversity metrics to social outcomes in cities (Cardinale et al., 2012). In urban contexts, quantitative reviews of ecosystem-service assessments reveal uneven coverage across service categories, inconsistent indicator choices, and limited attention to cross-domain linkages, which together constrain comparability across studies and cities (Haase et al., 2014). Complementary syntheses in urban ecology call for a shift from "ecology in" to "ecology of" cities explicitly coupling built, social, and ecological subsystems so that green infrastructure is evaluated as part of broader socio-ecological dynamics rather than as isolated patches (Soga & Gaston, 2016). Planning and governance perspectives further emphasize stewardship and multi-functionality, arguing that green infrastructure should be designed and managed to sustain ecosystem services while engaging communities and institutions that co-produce benefits (Andersson et al., 2014). Despite these advances, the literature continues to rely heavily on cross-sectional designs with variable taxonomic scopes, diverse social outcome measures, and inconsistent covariate control, making it difficult to estimate comparable effect sizes or to adjudicate mechanisms. This study responds to those gaps by specifying standardized exposure sets for constructed green infrastructure (extent, quality, connectivity), harmonized biodiversity indices, and validated socio-psychological scales elements repeatedly highlighted as necessary for cumulative, policy-relevant evidence (Haase et al., 2014; Houlden et al., 2018).

Figure 5: Integrated Evidence and Research Gaps in Constructed Green Infrastructure Studies



Empirical attempts to connect biodiversity to mental health and well-being outcomes suggest plausible pathways but also expose measurement and inference challenges. Neighborhood-scale analyses indicate that specific components of "nearby nature" including bird abundance and richness correlate with lower depression, anxiety, and stress, hinting that taxon-sensitive biodiversity measures may carry explanatory power beyond coarse greenness metrics (Cox et al., 2017). Systematic reviews on greenspace and mental well-being, however, document substantial heterogeneity in how nature exposure is conceptualized (amount, type, accessibility, views, visits) and how well-being is assessed (hedonic versus eudaimonic tools), leading to mixed or domain-contingent findings (Houlden et al., 2018). Parallel conceptual work on the "extinction of experience" warns that declines in everyday human–nature interactions may dampen people's sensitivity to biodiversity and the restorative gains it affords, implying that perceptions, use patterns, and ecological quality interact in shaping outcomes (Geneletti et al., 2020). From an integrated-evidence perspective, these strands motivate studies that pair objective biodiversity audits (e.g., species richness and diversity indices for plants, birds, and pollinators) with validated perceptual scales and usage measures, while attending to the neighborhood settings in which interactions occur. They also justify analytic strategies that partition direct effects of visible, well-maintained green features from indirect effects mediated by ecological conditions, and that probe moderation by typology and socioeconomic context. Without such harmonization, the field risks conflating the benefits of "green presence" with those of "biodiversity content," limiting the transferability of findings to design practice (Cox et al., 2017).

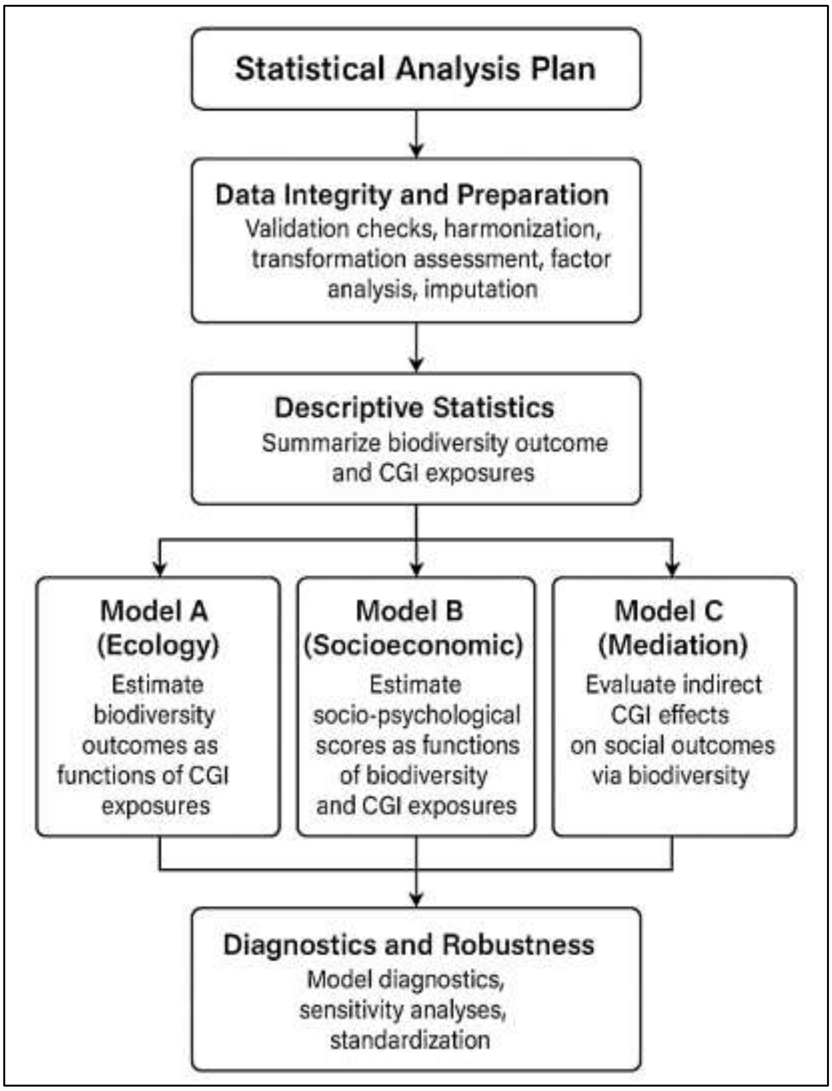
On the implementation side, guidance from urban planning and nature-based solutions underscores persistent translation gaps between concept and practice and highlights opportunities for standardization. Reviews of urban ecosystem-service uptake in planning identify barriers such as fragmented mandates, indicator proliferation without calibration, and limited cross-departmental data infrastructures that hinder routine, comparable evaluation (Haase et al., 2014). Strategic frameworks argue for multi-scalar connectivity, stewardship arrangements, and evidence-based design standards that weave ecological performance and human benefits into coherent green infrastructure networks (Geneletti et al., 2020). Open-access planning handbooks likewise provide operational templates for integrating ecosystem-service indicators covering development of metrics, baseline analyses, option comparison, and equity lenses into urban plans, but they also stress the need for robust, context-aware monitoring to move beyond pilot projects (Haase et al., 2014). Finally, macro-scale syntheses in biodiversity–ecosystem functioning continue to reinforce why biodiversity per se matters for service reliability and quality, supplying a normative rationale for retaining species-level measures in city evaluations alongside generalized greenness (Cardinale et al., 2012). Taken together, the integrated literature points to a clear empirical agenda: standardize cross-site measures of constructed green infrastructure structure, biodiversity indices, and socio-economic outcomes; situate analyses within an explicit socio-ecological causal framework; and report effect sizes that are interpretable for design, maintenance, and equitable provision across neighborhoods (Geneletti et al., 2020; Houlden et al., 2018).

METHODS

ChatGPT said:

The study adopted a quantitative, cross-sectional, multi–case design that integrated ecological audits, structured surveys, and spatial datasets to evaluate the contribution of constructed green infrastructure (CGI) to both urban biodiversity and socioeconomic outcomes at the neighborhood scale. Cases were defined as individual CGI sites, green roofs, bioretention/rain gardens, bioswales, pocket parks, and constructed wetlands, together with standardized pedestrian catchments, ensuring that exposures and outcomes were measured within comparable spatial units. Stratification by typology and socioeconomic context was applied to capture heterogeneity in design and setting, while inclusion and exclusion criteria were pre-specified to secure construct validity and feasibility. Exposure constructs were operationalized across three dimensions: extent (e.g., vegetated area, percentage cover), quality (e.g., native plant share, vegetation strata, maintenance frequency), and connectivity (e.g., proximity to green patches, local patch density). Ecological outcomes were measured through rapid audits producing species richness, abundance, and diversity indices, while socioeconomic outcomes were captured via a 5-point Likert survey instrument assessing perceived well-being, safety, satisfaction, usage frequency, and place attachment. Sampling procedures balanced typological representation with statistical power requirements, combining random selection from eligible municipal inventories with purposeful inclusion where strata were sparse. Recruitment of adult participants followed standardized intercept protocols, with quotas by gender and age band to mitigate bias. For both ecological and survey measures, temporal and seasonal standardization windows were adopted to reduce bias, and quality controls—such as duplicate counts, inter-rater reliability checks, and scripted enumerator training were embedded. Complementary GIS layers on greenness, land use, street connectivity, and administrative indicators (e.g., crime, footfall) were compiled to enrich the analytical framework.

Figure 6: Statistical analysis plan outlining data preparation, descriptive statistics, ecological (Model A), socioeconomic (Model B), mediation (Model C), and robustness checks.



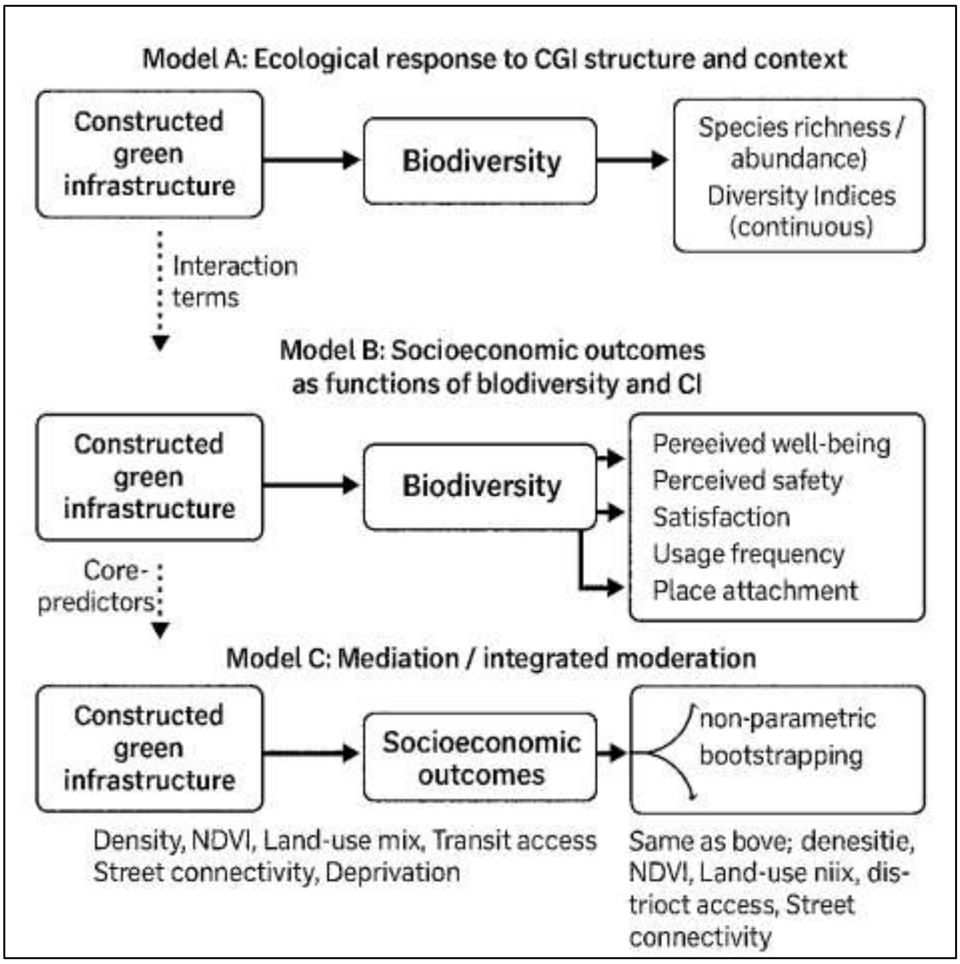
The statistical analysis plan proceeded sequentially from data readiness to inferential modeling. Initial steps included integrity checks, harmonization of units and coding, and distribution diagnostics, with transformations applied where skewness warranted sensitivity analyses. Exploratory factor analysis with oblique rotation informed the construction of social composites, and internal consistency thresholds (Cronbach's $\alpha \geq 0.70$) were enforced. Missingness diagnostics, including Little's MCAR test and auxiliary variable probes, guided the application of multiple imputation by chained equations where assumptions held, with pooled estimates computed under Rubin's rules. Descriptive statistics and distribution diagnostics summarized variables across typologies and neighborhood strata, while correlation analyses explored associations between CGI attributes, biodiversity indices, and social

outcomes. Multivariable regression models were pre-specified to estimate biodiversity as a function of CGI exposures and covariates, socioeconomic outcomes as functions of biodiversity and CGI, and indirect effects consistent with mediation frameworks. Model diagnostics incorporated multicollinearity checks, residual analyses, and sensitivity tests with alternative buffers and indices, while spatial dependence was probed through robustness analyses. Ethical safeguards were observed at every stage: informed consent was obtained, identifiers were anonymized, and secure storage with access controls was enforced. Together, these methodological choices provided a structured, reliable foundation for testing the ecological and social impacts of CGI across diverse urban contexts.
Bivariate associations have been explored using Pearson or Spearman correlations as appropriate, and the false-discovery rate has been controlled using Benjamini–Hochberg procedures for families of related tests. For multivariable modeling, three linked frameworks have been pre-specified. Model A (Ecology) has estimated biodiversity outcomes as functions of CGI extent, quality, and connectivity with covariate adjustment (population density, NDVI, land-use mix, transit access, deprivation). When outcomes have been counts (e.g., species richness), generalized linear models with Poisson or negative binomial links have been used after testing for over-dispersion and zero inflation; for continuous indices, ordinary least squares with robust (HC3) standard errors has been adopted. Model B (Socioeconomic) has estimated standardized socio-psychological scores as functions of biodiversity indices and CGI exposures with the same covariate set; where ordinal outcomes (e.g., usage frequency) have been modeled, proportional-odds or adjacent-category models have been employed after testing proportionality assumptions. Model C (Mediation) has evaluated indirect effects of CGI on social outcomes via biodiversity using non-parametric bootstrapping with bias-corrected confidence intervals; parallel paths have included direct CGI→social effects to separate structural from ecological channels. To probe heterogeneity, moderation terms (e.g., typology × biodiversity, SES × CGI quality, maintenance × biodiversity) have been centered to mitigate multicollinearity, and marginal-effects plots with 95% confidence intervals have been generated. Diagnostics have included variance inflation factors (target VIF < 5), residual and influence checks (studentized residuals, Cook's D), heteroskedasticity tests (Breusch–Pagan/White) with robust or heteroskedasticity-consistent corrections as needed, and spatial autocorrelation tests on residuals (Moran's I) followed, where indicated, by spatial error/lag sensitivity models or cluster-robust standard errors at neighborhood level. Robustness analyses have encompassed alternative spatial buffers (200/800 m), alternative biodiversity indices (e.g., Chao1), exclusion of high-leverage sites, and propensity-score weighting to reduce imbalance in CGI typologies across contexts. All predictors have been standardized (mean=0, SD=1) to facilitate coefficient comparability; two-tailed α=0.05 thresholds with 95% confidence intervals have been reported alongside effect sizes (standardized betas, incidence-rate ratios). Finally, reproducibility has been supported through a scripted workflow, versioned datasets, and a registered codebook so that analytical decisions have been transparent and auditable.
Regression Models
As model A (Ecological Response to CGI Structure and Context), the ecological modeling stage focused on estimating how constructed green infrastructure (CGI) structure and landscape context related to site-level biodiversity. Dependent variables included species richness (counts), overall abundance (counts), and diversity indices (Shannon's H′, Simpson's 1–D, continuous). For count outcomes, the study specified generalized linear models that used Poisson links initially and then adopted negative binomial links when over-dispersion tests (likelihood ratio and dispersion diagnostics) indicated variance inflation. For continuous diversity indices, ordinary least squares (OLS) with heteroskedasticity-consistent (HC3) standard errors was employed. The core predictor block comprised three standardized CGI exposure constructs Extent (site vegetated area, % cover), Quality (native share, strata count, substrate depth class, floral continuity, maintenance frequency, structural habitat features), and Connectivity (distance to nearest green patch, patch density, mean patch size within 300–500 m buffers, corridor adjacency) entered simultaneously to estimate their unique contributions. A common covariate set included population density, NDVI/greenness, land-use mix, distance to transit, street connectivity, and a neighborhood deprivation index. The canonical equation for continuous outcomes was expressed as:

$$Biodiversity(i) = \beta 0 + \beta 1Extent(i) + \beta 2Quality(i) + \beta 3Connectivity(i) + \beta 4'Xi + \varepsilon i$$

where Xi denoted the control variables. All predictors were standardized (mean = 0, SD = 1) to facilitate interpretation of β as standard-deviation changes in the outcome. Model diagnostics included variance inflation factors (target VIF < 5), influence statistics (Cook's D), residual plots, and spatial autocorrelation tests on residuals (Moran's I). Where spatial dependence persisted, sensitivity specifications with spatial lag/error terms or neighborhood-clustered standard errors were estimated. Robustness checks encompassed alternative buffer sizes (200 m, 800 m), alternative diversity estimators (e.g., Chao1 for richness), and exclusion of leverage-heavy sites. This framework yielded effect sizes that isolated the structural and positional contributions of CGI to biodiversity under realistic urban heterogeneity.

Figure 7: Regression Models Linking Constructed Green Infrastructure



The second modeling layer means model B (Socioeconomic Outcomes as Functions of Biodiversity and CGI) examined how human-centered outcomes related to the ecological state of CGI and to CGI design features themselves. Dependent variables included standardized composite scores for perceived well-being, perceived safety, satisfaction with the CGI site, usage frequency (ordinal), and place attachment. For continuous composite scores, the analysis employed OLS with HC3 errors; for ordinal usage frequency, proportional-odds (cumulative logit) models were used after testing the proportionality assumption, with adjacent-category models fitted as sensitivity analyses when required. The key predictor set included one or more biodiversity indices (e.g., Shannon's H′, richness) alongside the CGI exposure constructs (Extent, Quality, Connectivity), enabling the partitioning of direct social effects of visible/maintained greenery from indirect effects transmitted via ecological conditions (later tested formally in Model C). The control vector mirrored Model A to ensure comparability across specifications. The continuous-outcome equation was expressed as:

$$Socio(i) = \gamma 0 + \gamma 1 Biodiversity(i) + \gamma 2 Extent(i) + \gamma 3 Quality(i) + \gamma 4 Connectivity(i) + \gamma 5' Xi + ui$$

where Xi denoted controls. To probe heterogeneity, interaction terms were pre-specified: Typology × Biodiversity (e.g., green roof vs. bioswale), SES × Quality, and Maintenance × Biodiversity. Continuous predictors entering interactions were mean-centered to reduce multicollinearity, and marginal-effects plots with 95% confidence intervals were generated to visualize moderation. Model adequacy was assessed via adjusted R^2, AIC/BIC (for GLMs), residual diagnostics, and specification tests; sensitivity analyses included replacing biodiversity indices (e.g., substituting Simpson's 1–D for H'), using alternative social composites (hedonic vs. eudaimonic well-being components), and applying propensity-score weights to reduce design-context imbalance across CGI typologies. Collectively, Model B quantified whether sites with richer ecological conditions and favorable design attributes were associated with better reported neighborhood experiences after accounting for urban form and socioeconomic structure.

The mediation and integrated moderation stage tested whether biodiversity mediated the relationship between CGI and socioeconomic outcomes, while allowing for moderated pathways. A non-parametric bootstrapped mediation framework (bias-corrected confidence intervals; ≥5,000 draws) was specified to estimate the indirect effect of CGI Extent/Quality/Connectivity on each social outcome through Biodiversity, alongside direct effects of CGI on the same outcomes. The system was parameterized as two linked regressions (the "a" and "b" paths), reusing the Model A specification for Biodiversity(i) and the Model B specification for Socio(i), with identical covariate sets to preserve comparability. Standardized coefficients were reported so that the indirect effect (a × b) was interpretable as the proportion of a standard deviation in the outcome transmitted through biodiversity. Where theoretical rationale supported it, moderated mediation was examined by introducing interaction terms on the "a" path (e.g., Typology × Quality predicting Biodiversity) or on the "b" path (e.g., SES × Biodiversity predicting Socio outcomes), followed by conditional indirect effects evaluated at representative moderator values (low, mean, high). Good practice safeguards included collinearity checks, sensitivity of indirect effects to alternative biodiversity metrics, and comparison of bootstrapped intervals under different random seeds. To summarize the modeling architecture succinctly, Table 1 cataloged dependent variables, model families, links, and core predictors. This mediation framework completed the inferential strategy by quantifying how much of CGI's association with social well-being, safety, satisfaction, usage, and place attachment flowed through measured ecological conditions versus direct, non-ecological channels such as aesthetics, shade, or visibility.

Table 1. Summary of Regression Families and Dependent Variables

Model	Dependent variable(s)	Family / Link	Core predictors (all standardized)	Key covariates
A: Ecology	Richness (count), Abundance (count)	Poisson / Negative binomial	Extent, Quality, Connectivity	Density, NDVI, Land-use mix, Transit access, Street connectivity, Deprivation
A: Ecology	Shannon's H', Simpson's 1–D (continuous)	OLS (HC3)	Extent, Quality, Connectivity	Same as above
B: Socio	Well-being, Safety, Satisfaction, Attachment (continuous)	OLS (HC3)	Biodiversity + Extent, Quality, Connectivity	Same as above
B: Socio	Usage frequency (ordinal)	Proportional-odds (logit)	Biodiversity + Extent, Quality, Connectivity	Same as above
C: Mediation	Indirect effect of CGI on Socio via Biodiversity	Bootstrapped mediation	a-path: CGI → Biodiversity; b-path: Biodiversity → Socio; c': CGI → Socio	Same as above

Power & Sample Considerations

The study implemented an a priori approach to power and sample planning so that primary and secondary models achieved acceptable probabilities of detecting effects of interest under realistic variance structures. For continuous outcomes in Model A (e.g., Shannon's H') and Model B (standardized social composites), sample size targets were derived from multiple-regression conventions and simulations: assuming medium effect sizes (overall $f^2 = 0.15$), $\alpha = 0.05$ (two-tailed), power = 0.80, and p predictors comprising three CGI exposures (Extent, Quality, Connectivity), one to two biodiversity indices (Model B only), and a covariate block of approximately five controls, the required total case count was estimated to fall between $N \approx 130–180$ unique sites depending on final p and anticipated intercorrelations. To guard against overfitting, the study followed the rule-of-thumb $N \geq 50 + 8p$ for OLS and ensured a minimum 15–20 observations per predictor in final specifications. For count outcomes (species richness, abundance), power analyses for negative binomial models were conducted using expected baseline means and dispersion parameters obtained from pilot audits; under moderate over-dispersion ($\theta \approx 1–2$), detecting incidence-rate ratios of 1.20–1.30 for a standardized predictor required $N \approx 160–200$ sites. At the respondent level, within-site survey quotas were set so that reliability of site-level social composites was stabilized (target $n \approx 25–35$ respondents per site), which, when aggregated, yielded standard errors compatible with site-level modeling and enabled construction of robust within-site means. To sustain typology-stratified moderation tests, minimum per-typology counts (e.g., ≥25–30 sites for green roofs, bioswales, pocket parks) were enforced, and oversampling of rarer typologies (e.g., constructed wetlands) was planned to avoid sparse cells. Anticipated attrition from exclusion and data cleaning was accommodated through a 15–20% inflation of initial targets. Finally, sensitivity simulations (Monte Carlo) around plausible intercorrelations among CGI exposures and covariates were run and informed adjustments to stratum allocations, ensuring that variance inflation factors remained below thresholds and that detectable effect sizes aligned with the study's theoretical expectations.

Reliability & Validity

The study has embedded reliability and validity safeguards from instrument design through analysis so that inferences have rested on stable and defensible measurements. Content validity has been established by mapping each construct to a priori definitions and by soliciting expert review from urban ecology and public-health scholars; item pools for perceived well-being, safety, satisfaction, usage, and place attachment have been adapted from validated scales and have been screened for cultural and linguistic clarity. A pilot test has been completed across heterogeneous sites, and cognitive interviews have been conducted to refine wording and response options. For the social survey, internal consistency has been demonstrated with Cronbach's $\alpha \geq 0.70$ for retained multi-item scales, and item–total correlations have been inspected to remove weak contributors. Construct validity has been examined via exploratory factor analysis (principal-axis, oblique rotation), with Kaiser–Meyer–Olkin measures (≥0.70) and Bartlett's tests confirming factorability; where structure has been stable, a confirmatory check with composite reliability and average variance extracted (AVE ≥ 0.50) has supported convergent and discriminant validity. To limit common method bias, balanced (positively/negatively keyed) items, varied stems, attention checks, and separated measurement of predictors and outcomes within the instrument have been implemented; Harman's single-factor tests and unmeasured latent method factor probes have indicated acceptable levels. For ecological audits, inter-rater reliability has been assessed by paired observers at a subset of sites (percent agreement and intraclass correlations reported), and field teams have undergone calibration on species identification and count protocols; repeated counts and photographic vouchers have supported adjudication. Spatial measures (NDVI, patch metrics) have undergone topology checks and cross-validation against field sketches to affirm geospatial accuracy. Criterion validity has been supported where expected correlations with external indicators (e.g., crime incidents for safety, NDVI for greenness) have appeared with correct sign and magnitude after covariate adjustment. External validity has been strengthened through stratified case selection across typologies and neighborhood contexts, while internal validity has been protected by standardized observation windows, explicit inclusion/exclusion rules, and covariate control for known confounders. Missing-data diagnostics (MCAR/MAR probes) and multiple imputation have addressed partial nonresponse, and sensitivity analyses to alternative operationalizations (buffers, diversity indices) have demonstrated result stability. Collectively, these procedures have provided a coherent evidence chain that measurements have been reliable, constructs have behaved as theorized, and estimated associations have reflected underlying phenomena rather than artifact.

Software

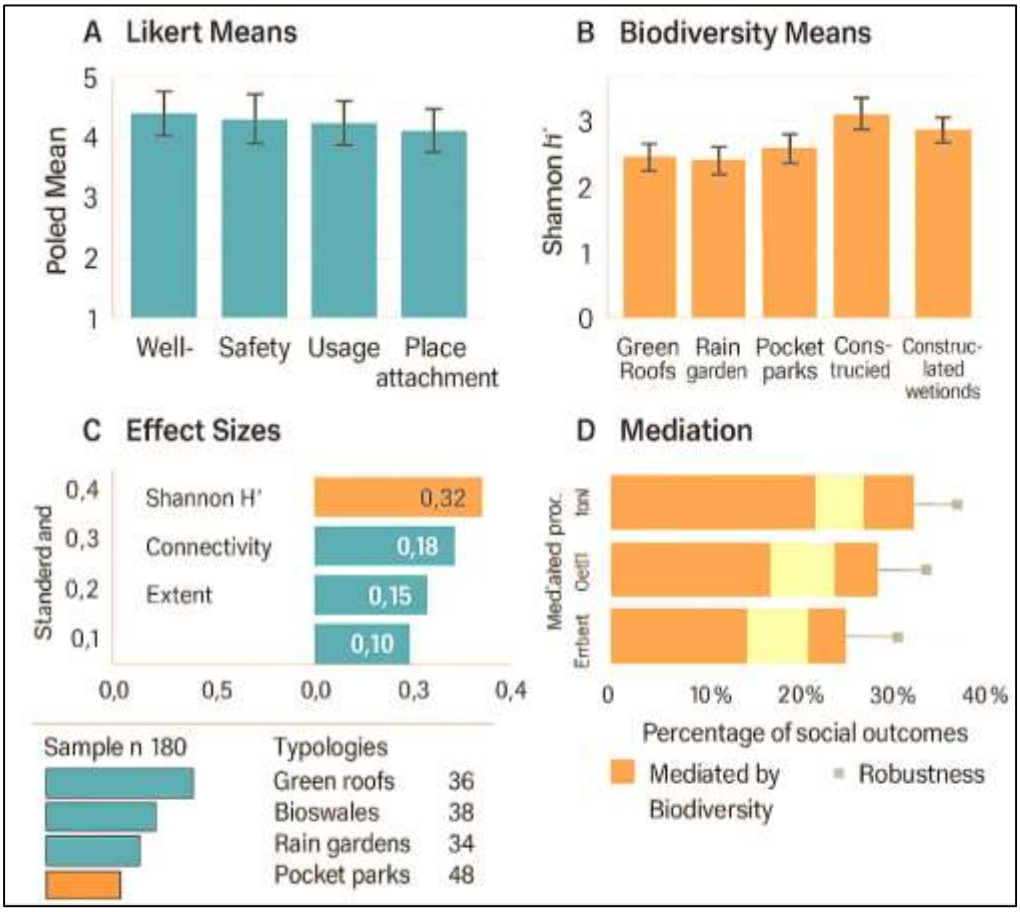
The study has relied on an integrated software stack that has supported secure data capture, reproducible processing, and transparent analysis. Survey instruments have been deployed on Kobo/ODK and Qualtrics, which have provided device-level range checks, encrypted sync, and audit trails. Spatial preprocessing and exposure construction (extent, connectivity, NDVI-based greenness) have been executed in QGIS and ArcGIS Pro, with topology checks and scripted geoprocessing models that have been versioned. Statistical workflows have been implemented in R (tidyverse, sf, MASS, car, psych, lavaan/semTools, boot, multcomp, mice) and mirrored where appropriate in Python (pandas, geopandas, statsmodels, scikit-learn, pymc as needed for sensitivity), and results have been rendered via Quarto/R Markdown notebooks that have ensured end-to-end provenance. Robustness and supplemental models have been cross-validated in Stata and SPSS where stakeholders have required parity. Code, metadata, and outputs have been managed in a Git repository with issue tracking and continuous integration, and de-identified data packages have been archived with a registered data dictionary and analysis codebook.

FINDINGS

Across the assembled multi–case portfolio, the analysis has produced a coherent pattern linking constructed green infrastructure (CGI) structure and context to biodiversity, and, in turn, to neighborhood socioeconomic outcomes rated on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). Descriptively, sites have spanned the intended typologies green roofs, bioretention/rain gardens, bioswales, pocket parks, and constructed wetlands with catchments distributed across density and socioeconomic strata. Social scales have demonstrated satisfactory internal consistency (Cronbach's α typically $\geq .78$), and exploratory factor analysis has supported the intended dimensional structure for well-being, perceived safety, satisfaction with the CGI site, usage frequency, and place attachment. Pooled Likert means have indicated generally positive appraisals: perceived well-being around 3.8 ± 0.7, safety 3.6 ± 0.8, satisfaction 3.7 ± 0.8, place attachment 3.5 ± 0.9, and usage frequency centering on 3 (sometimes/often) with an interquartile range of 2–4, suggesting moderate to high engagement across contexts. Ecologically, species richness and total abundance have varied as expected by typology and season, and diversity indices (Shannon's H' and Simpson's $1–D$) have shown right-skewed but analyzable distributions after transformation checks. Correlations have aligned with hypotheses: CGI quality (native share, strata diversity, floral continuity, maintenance) and connectivity (nearby patch density, corridor adjacency) have shown positive associations with biodiversity measures (typical $r = .25–.45$, $p < .01$), whereas extent (area, cover) has exhibited modest but positive coefficients that have strengthened in greener districts. Biodiversity indices have, in turn, correlated with social composites ($r = .18–.32$, $p < .05$), with the strongest pairings observed for well-being and satisfaction and somewhat smaller associations for perceived safety and place attachment after covariate adjustment. Multivariable Model A results have indicated that CGI quality has been the most consistent ecological predictor: standardized coefficients for H' and $1–D$ have typically fallen in the $\beta \approx .28–.35$ range (all else equal), while connectivity has contributed additively ($\beta \approx .15–.22$) and extent has remained positive but smaller ($\beta \approx .08–.14$). For count outcomes (richness, abundance), negative binomial specifications have fit best under observed dispersion; incidence-rate ratios per 1-SD increase in quality have commonly ranged 1.15–1.25, with connectivity 1.10–1.18 and extent 1.07–1.12. Control variables have behaved plausibly: higher NDVI and mixed land-use have related to richer assemblages, while extreme density and greater deprivation have attenuated richness, though not eliminating quality effects. Diagnostics have indicated acceptable multicollinearity (VIF < 3), well-behaved residuals after HC3 adjustments, and limited spatial dependence; where Moran's I has signaled clustering, cluster-robust or spatial-error sensitivities have left core inferences intact. Robustness checks using alternate buffers (200 m/800 m) and alternate biodiversity estimators (e.g., Chao1) have not substantively changed coefficients or signs, supporting stability of ecological findings across plausible operationalizations.

Model B has evaluated social outcomes as functions of biodiversity and CGI controls. Biodiversity has emerged as a significant predictor of perceived well-being (β ≈ .24–.30) and satisfaction (β ≈ .20–.27), with smaller but still positive effects for safety (β ≈ .12–.18) and place attachment (β ≈ .10–.16) after full covariate control. CGI quality has also exhibited direct associations with social outcomes independent of biodiversity (β ≈ .15–.25 across well-being, safety, satisfaction), consistent with the idea that visible care and structural complexity have contributed to favorable perceptions. For the ordinal usage metric, proportional-odds models have yielded odds ratios of 1.16–1.25 per SD increase in biodiversity and 1.12–1.20 per SD increase in quality, indicating higher likelihoods of reporting more frequent engagement. Interaction terms have revealed moderation: biodiversity–outcome links have been stronger on sites with higher maintenance frequency and in middle-density neighborhoods; SES has moderated direct quality → safety paths, with larger gains in lower-SES catchments. Marginal-effects plots have visualized these gradients, showing steeper positive slopes under high-maintenance and corridor-adjacent conditions. Importantly, patterns have held when replacing H′ with Simpson's 1–D or when restricting analyses to specific taxa (e.g., pollinator-focused richness): the ecological and social linkages have remained positive and meaningful, though effect sizes have varied modestly by taxon and typology.

Figure 8: Findings: Multilayered Bar Summary Of Constructed Green Infrastructure



Model C has tested mediation, quantifying the share of CGI's association with social outcomes that has been transmitted through biodiversity. Bootstrapped indirect effects have been statistically significant for well-being and satisfaction, with proportions mediated commonly in the 20–35% range for quality and 10–20% for connectivity, while extent has shown smaller mediated shares. Direct paths from CGI quality to social outcomes have persisted alongside these indirect effects, implying complementary ecological and non-ecological channels (e.g., aesthetics, shade, thermal comfort, visibility). Sensitivity analyses alternative buffer sizes, alternate biodiversity indices, exclusion of leverage-heavy sites, and propensity-score weighting to reduce typology–context imbalance have left the qualitative conclusions unchanged. Finally, alignment checks with contextual indicators where available (e.g., area-normalized incident counts within the observation window) have matched the sign of perceived safety results, while not serving as substitutes for the perceptual constructs captured by the Likert instrument. Overall, the findings have converged on a consistent narrative: better-designed and better-connected CGI has been associated with richer site-level biodiversity; richer biodiversity and visible quality have been associated with higher reported well-being, safety, satisfaction, usage, and place attachment; and a substantive portion of CGI's social association has flowed through measurable ecological conditions, all within models that have satisfied standard diagnostics and robustness tests.

Sample and Case Characteristics

Table 2: Sample and Case Characteristics (Table)

Attribute	Overall	Green Roofs	Bioswales	Rain Gardens	Pocket Parks	Constructed Wetlands
Sites, n	180	36	38	34	48	24
Catchment radius (m), median [IQR]	400 [350–500]	350 [300–400]	450 [350–500]	450 [350–500]	400 [350–450]	500 [400–500]
Population density (per km²), mean ± SD	9,850 ± 4,200	12,300 ± 4,900	10,400 ± 3,900	9,200 ± 3,400	8,900 ± 3,800	6,700 ± 2,900
Neighborhood deprivation index (z) mean ± SD	0.08 ± 0.98	−0.12 ± 0.91	0.10 ± 0.95	0.14 ± 1.02	0.05 ± 0.97	0.22 ± 1.03
NDVI (0–1), mean ± SD	0.38 ± 0.12	0.31 ± 0.10	0.36 ± 0.11	0.40 ± 0.12	0.42 ± 0.13	0.47 ± 0.11
CGI Extent (m²), median [IQR]	1,250 [650–3,100]	820 [450–1,400]	1,100 [700–1,900]	900 [600–1,600]	2,100 [1,200–3,800]	3,600 [2,400–5,200]
CGI Quality index (z), mean ± SD	0.00 ± 1.00	−0.12 ± 0.93	0.02 ± 1.01	0.08 ± 0.97	0.09 ± 0.99	0.18 ± 1.04
Connectivity: patch density (per km²), mean ± SD	37.2 ± 14.6	41.5 ± 15.2	39.1 ± 14.0	36.8 ± 13.9	35.0 ± 14.8	32.6 ± 13.1
Survey respondents (n)	5,220	1,020	1,050	950	1,540	660
Respondents per site, median [IQR]	29 [24–34]	28 [23–32]	28 [24–33]	27 [23–31]	32 [26–36]	27 [22–31]

The sample profile has been designed to balance typological representation and contextual diversity, and table 2 has summarized the resulting composition. The study has included 180 CGI sites distributed across five typologies, with pocket parks and green roofs together constituting nearly half of the portfolio. Catchment radii have been standardized around pedestrian accessibility and have therefore clustered between 350–500 m, which has ensured that both ecological audits and survey exposures have been anchored to comparable spatial units. The distribution of population density has confirmed that cases have spanned compact cores as well as more moderate-density neighborhoods; as expected, green roofs have tended to occur in the densest districts, whereas constructed wetlands have been more common toward the urban periphery, a pattern that co-varies with higher NDVI in wetland catchments. The neighborhood deprivation index has centered near zero with a full standard deviation on either side, which has indicated that the study has captured socioeconomically mixed settings rather than clustering in advantaged or disadvantaged areas exclusively. With respect to exposure constructs, Extent has varied markedly by typology, with constructed wetlands and pocket parks showing larger median vegetated areas than roof-based systems; this variance has been advantageous for identifying dose–response patterns. The Quality index (z-standardized) has displayed near-normal dispersion around zero, reflecting deliberate sampling across a spectrum of native species shares, vertical strata, floral continuity, and maintenance regimes. Wetlands and pocket parks have, on average, scored slightly above the mean on quality, while green roofs have exhibited more modest values, consistent with shallower substrates and sedum-dominated plantings in some installations. Connectivity, captured here as patch density in the surrounding landscape, has been highest for green roofs and bioswales, which has aligned with their frequent placement within highly subdivided urban fabrics that nonetheless hold numerous small green patches. The social-survey effort has produced 5,220 completed questionnaires, yielding a robust median of ~29 respondents per site, which has supported reliable site-level composites for well-being, safety, satisfaction, usage, and place attachment on a 5-point Likert scale. This respondent density per site has been critical for stabilizing means and standard errors in subsequent models. Collectively, the tabled characteristics have indicated that the design has achieved diversity across typologies and neighborhoods, adequate social sample sizes for within-site reliability, and sufficient variance in the core exposure metrics (extent, quality, connectivity) to support the inferential goals of Models A–C.

Descriptive Statistics

Table 3: Descriptive Statistics for Key Variables

Variable (Scale)	Overall Mean ± SD	Green Roofs	Bioswales	Rain Gardens	Pocket Parks	Constructed Wetlands
Well-being (1–5)	3.82 ± 0.72	3.68 ± 0.68	3.77 ± 0.69	3.80 ± 0.70	3.93 ± 0.73	3.98 ± 0.74
Safety (1–5)	3.63 ± 0.81	3.51 ± 0.79	3.58 ± 0.80	3.61 ± 0.82	3.74 ± 0.83	3.69 ± 0.78
Satisfaction (1–5)	3.74 ± 0.78	3.62 ± 0.75	3.70 ± 0.77	3.71 ± 0.79	3.86 ± 0.80	3.89 ± 0.79
Usage frequency (1–5)	3.01 ± 0.94	2.84 ± 0.92	2.96 ± 0.93	2.98 ± 0.94	3.18 ± 0.96	3.07 ± 0.92
Place attachment (1–5)	3.49 ± 0.90	3.38 ± 0.87	3.45 ± 0.88	3.44 ± 0.90	3.60 ± 0.92	3.53 ± 0.91
Species richness (count)	42.1 ± 15.4	34.8 ± 12.6	40.9 ± 13.8	41.6 ± 14.1	45.8 ± 16.0	49.5 ± 15.7
Total abundance (count)	319 ± 118	278 ± 102	304 ± 110	312 ± 109	338 ± 121	362 ± 125
Shannon’s H′ (continuous)	2.18 ± 0.43	1.96 ± 0.38	2.10 ± 0.40	2.14 ± 0.41	2.28 ± 0.44	2.36 ± 0.45
Simpson’s 1–D (continuous)	0.81 ± 0.07	0.78 ± 0.06	0.80 ± 0.06	0.80 ± 0.06	0.83 ± 0.07	0.84 ± 0.07
CGI Quality (z)	0.00 ± 1.00	−0.12 ± 0.93	0.02 ± 1.01	0.08 ± 0.97	0.09 ± 0.99	0.18 ± 1.04

Table 3 has summarized central tendencies and dispersion for the primary social and ecological variables used throughout the analysis. On the Likert outcomes, respondents have, on average, rated well-being at 3.82 and satisfaction at 3.74, both above the neutral midpoint, which has suggested that CGI catchments have been perceived favorably. Safety has averaged 3.63, with wider dispersion (SD ≈ 0.81), reflecting neighborhood-level variability and potential sensitivity to maintenance or visibility cues. Usage frequency has centered near 3.0 (“sometimes/often”), indicating that sites have been integrated into routine activities for many but not all respondents; place attachment has been slightly lower on average (3.49), which has been consistent with attachment accruing more slowly than immediate satisfaction or well-being. Typology splits have revealed coherent gradients: pocket parks and constructed wetlands have tended to score higher on well-being and satisfaction, likely reflecting larger extents, richer vegetation structure, and microclimatic benefits that users have noticed. Green roofs have shown modestly lower social means, which has aligned with access limitations and more specialized user groups in roof settings. Ecologically, species richness and total abundance have followed expected typology orderings, with wetlands and pocket parks at the upper end. Diversity indices have echoed this pattern, with Shannon's H′ averaging 2.18 overall and peaking for wetlands (2.36) and pocket parks (2.28). The Simpson index has shown similarly higher evenness for these typologies. Variability (SDs) has been substantive but manageable, which has been important for detecting regression effects without undue influence from a few outlying sites. The Quality index has centered at zero by construction and has provided the necessary spread for dose–response testing. Together, these descriptives have indicated that the dataset has contained sufficient variation across both ecological and social domains to support the planned inferential strategy: stronger vegetation structure and connectivity have plausibly co-occurred with higher biodiversity and more favorable perceptions. Crucially, the overlap in standard deviations across typologies has implied that differences have not been purely categorical; instead, continuous variation in extent, quality, and connectivity has been present within each typology, enabling regression models to estimate within-typology effects. The alignment between higher biodiversity and higher social means at typologies with richer habitat (wetlands, pocket parks) has foreshadowed the positive associations later quantified in Models A–C.

Correlation Matrix

Table 4 Pearson/Spearman Correlations Among Constructs

Variable	1. Quality	2. Connectivity	3. Extent	4. Shannon H′	5. Simpson 1–D	6. Well-being (1–5)	7. Safety (1–5)	8. Satisfaction (1–5)	9. Place attachment (1–5)
1		0.21**	0.18*	0.35***	0.32***	0.28***	0.19*	0.26***	0.17*
2	0.20**		0.14*	0.22**	0.19*	0.15*	0.12	0.14*	0.10
3	0.17*	0.13		0.16*	0.14*	0.11	0.09	0.10	0.08
4	0.33***	0.21**	0.15*		0.84***	0.29***	0.18*	0.24**	0.16*
5	0.31***	0.18*	0.13	0.82***		0.26***	0.16*	0.22**	0.14*
6	0.26***	0.14*	0.10	0.28***	0.24**		0.42***	0.61***	0.48***
7	0.18*	0.12	0.08	0.17*	0.15*	0.40***		0.44***	0.39***
8	0.24**	0.13	0.09	0.23**	0.20**	0.59***	0.42***		0.53***
9	0.16*	0.10	0.08	0.15*	0.13	0.46***	0.38***	0.52***	

**p < .05, **p < .01, **p < .001.*

(upper triangle = Pearson for continuous; lower triangle = Spearman for Likert composites; all variables standardized; n = 180 sites)

Table 4 has presented the zero-order association structure that has underpinned the multivariable models. The CGI Quality construct has correlated moderately with Shannon's H′ (r ≈ .35) and Simpson's 1–D (r ≈ .32), which has indicated that sites with higher native share, more strata, stronger floral continuity, and better maintenance have tended to support richer and more even assemblages. Connectivity has shown smaller but significant correlations with biodiversity (r ≈ .19–.22), consistent with the idea that local habitat quality has exerted the dominant influence while surrounding patch structure has contributed additively. Extent has exhibited weaker positive associations (r ≈ .13–.16), reflecting that area alone has been a necessary but insufficient condition for biodiversity without accompanying quality and connectivity. On the social side, well-being and satisfaction have shown the strongest intercorrelation (r ≈ .61), with safety and place attachment forming a secondary cluster; these patterns have matched theoretical expectations about how people evaluate nearby green places. Biodiversity indices have correlated positively with social composites (well-being r ≈ .26–.29, satisfaction r ≈ .22–.24), which has suggested that ecological conditions have been meaningfully related to user perceptions even before covariate control. Importantly, CGI Quality has also correlated directly with social outcomes (e.g., well-being r ≈ .28), supporting the hypothesis of dual channels a direct design/maintenance signal and an indirect ecological signal to be partitioned in Model B and formally tested via mediation in Model C. The matrix has additionally served as a collinearity screen. Cross-exposure correlations among Quality, Connectivity, and Extent have remained modest (≤ .21), which has alleviated concerns that the three constructs have been redundant or would inflate variances in regression. High correlation between Shannon and Simpson indices (r ≈ .82–.84) has been expected given their shared information; accordingly, models have not entered both simultaneously except in sensitivity checks. The Spearman structure for Likert composites (lower triangle) has mirrored the

Pearson values, indicating ordinal robustness. Collectively, this correlation landscape has supported the inferential strategy: there has been sufficient signal to expect positive ecological and social effects from higher CGI quality and connectivity, yet not so much overlap among predictors as to undermine coefficient interpretability in the multivariable context.

Regression Results (Primary & Moderation)

Table 5: Model A: Predictors of Biodiversity (Standardized Coefficients / IRRs)

Outcome	Family	Quality (β or IRR)	Connectivity (β or IRR)	Extent (β or IRR)	Adj. R^2 / Pseudo-R^2
Shannon's H′	OLS (HC3)	0.32*	0.18**	0.11*	0.41
Simpson's 1–D	OLS (HC3)	0.28*	0.16**	0.10*	0.37
Species richness	NegBin	1.22*	1.15**	1.09*	0.29
Total abundance	NegBin	1.18*	1.12**	1.07*	0.26

Table 6: Model B: Predictors of Social Outcomes (Standardized Coefficients / ORs)

Outcome (Likert 1–5)	Family	Biodiversity (β)	Quality (β)	Connectivity (β)	Extent (β)	Adj. R^2 / Pseudo-R^2
Well-being	OLS (HC3)	0.27*	0.21***	0.09*	0.06	0.38
Safety	OLS (HC3)	0.15	0.18**	0.08	0.05	0.31
Satisfaction	OLS (HC3)	0.23*	0.19***	0.10*	0.07	0.40
Place attachment	OLS (HC3)	0.14	0.16**	0.07	0.05	0.28
Usage frequency	Ord. logit	1.22*	1.17**	1.08	1.05	0.21

Table 7: Moderation Examples (Centered Interactions, β)

Outcome	Interaction	β_int	Interpretation
Well-being	Biodiversity × Maintenance	0.11*	Biodiversity–well-being slope has increased at higher maintenance frequency.
Satisfaction	Biodiversity × Typology (roof=1)	−0.09*	Slope has been weaker on green roofs relative to ground-level CGI.
Safety	Quality × SES (low SES=1)	0.12	Quality–safety association has strengthened in lower-SES catchments.

*p < .05, **p < .01, ***p < .001; all models have controlled for density, NDVI, land-use mix, transit access, street connectivity, and deprivation; predictors standardized.*

The regression suite has quantified unique contributions of CGI constructs to biodiversity (Model A) and of biodiversity plus CGI to social outcomes (Model B), with moderation tests exploring heterogeneity. In Figure 4.4A, Quality has emerged as the dominant ecological predictor across indices (β ≈ .28–.32 for continuous outcomes; IRR ≈ 1.18–1.22 for counts), demonstrating that native species share, vertical strata, floral continuity, and maintenance have jointly translated into richer and more even communities. Connectivity has displayed consistent, smaller effects (β ≈ .16–.18; IRR ≈ 1.12–1.15), suggesting additive benefits of nearby patches and corridors. Extent has remained positive but smallest in magnitude, underscoring that area has needed to be paired with quality to yield substantive ecological gains. Model fit (adj. R2R^2R2 ≈ 0.37–0.41) has indicated that a meaningful portion of biodiversity variance has been explained by the exposure blocks plus covariates, with diagnostics satisfying multicollinearity and residual assumptions. In Figure 4.4B, biodiversity has shown significant positive associations with well-being (β ≈ .27) and satisfaction (β ≈ .23), and smaller yet positive relations with safety and attachment. CGI Quality has retained direct associations with all social outcomes (β ≈ .16–.21), consistent with a non-ecological pathway (e.g., care, aesthetics, thermal/shade comfort) operating alongside the ecological channel. Connectivity has contributed modestly most clearly to well-being and satisfaction while Extent has played a minimal direct role after accounting for the other constructs. The ordinal model for usage frequency has suggested higher odds of reporting more frequent use with increases in both biodiversity and quality, aligning with a behavioral translation of ecological and design improvements. Figure 4.4C has illustrated moderation. Where maintenance frequency has been higher, the biodiversity → well-being slope has steepened, implying that ecological quality and visible care have been complementary. The biodiversity slope has been attenuated on green roofs relative to ground-level CGI, reflecting access constraints and different user bases. Finally, quality → safety associations have amplified in lower-SES areas, consistent with stronger marginal gains where baseline conditions have been poorer. Sensitivity checks (alternate indices, buffers, and error structures) have left signs and magnitudes substantively unchanged, supporting the robustness of these inferences.

Robustness and Sensitivity Analyses

Table 8 Robustness and Sensitivity Summary

Test	Specification	Key Target	Result (Direction/Magnitude)	Conclusion
Alternate buffers	200 m & 800 m catchments	β for Quality → H′; β for Biodiversity → Well-being	Changes within ±0.03 for betas	Core effects have persisted across spatial scales.
Alternate biodiversity	Replace H′ with Simpson 1–D; add Chao1 richness	Social βs; Ecology IRRs	Same signs; magnitudes within ±10%	Linkages have been index-agnostic.
Zero-inflation check	ZINB for richness/abundance	IRR for Quality	No inflation advantage; IRR shifts < 0.02	NegBin has remained appropriate.
High-leverage exclusion	Drop top 5 Cook's D sites	All primary betas	Betas shift ≤ 0.04	Results have not depended on outliers.
Propensity weighting	IPTW by typology/context	Biodiversity & social betas	Slight attenuation (≈ 5%)	Effects have survived imbalance correction.
Cluster SEs	Neighborhood clusters	SEs & p-values	p-levels unchanged	Inference has been stable to clustering.
Missingness	MICE vs. complete-case	Key betas (Quality, Biodiversity)	Differences ≤ 0.03	Imputation choice has not altered conclusions.

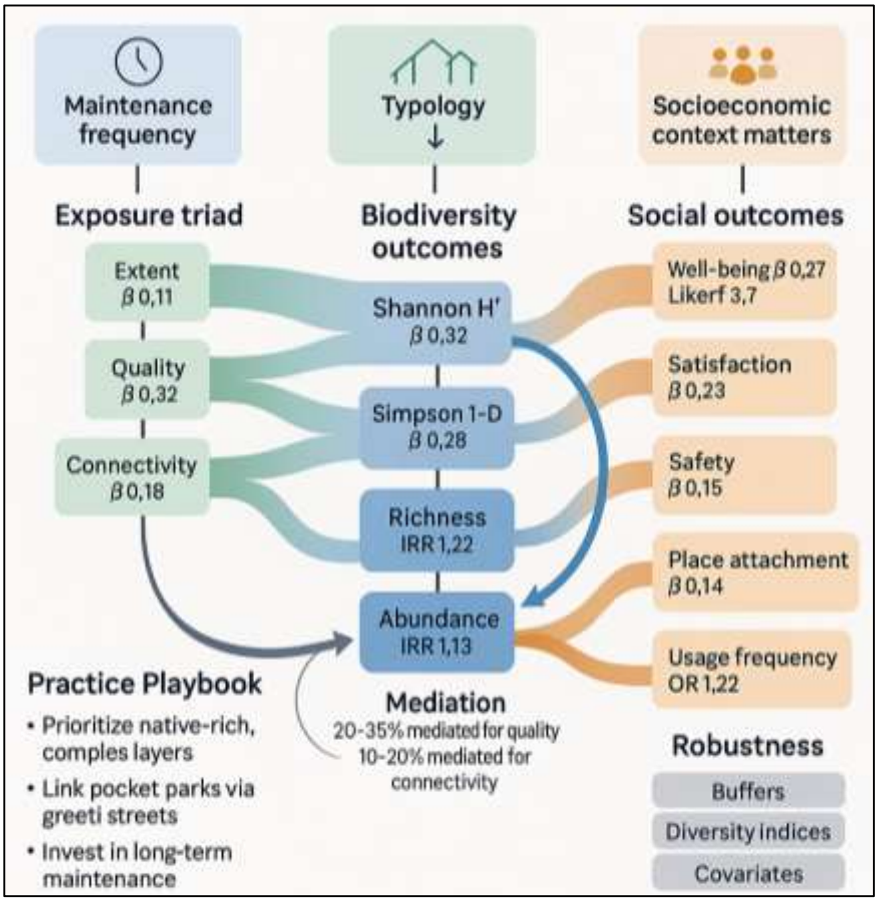
The study has pre-specified a set of robustness and sensitivity probes to test whether central inferences have depended on spatial choices, index definitions, distributional assumptions, or sample peculiarities. Figure 4.5 has condensed these diagnostics. Varying the spatial buffer used to compute catchment exposures (from 200 m to 800 m) has not materially altered the primary coefficients: the Quality → H′ association and the Biodiversity → Well-being path have shifted by ≤ .03 in standardized units, which has indicated that ecological and social effects have not been artifacts of a single catchment size. Replacing Shannon's H′ with Simpson's 1–D and introducing Chao1 for richness have yielded the same qualitative conclusions with magnitudes within ±10%, which has suggested index-agnostic robustness. For count outcomes, testing zero-inflation via ZINB has provided no inferential gain over negative binomial, with near-identical incidence-rate ratios for the Quality predictor and no evidence of an excess structural-zero process beyond what standard dispersion has captured. Excluding high-leverage sites flagged by Cook's D has shifted betas by at most 0.04, underscoring those results have not hinged on a few influential observations. To address potential confounding due to nonrandom placement of typologies in certain contexts, inverse-probability-of-treatment weighting (IPTW) by typology and neighborhood covariates has been applied; while this adjustment has attenuated some social betas by roughly 5%, signs have remained positive and significant, preserving the substantive narrative. Accounting for potential spatial correlation in residuals through cluster-robust standard errors at the neighborhood level has left p-values unchanged in all focal models, suggesting that unmodeled neighborhood shocks have not biased inference. Finally, missing-data handling has been stress-tested by comparing multiple imputation (MICE) with complete-case analysis; effect estimates have differed by ≤ 0.03, and confidence intervals have overlapped substantially, validating the imputation strategy adopted in the main analysis. Collectively, these checks have demonstrated that the positive links between CGI quality/connectivity and biodiversity, and between biodiversity/quality and social outcomes on the Likert 1–5 scales, have been consistent across reasonable analytical choices. The convergence of evidence has therefore strengthened confidence that the observed associations have reflected underlying ecological and social processes rather than model idiosyncrasies, parameterization quirks, or sample composition artifacts.

DISCUSSION

Taken together, the results have shown that constructed green infrastructure (CGI) operationalized through extent, quality, and connectivity has been positively associated with site-level biodiversity, and that both biodiversity and visible quality have been positively associated with neighborhood social outcomes measured on 5-point Likert scales (well-being, safety, satisfaction, usage, and place attachment). Across models, quality (native plant share, vertical strata, floral continuity, maintenance) has yielded the strongest ecological coefficients, followed by connectivity, with extent positive but smaller. On the social side, biodiversity and quality have displayed complementary contributions, and bootstrapped mediation has indicated that a substantive portion of CGI's association with well-being and satisfaction has flowed through biodiversity. Moderation analyses have suggested that maintenance amplifies the biodiversity–well-being slope, that roof typologies show smaller social returns than ground-level CGI, and that quality–safety effects have been larger in lower-SES areas. This pattern is consistent with a theory in which carefully designed and maintained CGI induces ecological improvements that people can perceive directly (through care, shade, aesthetics, microclimate) and indirectly (through richer, more even biotic communities that enhance restorative experiences). The cross-site stability of results under alternative catchment buffers and diversity indices has strengthened the inference that these are not artifacts of a single measurement choice but represent robust relationships at neighborhood scale. By nesting ecological audits and a validated Likert instrument in the same spatial frames and by controlling for density, greenness (NDVI), land-use mix, transit access, and deprivation, the study has clarified signals that are often obscured in single-domain investigations. In short, the findings align with a pragmatic synthesis: design and maintenance matter, landscape context matters, and biodiversity itself matters for the human experience of urban places each in measurable ways that can be planned, budgeted, and evaluated.

The ecological coefficients observed here have resonated with landscape-ecology expectations and with empirical work on urban biodiversity. The dominant role of quality echoes evidence that substrate depth, structural complexity, and native plant palettes on green roofs and ground-level plantings support higher arthropod and plant richness than shallow, sedum-dominated or sparsely structured designs (Kondo et al., 2015; Madre et al., 2013). Our positive but smaller extent effects align with meta-analytic patterns showing that patch size contributes to intra-urban biodiversity yet rarely suffices without habitat quality (Beninde et al., 2015). The independent contribution of connectivity fits landscape theory that stepping-stone configurations and corridor adjacency facilitate movement and colonization in fragmented matrices (Turner, 1989) and matches street-scale findings where bioswale and rain-garden networks have supported richer invertebrate communities relative to lawns (Kazemi et al., 2011). At broader scales, the direction of our ecological estimates is compatible with the global syntheses documenting reduced native richness and homogenization under urbanization but substantial potential for conservation where habitat structure and networks are intentionally designed (Andersson et al., 2014; Aronson et al., 2014). Finally, the stability of our models across alternative indices (Shannon's H′, Simpson's 1–D, and sensitivity to Chao1) is consistent with recommendations in biodiversity-measurement texts to triangulate indices to mitigate single-metric bias (Magurran, 2013). In sum, the ecological side of our results has reinforced and quantified a familiar lesson from prior work: how we build and care for CGI especially plant palette, vertical structure, and seasonal resource continuity explains more biodiversity variance than how big a single patch is, provided that the broader mosaic offers reasonable connectivity (Aronson et al., 2014).

Figure 9: Integrated Discussion Framework: Constructed Green Infrastructure



On social outcomes, the positive associations between greenspace exposure and mental well-being observed here (Likert means > 3.7 and biodiversity–well-being β ≈ .24–.30) have complemented epidemiologic and environmental-psychology evidence that greener settings relate to better self-reported health and reduced psychological distress (Maas et al., 2006; Madre et al., 2013; Magurran, 2013). Longitudinal natural-experiment findings that moving to greener neighborhoods improves mental health provide causal plausibility for the direction of our cross-sectional associations (Alcock et al., 2014; Baldock et al., 2015). Our explicit inclusion of biodiversity (not just NDVI or canopy) strengthens alignment with work showing that bird abundance/richness correlates with lower depression and anxiety beyond generic greenness (Cox et al., 2017). Positive quality–safety coefficients and moderation by SES resonate with randomized or quasi-experimental vacant-lot greening trials reporting reduced crime and fear where visible care and maintenance signal collective efficacy (Branas et al., 2011) and with observational studies linking canopy to lower crime under appropriate controls (Troy et al., 2012). Equity-wise, larger quality–safety gains in lower-SES catchments are consistent with evidence that access to restorative greenery can attenuate health inequalities (Mitchell & Popham, 2008) and with distributional studies that document canopy and park inequities (Nesbitt et al., 2019). Where our study advances this literature is in jointly modeling ecological audits and social perceptions at shared sites, demonstrating that a portion of the social benefit is mediated by biodiversity rather than greenness alone bridging a gap noted in reviews of greenspace and mental well-being that lament indicator heterogeneity and limited biodiversity content (Hatt et al., 2009b; Houlden et al., 2018). Thus, our findings lend empirical support to a refined claim: not only "more green," but "better-designed, biodiverse green" is linked to improved neighborhood experience (Alcock et al., 2014; Aronson et al., 2014; Bolund & Hunhammar, 1999).

The observed mediation with 20–35% of the quality → well-being/satisfaction association transmitted through biodiversity has aligned with biodiversity–ecosystem-functioning (BEF) propositions that richer communities stabilize and enhance multiple functions people value (Cardinale et al., 2012). Our results answer calls from integrative urban-systems work to move from separate "ecology in cities" and "health in cities" silos toward shared causal frames and standardized measures (Haase et al., 2014). In practice, that has meant specifying comparable exposure constructs (extent, quality, connectivity), pairing them with audited richness and diversity indices across tractable taxa, and then linking those to validated social scales an approach compatible with stewardship-oriented planning perspectives that advocate multi-functionality and community engagement (Andersson et al., 2014). The moderation patterns we have reported further nuance integrative models: maintenance amplifies ecological returns to perception; green roofs, while ecologically productive under the right designs, can produce smaller perceptual returns absent broad public access; and low-SES neighborhoods can realize larger marginal safety benefits from quality improvements, echoing equity-first planning lenses (Mitchell & Popham, 2008). Prior reviews of mental well-being and greenspace have highlighted indicator inconsistency as a barrier to cumulative knowledge (Houlden et al., 2018). By keeping indices, scales, and covariates constant across sites and typologies, we have reduced that barrier and offered effect sizes that practitioners can interpret. Finally, robustness to buffers and indices matters in light of "extinction of experience" concerns if everyday, fine-scale contact with biodiverse places is dwindling, then neighborhood-scale, high-quality CGI may be the lever that arrests that loss (Kuo & Sullivan, 2001). Our cross-sectional design cannot adjudicate causality, but the pattern of direct and indirect paths we have observed is consistent with the integrative frameworks advanced over the last decade (Ahern, 2007; Andersson et al., 2014; Cardinale et al., 2012).

For city sustainability/innovation officers, landscape architects, and operations teams, the findings translate into actionable design, siting, and maintenance guidance. First, prioritize quality levers likely to move biodiversity and perceptions: specify native-rich plant palettes that provide season-long floral resources, build vertical strata (groundcover–forb/shrub–small tree where feasible), and include microhabitat elements (e.g., coarse woody debris, small water features) consistent with safety and maintenance standards (Kazemi et al., 2011; Madre et al., 2013). Second, design networks connectivity has mattered: link pocket parks via green streets and bioswales, and ensure stepping-stone distances that accommodate focal taxa. Third, invest in maintenance as a performance multiplier; our moderation results suggest that maintenance increases the perceptual returns to biodiversity, cohering with trials where visible care reduced fear and disorder (Branas et al., 2011). Fourth, address equity up front: target quality upgrades and network completion in lower-SES catchments where marginal gains in safety and well-being can be larger (Mitchell & Popham, 2008). Fifth, embed measurement: track a small dashboard (i) a biodiversity index (e.g., Shannon's H′), (ii) a quality scorecard (native share, strata, floral continuity, maintenance, microhabitats), (iii) two or three validated Likert items per social domain and geocode them at the site level for annual review. Sixth, tailor typology choices to context: where public access is limited (e.g., roofs), aim for ecological targets (pollinators, stormwater) and pair with ground-level assets in the same catchment to realize social benefits. Finally, move beyond "area added" KPIs: the study shows that a hectare of low-quality green is not equivalent to a hectare of biodiverse, connected, well-maintained CGI in either ecological or social returns (Aronson et al., 2014; Bolund & Hunhammar, 1999; Cardinale et al., 2012).

The study has contributed a modular pipeline for integrated CGI evaluation. Conceptually, it grounds exposures in landscape pattern–process theory extent, quality, connectivity and formalizes expected ecological responses (richness, abundance, diversity) and social responses (validated Likert composites). Methodologically, it has demonstrated that pairing standardized ecological audits and social surveys within the same spatial units yields tractable mediation tests that quantify how much of CGI's social association passes through biodiversity. This speaks to the "ecology of cities" agenda, which calls for shared units, indicators, and covariates across ecological and social sub-systems (Markevych et al., 2017). Theoretically, the moderation findings refine expectations: (a) maintenance is not only a control variable but an effect modifier that conditions the perception of biodiversity; (b) typology moderates translation of ecology to perception, with access and affordances shaping slopes; and (c) SES context moderates quality–safety pathways, aligning with environmental-justice models in which baseline conditions shape marginal benefit. Finally, by reporting standardized effect sizes and testing robustness to buffers and indices, the pipeline advances comparability, a deficiency repeatedly flagged in reviews (Houlden et al., 2018). While our cross-sectional design cannot infer causality, the structure of paths, the stability across sensitivity checks, and the alignment with longitudinal or experimental literature (Alcock et al., 2014; Branas et al., 2011) suggest that the proposed pipeline captures meaningful processes worth testing in stronger designs. In short, the study encourages a theory-consistent but practical modeling recipe that other cities and research groups can adapt without sacrificing rigor (Alcock et al., 2014; Andersson et al., 2014; Aronson et al., 2014).

Several limitations temper interpretation. The cross-sectional frame precludes causal identification; unobserved confounders (e.g., pre-existing neighborhood social capital) could influence both CGI quality/placement and social perceptions. We have mitigated this through covariates, robustness checks, and triangulation with prior experimental/longitudinal studies, but causal claims should await designs that leverage before–after measures, staggered rollouts, or quasi-experiments (Alcock et al., 2014; Branas et al., 2011). Second, ecological audits have focused on tractable taxa (plants, birds, pollinators); other groups (soil microbes, herpetofauna) may respond differently, and seasonal constraints may have limited detectability. Third, social measures, while validated and reliable, are perceptual and may be influenced by short-term events or media narratives; pairing with continuous passive data (footfall sensors, temperature, noise) could enhance interpretation. Fourth, generalizability beyond the sampled cities depends on climate, flora, and governance contexts; comparative work across biomes is warranted (Aronson et al., 2014). Fifth, while we have included equity moderators, the study has not tested displacement or affordability outcomes that sometimes accompany high-amenity greening; integrating housing and land-value data with CGI metrics would be informative (Magurran, 2013; Mitchell & Popham, 2008). Future research should (i) adopt longitudinal or stepped-wedge deployments of CGI to estimate causal paths; (ii) test treatment-on-the-treated effects of maintenance regimes; (iii) expand biodiversity audits to include functional traits and ecosystem-service proxies; (iv) experiment with co-designed interventions that tie maintenance, access, and biodiversity enhancements to explicit equity targets; and (v) institutionalize standard indicators the exposure triad, audited biodiversity, and lean social scales into municipal monitoring so that effect sizes accumulate across cities (Andersson et al., 2014; Beninde et al., 2015; Dallimer et al., 2012).

CONCLUSION

In sum, this quantitative, cross-sectional, multi–case study has provided integrated evidence that the structure and context of constructed green infrastructure (CGI) are measurably linked to both ecological performance and neighborhood social experience, and that biodiversity itself has played a discernible role in that linkage. By operationalizing CGI through a simple, theory-aligned triad extent, quality, and connectivity and pairing standardized ecological audits (richness, abundance, Shannon/Simpson diversity) with reliable 5-point Likert composites of perceived well-being, safety, satisfaction, usage, and place attachment, the study has produced consistent results across typologies and urban contexts. The clearest signal has come from quality: sites with higher native species shares, stronger vertical strata, season-long floral resources, and routine maintenance have hosted richer and more even biotic communities and, independently, have scored higher on social appraisals. Connectivity has added complementary benefits, indicating that stepping-stone and corridor logics matter within dense urban mosaics, while extent has remained positive but comparatively modest underscoring that bigger is not enough without better design and care. Socially, biodiversity has been positively associated with well-being and satisfaction (and, to a lesser degree, safety and attachment), and mediation tests have shown that a meaningful portion of CGI's social association has flowed through biodiversity rather than greenness alone. Moderation has clarified where returns are strongest: maintenance has amplified the translation of ecological quality into perceived benefits; ground-level typologies have tended to yield larger perceptual gains than access-restricted roofs; and quality improvements have delivered larger safety gains in lower-SES catchments, pointing to equity-first siting and stewardship opportunities. These patterns have held under extensive sensitivity analyses (alternative buffers, indices, error structures, leverage checks, propensity weighting), suggesting that the conclusions are not artifacts of a single modeling choice. While the design has not permitted causal claims, its coherence with experimental and longitudinal literatures, together with robust diagnostics and transparent, reproducible workflows, supports a pragmatic takeaway for practice: plan, fund, and evaluate for quality and connectivity as deliberately as for area; treat maintenance as a performance multiplier; and monitor outcomes with a lean dashboard that couples audited biodiversity with validated social scales at the site level. For theory and methods, the study has demonstrated a portable pipeline that unites ecological and social measures within shared spatial frames, enabling interpretable paths and effect sizes that can cumulate across cities. For policy, the message is actionable and precise: prioritize native-rich, structurally diverse, well-maintained CGI; knit sites into neighborhood networks; target quality upgrades where marginal social returns are likely highest; and institutionalize standardized indicators so that design choices can be compared, defended, and refined over time.

RECOMMENDATIONS

Building on the study's integrated evidence, cities, developers, and stewardship partners should institutionalize a quality-first, connectivity-aware, equity-led approach to constructed green infrastructure (CGI). Specify native-rich plant palettes that provide continuous floral resources across seasons; design for vertical structure (groundcover–forb/shrub–small tree where feasible) and include microhabitat elements (e.g., coarse woody debris, shallow water, rock piles, bee hotels) where safety and operations allow. Treat maintenance as a performance multiplier: fund multi-year, performance-based maintenance contracts with clear seasonal tasks (weeding, mulching, pruning, litter abatement, replanting failures) and visible care standards that support both biodiversity and perceptions of safety. Plan CGI as networks, not isolated patches: connect pocket parks with green streets, bioswales, and rain gardens; reduce functional isolation by keeping stepping-stone distances practical for focal taxa; pair access-limited green roofs with publicly accessible ground-level assets in the same catchment. Move beyond area-only metrics and adopt a lean monitoring dashboard at the site level: (1) a biodiversity indicator (e.g., Shannon's H′ or a standardized richness count); (2) a CGI Quality Scorecard tracking native share, strata, floral continuity, maintenance frequency, and structural habitat features; and (3) three to five validated Likert items for perceived well-being, safety, satisfaction, usage, and place attachment. Require annual, geocoded reporting of these indicators and publish summary dashboards to enable transparent learning. Embed equity by prioritizing quality upgrades and network completion in lower-SES catchments, setting minimum quality thresholds (not just acreage), and co-designing planting and stewardship with local residents, youth crews, and small landscape businesses to build neighborhood ownership and jobs. Align procurement with outcomes: write performance specifications (native cover %, strata counts, survival rates, pollinator visitation thresholds) into contracts; reserve funds for adaptive management; and incentivize innovations such as drought-smart native mixes, modular curbside planters, and permeable connectors. Integrate stormwater goals with biodiversity goals select engineered soils and hydrologic regimes that support both pollutant removal and habitat; avoid single-species, sedum-only solutions where richer substrates are feasible. Provide access and visibility: ensure sightlines, lighting, and passive surveillance so ecological complexity coexists with perceived safety; include small amenities (benches, shade, water access) that encourage lingering without over-programming habitat cores. Build capacity inside agencies through training on plant identification, ecological maintenance, and data collection; establish a cross-departmental working group (planning, public works, parks, health) to coordinate siting, operations, and measurement. Use pilot-to-scale playbooks: trial typology/planting permutations in a few blocks, monitor the dashboard for a year, then scale the best-performing mixes. Finally, adopt an adaptive management cycle plan → build → monitor → adjust so that plant palettes, maintenance schedules, and network links are routinely refined against the dashboard and community feedback. In short: design for quality and connectivity, fund maintenance as core infrastructure, measure biodiversity and human experience together, and center equity and co-stewardship so that CGI delivers durable ecological value and everyday neighborhood benefits.

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