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Author Contributions

DLW: wrote the manuscript. All authors conceptualized the analyses and comparative approaches. AO, CD, NF and SO: constructed the data sets. DLW, AO, and CD: conducted analyses. All authors read, edited, revised, and approved the final manuscript.

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Abstract

Perpetual conservation easements (CEs) are primarily voluntary instruments that place private land under conservation restrictions while often allowing continued human uses permitted under state enabling statutes and bolstered by federal tax law. Specified purposes vary with landowner intentions and can span biological preservation, agricultural viability, recreation, and other purposes. However, how CE purpose, landscape characteristics, and surrounding human modification interact to affect ecological integrity outcomes of a CE remains unclear.

Given that CEs are geographically dispersed across rural to urban land use gradients, we may expect variation in their ecological integrity even when CE purposes are the same. We estimated ecological integrity of over 2,500 CEs across twelve counties in six US states using the Human Modification Index (HMI) and tested whether CE HMI variation could be explained by CE purpose, stewardship organization, county identified land use, and size.

CE purpose significantly predicted HMI for easements with a biological, historical, recreation, and general classification, showing lower human modification than agricultural CEs. Testing the interaction between CE size and purpose, HMI generally declined as CE size increased (less human modification), except for historic CEs, which showed significantly increasing HMI with size. Biological and general CEs had significantly shallower slopes than agricultural CEs, though HMI still decreased as size increased. County identified land use and stewardship organization were not significant predictors. Western counties generally had lower HMI, Northeastern counties the highest, and the Southeast and Midwest showed intermediate values, though substantial within-region variability existed.

Keywords: conservation easement, purpose, holder type, land cover, ecological integrity

Conceptual Framework

CE Purposes and Land Use Designations

A CE is established through a formal legal agreement between a property owner, the grantor, and a grantee, which may be a land trust (non-governmental organization, NGO) or a local, state, or federal governmental entity. A fundamental regulatory requirement is the designation of a purpose, though a CE may include multiple, such as agricultural, biological, ecological, historical preservation, recreational access, and scenic and open space, as defined by the grantor and shaped by the state's CE enabling law and, if applicable, IRS requirements for qualified conservation contributions (Dyckman et al., under review; Owley & Rissman, 2016). CE purposes vary considerably depending on land trust mission, landowner preferences, regional conservation priorities, and federal tax incentives (Brunson and Huntsinger, 2008; Rissman et al., 2007; Dyckman et al., 2024). Allowable and restricted activities are determined on an easement-by-easement basis: restricted activities are those that would develop or use the land beyond the stated purpose, while allowable activities could include recreational amenities, land management practices, or existing uses such as forestry or agriculture (Parker & Thurman, 2024).

Flynn (2021) describes the history and evolution of the “conservation purpose” requirements in the Internal Revenue Code 170(h) and highlights ongoing debates about whether these broad statutory purposes are sufficient to ensure public benefit. Flynn (2021) argues that the differential requirements of the Section 170(h) purposes may result CEs with little public benefit, and proposes that all CEs align with governmental conservation policy and demonstrate significant public benefit (currently required only for the open-space purpose, whether for scenic enjoyment of the general public or pursuant to a clearly delineated governmental conservation policy, and not required for CEs with purposes of outdoor recreation for the general public, protection of a relatively natural habitat, or preservation of historical land or structures). Yet despite these debates, little empirical research has examined whether CEs with different stated purposes actually differ in conservation outcomes, a foundational question for assessing whether purpose-related policy reforms are warranted.

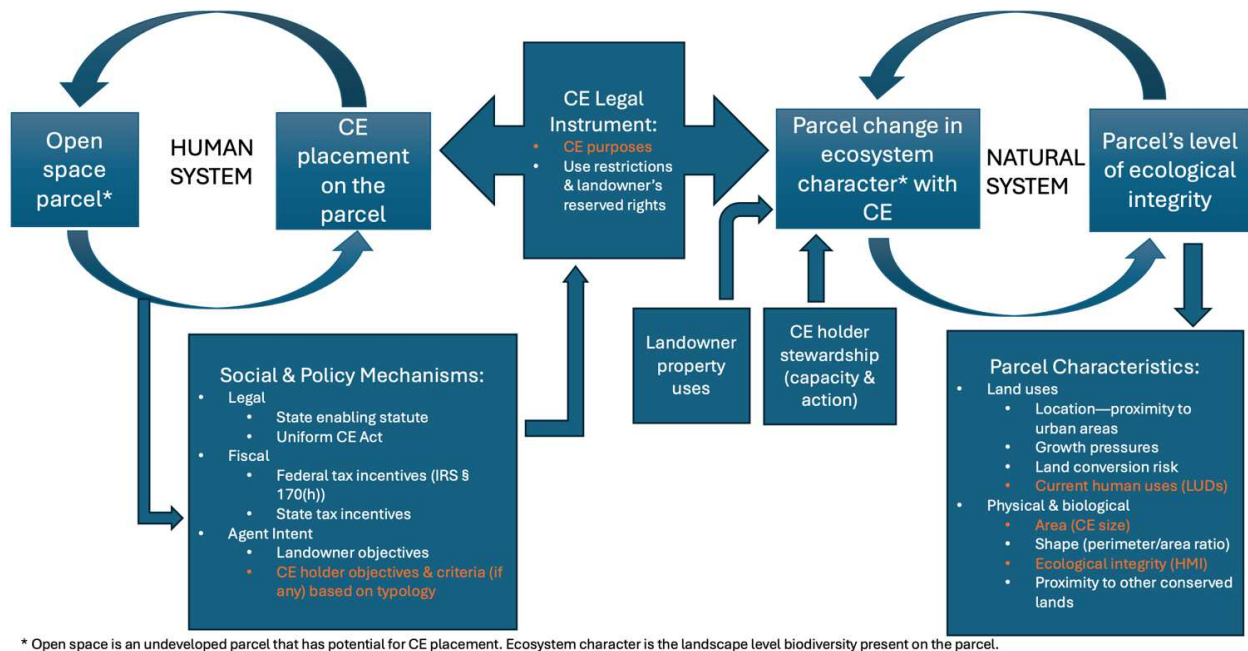


Fig 1 Parcel-Level Model of the Coupled Natural and Human Systems' Relationship with CE Placement and a Parcel's Ecosystem Character with a CE. *Orange indicates variables used in the analysis.

In addition and separately to CE purposes, the county tax assessor administratively assigns each parcel (CE and non-CE parcels) into a land use designations (LUDs) that reflects the property's actual and/or aspirational land use using locally determined factors such as land use planning priorities, and taxation objectives (note that these are not equivalent to zoning districts) (Dyckman et al., 2024). LUDs tend to be singular designations as dictated within the constraints of local land use controls and may or may not align with CE Purpose designation(s) (e.g., CEs on parcels with an agricultural LUD may support or restrict agricultural use) (Dyckman et al., 2024). Dyckman et al. (2024) posited that because LUDs influence ownership costs through taxation and permissible uses, the underlying LUD may induce economic use of the property to offset ownership costs, presumably decreasing ecological integrity. However, Dyckman et al. (2024) did not empirically test the relationship between CE LUD and ecological integrity.

Ecological Integrity

The effectiveness of CEs as instruments supporting biological conservation or improving ecological conditions on CE lands is not well understood (Kiesecker et al., 2007; Rissman et al., 2007; Kolarik et al., 2025). A CE can be placed without a specific focus on biological conservation, and the use of CEs to support working lands such as agriculture and forestry adds to the difficulty of identifying lands that may support conservation through the lens of ecological integrity. Assessing ecological integrity at regional and continental scales is problematic given the impediments of in-situ assessment. Continental-scale surveys must therefore rely on remotely sensed data or indices derived from it. Penn et al. (2024) reviewed the field and identified 95 unique indicators and 109 multi-metric index systems developed over the past two decades to measure ecological integrity across ecosystems and geographic scales, underscoring both the diversity of approaches and the lack of standardization.

Many of these metrics rely on in-situ data collection to derive measures such as richness, integrity, abundance, biomass, and diversity (Penn et al., 2024), which largely limits their use to smaller geographic areas and introduces issues of interpretability across ecosystems. Few tools measure anthropogenic impact across different ecosystems at larger scales. Most take the form of indices and models designed to inform how humans alter natural landscapes. For example, the Ecological Footprint (Wackernagel & Rees, 1996), Human Modification Index (Theobald, 2013), Human Footprint (Sanderson et al., 2002), and Anthropogenic Biomes (Ellis & Ramankutty, 2008) each measure the impact of human activity on the landscape in various forms. A key difference among these tools is spatial coverage, specifically whether they are spatially continuous at a continental or global scale, which allows large-scale analyses using a common measure across the landscape. Of those above, the Human Modification Index (Theobald, 2013), Human Footprint (Sanderson et al., 2002), and Anthropogenic Biomes (Ellis & Ramankutty, 2008) provide continuous coverage at continental or global scale.

To estimate ecological integrity, we used the Human Modification Index (HMI), as it met our need to estimate ecological integrity within our study area boundaries. HMI is a spatially continuous measure of human modification based on multiple input stressors including proportion of land cover, housing density, distance from roads, spatial impact of roads due to size and traffic volume, pollution, invasive species, and resource extraction (Theobald, 2012, 2013). Two factors are calculated for each stressor, intensity and footprint, where intensity measures the degree of the stressor at a location and footprint measures its areal extent (Theobald, 2013). The final raster dataset has a spatial resolution of 90 m with values bounded from 0.0 (low) to 1.0 (high) (Theobald, 2013). The advantage of HMI is its ability to capture a wider lens of human modification, incorporating potential landscape-scale effects of stressors (such as roadways) that may not physically overlap the CE but may nonetheless affect its ecological integrity. It is useful for comparing relative levels of human impact in regional assessments and where field data are unavailable or inaccessible, as is the case for CEs.

Objectives

This study addressed three primary objectives to further understand the coupled natural and human systems relationship (Fig 1). First, we characterized spatial variation in HMI across four regions (Northeast, Midwest, Southeast, and West) of the continental US, focusing on growth-pressured areas (Dyckman et al., 2024). Second, we examined how CE size is associated with HMI. Third, we evaluated how CE purpose, holder type, and LUD, as institutional and land-use characteristics, are associated with differences in HMI. Of particular importance is the potential relationship between CE purpose and estimated ecological integrity of the CE-encumbered land, given the legally binding nature of CE purpose language in governing allowable land uses at the time of easement placement. We tested four hypotheses focused on key CE characteristics, Holder Type, LUD, Purpose, and Size: [H1] Mean HMI differs between Holder Type, reflecting differences in management strategies and their influence on landscape condition; [H2] Mean HMI differs by LUD, reflecting differences across CEs as a baseline measure of ecological integrity at the time of initial placement; [H3] Mean HMI differs by CE purpose, reflecting differing CE objectives, for example working lands versus preservation; and [H4] Smaller CEs have higher mean HMI than larger CEs due to edge effects, especially in urbanizing landscapes.

Methods

Data Sources

To capture ecosystem variability across the United States, we selected 12 counties in six states distributed across four regions: West (California: Sonoma (SON), Sacramento (SAC); Colorado: Boulder (BLD), Mesa (MES)), Midwest (Minnesota: Douglas (DGL), Washington (WAS)), Northeast (Pennsylvania: Lebanon (LEB), York (YRK)), and Southeast (South Carolina: Charleston (CHS), Greenville (GVL); Virginia: Albemarle (ALB), Loudoun (LDN)). County selection prioritized urbanization pressure (population growth exceeding the US median, 2000–2010). We obtained CE spatial boundaries and legal instruments from 1997–2009 from county administrative offices, triangulated using methods described in Overby et al. (2022) and Dyckman et al. (2024). The final dataset included 2,590 active conservation easements across all counties. Additional methodological detail is available in prior work (Overby et al., 2022; Dyckman et al., 2024; Dyckman et al., 2025).

Categorical

For categorical analyses and visualization, the analytical dataset was reduced from 2,590 to 2,503 records after excluding CE records lacking original LUD values. To maintain consistency, we kept this subset for all analyses except regional HMI and size analyses. Mean HMI, extracted for each CE parcel, was summarized by county and region and compared across CE Purpose, Holder Type, and LUD categories (see below). These unweighted averages across categories with differing sample sizes may differ from parcel-level county and regional means.

CE Purpose

CEs may have one or more purposes depending on landowner and/or land trust intent. We created a codebook to categorize the conservation purposes of each CE, using deductive codes from Section 170(h) of the Internal Revenue Code and inductive codes from the CE legal documents (Dyckman et al., 2024). In total, the codebook included 31 unique purposes plus an "other" category for less commonly cited reasons. We coded purposes sequentially as they appeared in the legal document, coding Section 170(h) codes first when present. All CEs contained at least one purpose but could contain up to 16. Here, we report only the first purpose; see Dyckman et al. (2024) for an analysis

of all CE purposes in this dataset. We consolidated the 31 purposes to align with broader IRS CE purpose categories: Agriculture (Ag), Biological (Bio), Developed (Dev), General (Gen), Historic (Hist), Recreation (Rec), and Scenic-Open (Sce) (Internal Revenue Code, 26 U.S.C. § 170(h)(4)(A), 1980).

The Theobald (2013) crosswalk provides broad land use categories for interpreting HMI values relative to human modification across the study landscape (Table 1). CEs with mean HMI values approaching 0 reflect predominantly undeveloped conditions, mid-range values (0.4 to 0.7) suggest influence from agricultural or residential land uses in the surrounding landscape, and values approaching 1.0 indicate proximity to or overlap with heavily modified land uses such as transportation infrastructure or industrial development.

However, the CE purpose aggregation classes did not map directly to the Theobald (2013) land use categories (Table 1). Where clear matches existed, we applied the following crosswalk: Biological (Bio) to Undeveloped (HMI = 0.0); Recreation (Rec), Scenic-Open (Sce), and Historic (Hist) to Recreation (HMI = 0.2); General (Gen) to Unknown (HMI = 0.3); and Agriculture (Ag) to Agriculture (HMI = 0.5). The Developed (Dev) class presented the least straightforward mapping, as it encompasses Residential, Resource Extraction, and Mixed-use developed land uses in the Theobald (2013) scheme, corresponding to reference values of 0.7, 0.8, and 0.9, respectively. We assigned a reference value of 0.8 to this class as a representative midpoint for comparison.

Table 1 Theobald crosswalk mapped to study CE Purposes

Land Use Category	Human Modification Index	Study Crosswalk
	HMI (0–1)	Easement Reason
Undeveloped	0.0	Bio
Recreation	0.2	Rec_Education, Scenic, Historical
Unknown	0.3	General
Agriculture	0.5	Ag
Residential	0.7	Developed_Extraction
Resource extraction	0.8	Developed_Extraction
Mixed use developed	0.9	Developed_Extraction
Industrial	1.0	
Transportation	1.0	

CE Holder Type

A CE holder is the entity that holds the legal interest in a CE and monitors and enforces its terms, whether in perpetuity or for a fixed term (e.g., 20 or 30 years). For qualified conservation donations under US tax law, CE holders may include federal, state, and local government agencies and NGOs such as land trusts and conservancies. Other private entities may hold CEs but are not eligible for tax deduction if the CE is donated. When coding the CE legal document, we assessed holder type, coding into one of nine categories (Land Trust, Federal, State, County, City, Foundation, Nonprofit (not a land trust), Special District, and Other). We consolidated these into six categories to reduce complexity and improve interpretability, especially among less common holder types. NGOs, including land trusts, homeowner associations, foundations, and conservancies, were grouped into a single NGO category. Government holders were disaggregated into three levels: Local Government (Loc. Gov.), encompassing cities, counties, and districts; State Government (St. Gov.), comprising state agencies and departments; and Federal Government (Fed. Gov.), including only federal agencies. Private holders were retained as a separate category.

CE Land Use Designation (LUD)

LUDs were derived from county assessor parcel records associated with each CE across all study counties through a coding instrument that produced 549 unique master codes (Dyckman et al., 2024). The original schema resulted in

11 LUD categories, which we consolidated into four broad land use groups for analytical clarity: Urban Built-Up (Urb), Public & Open Space (Pub), Agriculture (Ag), and Residential (Res).

CE Size

CE size is reported in acres and was derived from GIS-calculated shape area measurements. Acreage for each CE parcel was used in weights to calculate the weighted mean HMI for each county.

Human Modification Index (HMI)

HMI values were extracted for county parcels using Version 8 of the global HMI dataset (Theobald et al., 2020), which quantifies anthropogenic modification of the land surface at 90 m resolution. Spatial processing was conducted in both ArcGIS Pro and R. In ArcGIS Pro, all county parcel datasets were reprojected to USA Contiguous Albers Equal Area Conic to match the coordinate reference system of the HMI raster. The HMI raster was then clipped to each county extent plus a 1 km buffer to capture CEs crossing county boundaries and resampled to 5 m resolution to minimize raster cell overlap with CE boundaries. In R, using the terra (Hijmans, 2025) and sf (Pebesma, 2018) packages, parcel feature classes for each county were read from county-specific ESRI geodatabases and converted to spatial vector objects. Mean HMI values were extracted for each parcel using terra::extract() with na.rm = TRUE. Parcel records were matched to extraction results using a project-assigned unique identifier, and mean HMI values were written as new attributes to each county geodatabase feature class.

To assess whether the distribution of human modification across conserved lands reflected the area-weighted contribution of individual easements, an acre-weighted mean HMI was computed for each county using the base R function weighted.mean() (Equation 1).

$$\bar{H}_w = \frac{\sum_{i=1}^n a_i h_i}{\sum_{i=1}^n a_i}$$

where $\bar{H}_w$ is the acre-weighted mean Human Modification Index for a given county, h_i is the mean HMI value for conservation easement i , a_i is the area in acres of conservation easement i , and n is the total number of conservation easements within the county.

Modeling

Linear Mixed-Effects Model

To examine the influence of CE characteristics on mean HMI of each CE in the 12 counties, a linear mixed-effects model (LMM) in R (Brown, 2021) was fit using the lme4 package (Bates et al., 2015), and Satterthwaite-approximated p-values for fixed effects were obtained with lmerTest (Kuznetsova et al., 2017). The total number of observations was 2,503 across 12 counties. The response variable was mean HMI per CE parcel, rounded to tenth decimal places, on its original 0–1 scale. The fixed effects included CE holder type, CE purpose, LUD, and log-transformed CE area (natural log, base e), with a CE purpose $\times$ CE log-area. Reference levels were Federal Government for holder type, Ag for CE purpose, and Ag for LUD; although sharing a label, these reflect distinct classification structures. County was included as a random intercept to account for spatial clustering of CEs within counties which was informed by previous research of this data set (Dyckman et al., 2025). Fixed effect estimates, standard errors, t-values, and p-values were extracted using the broom.mixed package (Bolker & Robinson, 2025), with p-values derived using Satterthwaite degrees of freedom approximation as implemented in lmerTest. Ninety-five percent confidence intervals were computed for all fixed effects and visualized in a coefficient plot using ggplot2, with terms ordered by effect size. Predicted HMI across the observed CE size range was plotted by conservation purpose using model-derived predictions on the log-transformed scale, back-transformed to acres for display, with 95% confidence intervals shown as shaded bands and lines clipped to the observed area range within each purpose category.

Results

Regional Patterns

HMI Mean by CE Acres and Weighted Acres

Overall CE HMI was highly variable across all counties and regions. Initial analysis shows CEs in Washington, Minnesota, had the highest mean (0.71), while Mesa in Colorado had the lowest HMI mean (0.44) (Table 2). The Western counties had the lowest overall mean HMI (0.50), followed by the Southeast and Midwest (both had 0.59) and the Northeast, which had the highest mean (0.66). These differences are modest in absolute terms, yet the values collectively suggest that exurban CE lands represent relatively open landscapes with some degree of anthropogenic modification. For reference, the Theobald crosswalk associates an HMI value near 0.5 with agricultural land use, providing context for interpreting the lower end of the observed range.

In several counties, the weighted mean was notably lower than overall mean for each county, indicating that easements are distributed unevenly across the landscape based on size and HMI value (Fig. 2). For example, GVL presents the most striking contrast between unweighted and weighted HMI mean, while its unweighted mean of 0.63 is comparable to LDN, the weighted mean is 0.33, suggesting that larger easements are concentrated in markedly less-developed areas. While the close alignment between DGL's unweighted and weighted HMI means (0.46 and 0.46) are the most consistent across all counties and suggesting that the minimal gap between unweighted and weighted means indicate relatively uniform distribution of CEs across the landscape in both size and HMI value.

Table 2 Human Modification Index (HMI) and CE Size by county and region

		gHM (0–1)				Area (ac)			
County	n	Mean	SD	Min	Max	Mean	SD	Min	Max
Midwest									
DGL	64	0.46	0.08	0.24	0.75	60.2	56.0	3.08	232.4
WAS	242	0.71	0.16	0.29	1.00	15.2	28.9	0.02	256.0
Northeast									
LEB	107	0.68	0.12	0.42	0.98	112.7	59.8	11.88	353.2
YRK	291	0.63	0.10	0.45	1.00	118.3	116.6	0.11	887.8
Southeast									
ALB	345	0.51	0.19	0.21	1.00	202.8	250.5	6.51	1508.1
CHS	181	0.54	0.17	0.23	1.00	187.2	298.3	0.02	1779.3
GVL	99	0.63	0.23	0.26	1.00	346.6	2607.3	0.03	25944.5
LDN	432	0.66	0.15	0.36	1.00	98.1	146.5	0.01	1268.8
West									
BLD	495	0.62	0.22	0.15	1.00	67.0	205.5	0.12	3358.5
MES	145	0.44	0.31	0.03	1.00	423.2	1078.0	2.01	10168.4
SAC	65	0.51	0.18	0.22	1.00	370.0	946.6	0.88	5536.5
SON	124	0.46	0.24	0.13	1.00	471.0	1461.2	0.30	10675.0

Median size analysis: Small versus Large CEs

Within each county, CEs were classified as either large or small using a median split based on easement area (acres) (Fig 3). Easements greater than or equal to the county-level median area were designated as large CEs, while those falling below the median were designated as small CEs. This county-level stratification ensured that size classifications reflected local distributions rather than an all-county global threshold.

These results illustrate both the potential influence of CE size on HMI value and the considerable range in median size across counties, from 319.1 acres in MES to 0.1 acres in WAS. The pattern suggests that smaller CEs tend to occur in more urbanized contexts, which is consistent with higher HMI values. In contrast, DGL and YRK exhibited

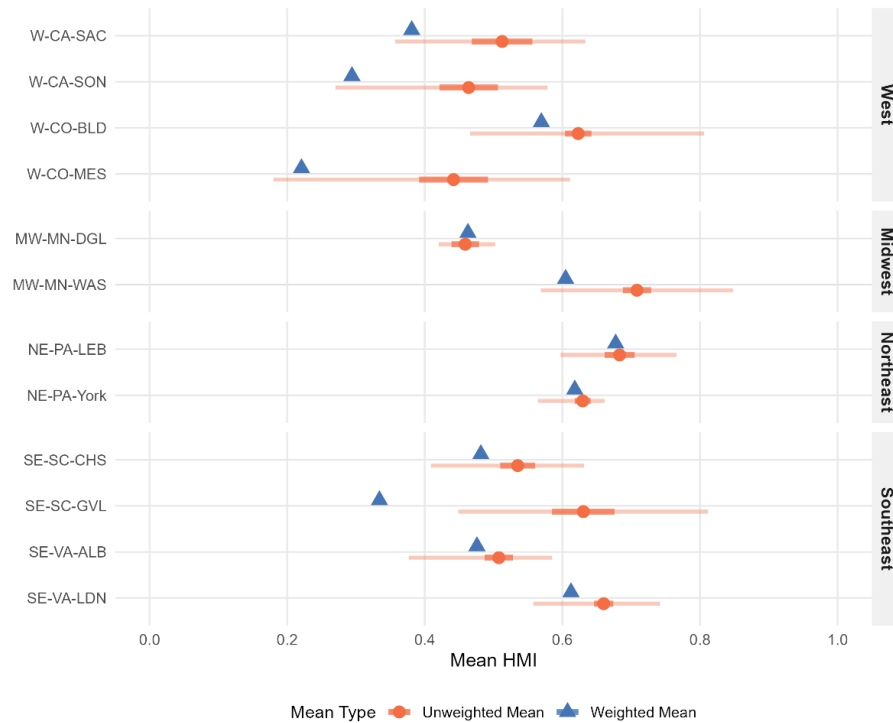


Fig 2 HMI mean by CE size (acres) and weighted size (acres). Points and triangles show mean HMI. Unweighted bars show IOR and 95% CI.

the least HMI mean differentiation between size classes, with minimal variation in HMI across both counties. The remaining counties, SAC, SON, BLD, LEB, CHS, ALB, and LDN, showed modest shifts in HMI between large and small CEs, with lower values recorded for large CEs.

CE Purpose

The heatmap reveals several patterns in the distribution of the first identified CE purpose in each instrument categories across counties. Bio was the only purpose present in all 12 counties, while Dev was the least represented, appearing in only three. See was absent from LEB; Ag was absent from both South Carolina counties (GVL and CHS); and Gen was absent from both LEB and DGL. Hist was present in five counties (LDN, ALB, GVL, CHS, and BLD), as was Rec (LDN, ALB, MES, BLD, and GVL). See was the most represented purpose overall (52% of CEs) and was the dominant category in LDN (82%), WAS (73%), GVL (64%), SON (64%), BLD (34%), and SAC (32%).

With the exception of the single Dev CE in GVL, all county means for all categories exceeded the continental US HMI value of 0.375 reported by Theobald et al. (2013). Overall, comparison with the Theobald crosswalk shows reasonable agreement for Ag but higher observed HMI values across most other categories, indicating these easements are generally located in highly anthropogenically modified landscapes, a likely result of the study sites being located in exurban areas across the conterminous US. The Dev global mean of 0.45 is likely not a representative measure of developed landscapes, attributable to limited county representation and the use of CEs as study units rather than the broader landscape; one would expect higher HMI values in developed landscapes closer to the Theobald crosswalk value of 0.80. Similarly, the Hist global mean of 0.76 is likely influenced by small sample size ($n = 30$) and limited representation across counties.

Holder Type

Mean HMI, extracted for each easement parcel, was summarized by county and region and compared across five CE holder type categories (Fig 5). NGO was the only holder type present in all 12 counties, while Fed. Gov. and Other

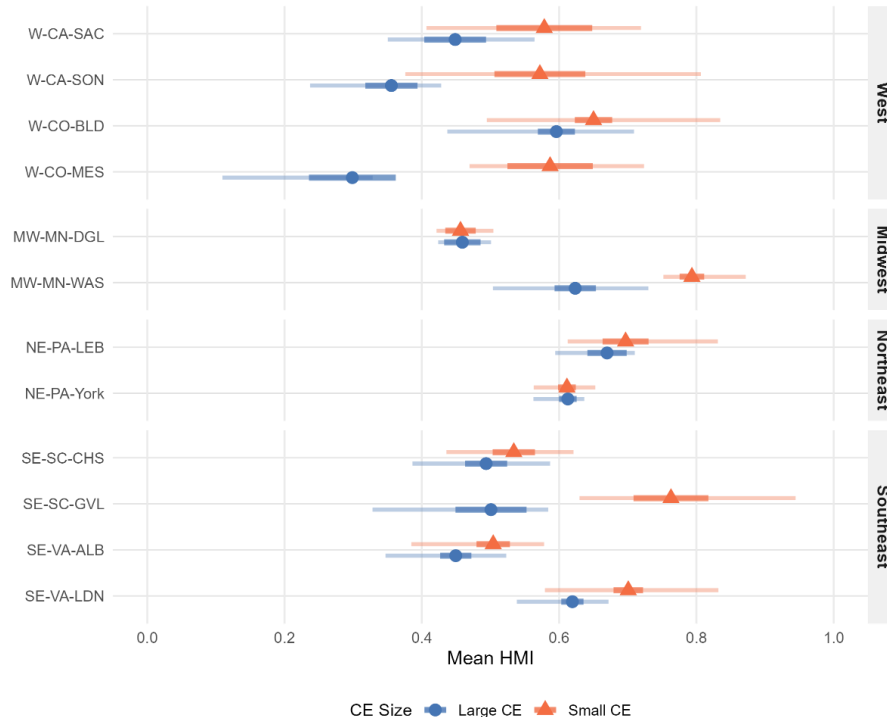
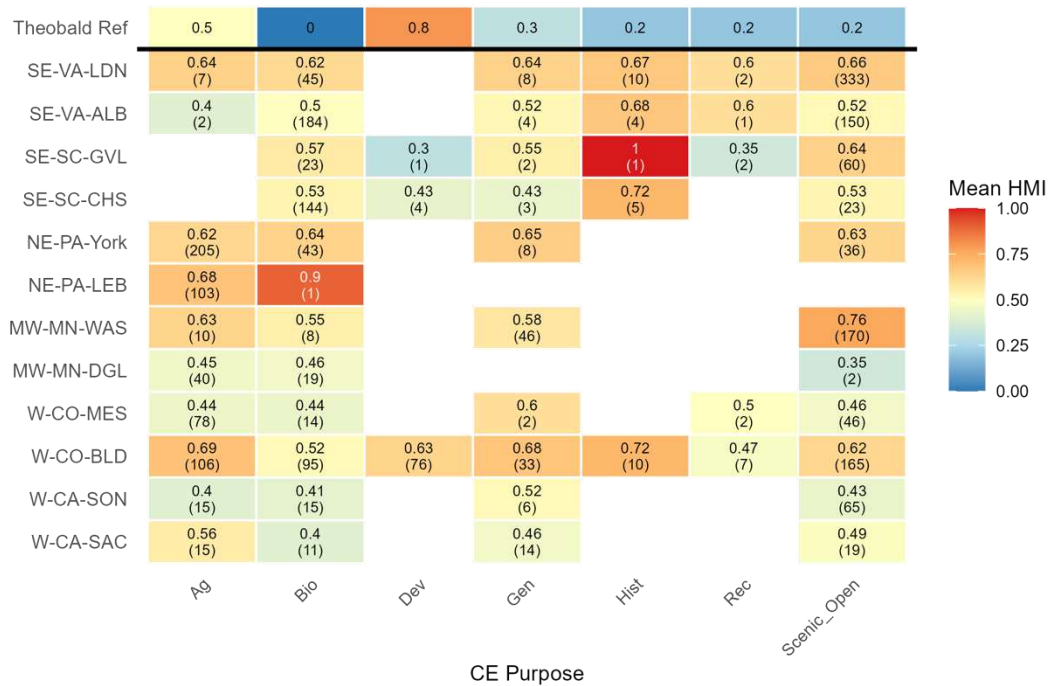


Fig 3 Mean HMI size analysis: small versus large CEs. Points and triangles show mean HMI. Unweighted bars show IQR and 95% CI.



Cell values indicate mean HMI with n in parentheses. Top row shows Theobald et al., (2013) crosswalk reference values.

Fig 4 Mean HMI by CE Purpose and county. Top row shows Theobald (2013) crosswalk reference values with (n) for each cell.

were the least represented, each appearing in only five counties. Local Government Loc. Gov. was absent from DGL, and St. Gov. was absent from BLD, CHS, and GVL, with CHS and GVL both located in South Carolina.

Loc. Gov. was the most represented holder type overall (48% of CEs) and was the dominant category in BLD (96%), WAS (82%), SON (72%), and LDN (55%). NGO was the second most common holder type and dominated in CHS (98%), MES (96%), SAC (76%), ALB (71%), and GVL (54%). St. Gov. had the third highest count, with YRK having the largest share of its CEs held by this type (50%).

Global means across counties were similar among holder types, including Fed. Gov. (0.54), Loc. Gov. (0.65), NGO (0.54), Other (0.60), and St. Gov. (0.54), suggesting comparable levels of anthropogenic modification across holder type categories. One notable exception was Fed. Gov. in LDN (0.90), though this value is based on a single CE and should be interpreted with caution.

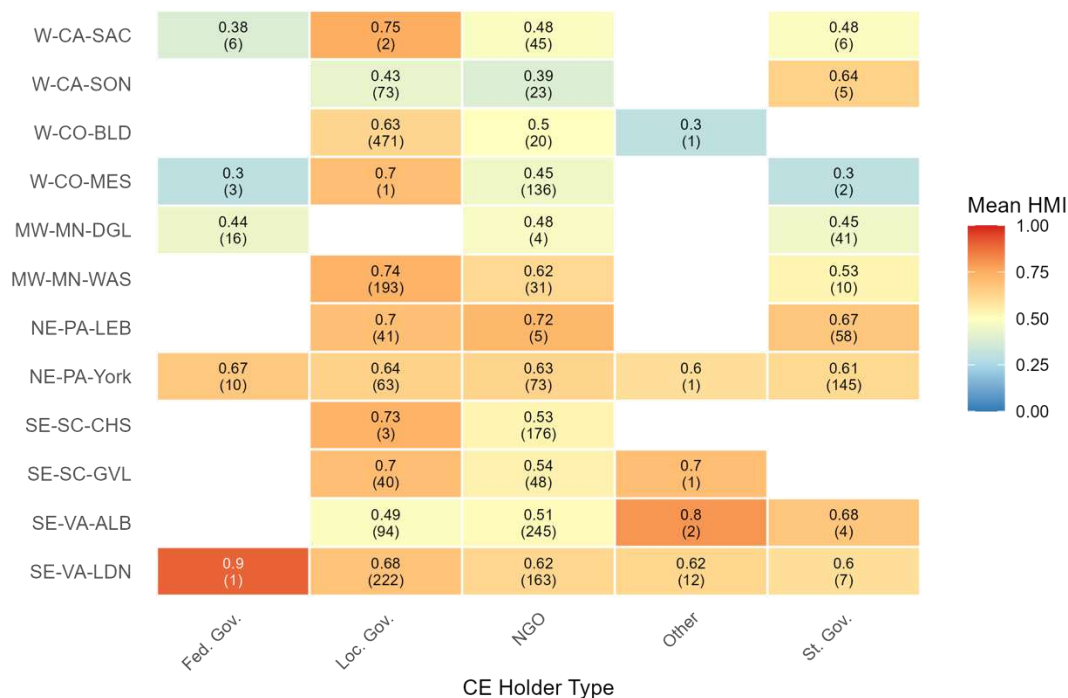


Fig 5 Mean HMI by CE Holder Type and county with (n) for each cell.

Land Use Designation (LUD)

Mean HMI, extracted for each easement parcel, was summarized by county and region and compared across four county tax assessor LUDs, administratively assigned classifications including Ag, Pub, Res, and Urb (Fig 6). Urb was absent from both California counties (SAC and SON), while the remaining three categories were represented in all 12 counties (Ag, Pub, Res).

Res was the most represented LUD type overall (44% of CEs) and was the dominant category in the Southeast counties CHS (50%), GVL (65%), ALB (99%), LDN (56%) and WAS (76%) in the Midwest. Ag was the second most common LUD type and dominate in all other counties SAC (72%), SON (73%), BLD (49%), MES (93%), DGL (67%), LEB (94%), YRK (60%). This is followed by Pub where notably this was second dominate LUD in BLD (25%) and Urb.

Global means across counties by LUDs include: Ag (0.52), Pub (0.55), Res (0.58), and Urb (0.65), suggesting increasing values across increasing levels of expected human modification. One notable exception was Urb in MES (0.2), though this value is based on a single CE and should be interpreted with caution.

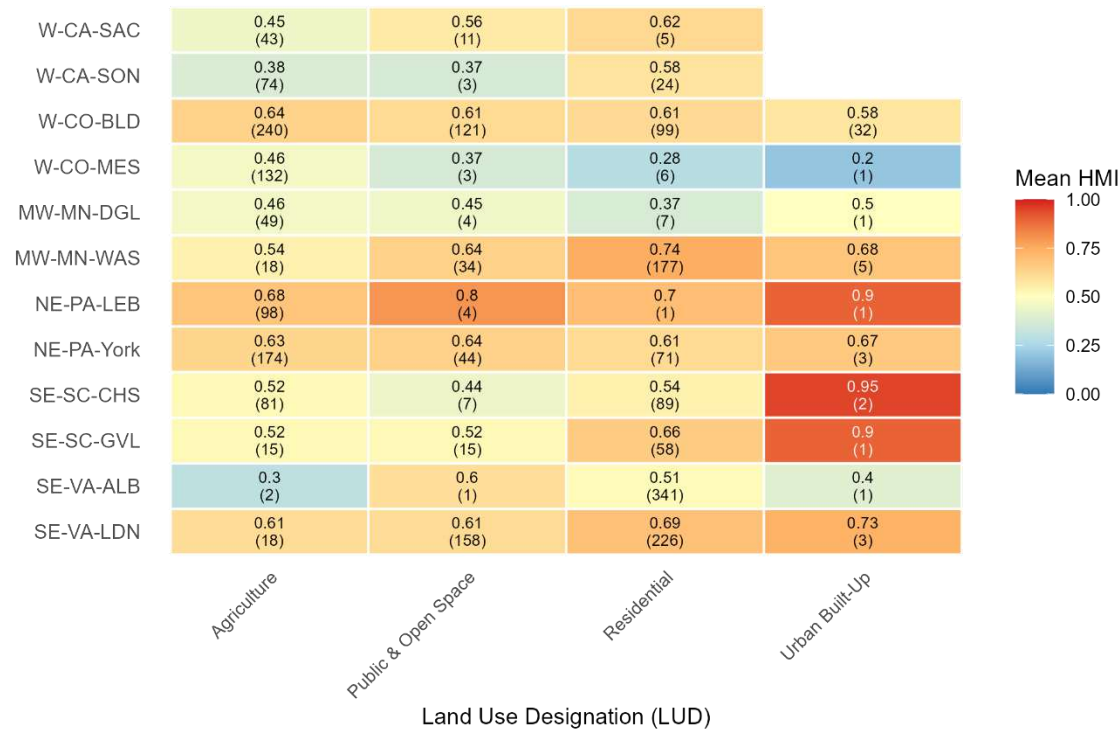


Fig 6 Mean HMI by CE Land Use Designation (LUD) and county with (n) for each cell.

Linear Mixed-Effects Model

To examine the influence of easement characteristics on human modification, a linear mixed-effects model was fit where the response variable was mean HMI for each parcel. We predicted that Holder Type, LUD, Purpose, and CE Size would have detectable effects on ecological integrity as measured by HMI.

Fixed effect estimates and significance levels ($p < 0.05$, $p < 0.01$, $p < 0.001$) are reported in Table 3. The intercept was significant ($p < 0.001$), with an estimate of 0.759. The conditional R^2 was 0.284, indicating that fixed and random effects combined explained approximately 28% of the variance in HMI across all conservation easements. The marginal R^2 was 0.151, indicating that fixed effects alone explained approximately 15% of the variance, driven primarily by CE purpose and size rather than holder type or LUD. The difference between the two measures (0.133) suggests meaningful county-level clustering, consistent with the inclusion of county as a random intercept and with previous research on this dataset, where Dyckman et al. (2025) found that clustering patterns across most counties were related to CE size.

The first hypothesis [H1] was not supported by the results. Relative to federally held easements, local government and other holder types were associated with slightly higher HMI values, while NGO and state government holders were associated with slightly lower HMI values, though none were significant predictors (Table 3, Fig 7).

Our results found no influence of LUD on HMI [H2] (Table 3, Fig 7). HMI varied both within and across regions for the LUD categories, consistent with Dyckman et al. (2024), but the overall differences were not significant.

Results supported [H3], indicating that CE purpose is a significant predictor of HMI (Table 3, Fig 7). Four of the six non-reference CE purposes were significant predictors of HMI, and relative to agricultural easements, all six were associated with lower HMI values. Rec easements showed the strongest negative association ($p < 0.01$, $\beta = -0.280$), followed by Gen ($p < 0.01$, $\beta = -0.149$), Bio ($p < 0.001$, $\beta = -0.145$), and Hist ($p < 0.05$, $\beta = -0.105$). Dev ($p = 0.099$, $\beta = -0.069$) and Sce ($p = 0.152$, $\beta = -0.045$) were not significant. These results suggest that, relative to the Ag reference, Bio, Gen, Rec, and Hist CEs are associated with less modified landscapes.

Table 3 Fixed effect estimates and summary statistics for linear mixed-effects model

Term	Model Estimates		Inference		Confidence Interval	
	Estimate	SE	t-value	p-value	Lower 95% CI	Upper 95% CI
(Intercept)	0.759	0.051	14.995	< 0.001	0.659	0.859
HLDR_TypeLoc. Gov.	0.005	0.035	0.144	0.886	-0.063	0.073
HLDR_TypeNGO	-0.006	0.034	-0.186	0.853	-0.073	0.060
HLDR_TypeOther	0.020	0.055	0.363	0.716	-0.088	0.129
HLDR_TypeSt. Gov.	-0.024	0.035	-0.697	0.486	-0.093	0.044
land_use_groupedPublic and Open Space	0.006	0.012	0.459	0.646	-0.019	0.030
land_use_groupedResidential	-0.004	0.011	-0.333	0.739	-0.026	0.018
land_use_groupedUrban Built-Up	0.002	0.027	0.070	0.944	-0.051	0.054
ReasonBio	-0.145	0.035	-4.125	< 0.001	-0.214	-0.076
ReasonDev	-0.069	0.042	-1.652	0.099	-0.150	0.013
ReasonGen	-0.149	0.046	-3.209	< 0.01	-0.240	-0.058
ReasonHist	-0.105	0.051	-2.062	< 0.05	-0.205	-0.005
ReasonRec	-0.280	0.094	-2.991	< 0.01	-0.463	-0.096
ReasonScenic_Open	-0.045	0.031	-1.434	0.152	-0.106	0.016
log_CEAarea_Ac	-0.040	0.006	-6.300	< 0.001	-0.052	-0.028
ReasonBio:log_CEAarea_Ac	0.017	0.008	2.152	< 0.05	0.002	0.032
ReasonDev:log_CEAarea_Ac	-0.018	0.015	-1.206	0.228	-0.047	0.011
ReasonGen:log_CEAarea_Ac	0.031	0.012	2.666	< 0.01	0.008	0.054
ReasonHist:log_CEAarea_Ac	0.055	0.018	3.007	< 0.01	0.019	0.092
ReasonRec:log_CEAarea_Ac	0.037	0.024	1.559	0.119	-0.009	0.083
ReasonScenic_Open:log_CEAarea_Ac	0.002	0.007	0.237	0.813	-0.012	0.015

Results supported [H4] (Table 3, Fig 7); log-transformed CE size was a significant negative predictor of HMI ($p < 0.001$, $\beta = -0.040$), with larger easements associated with lower landscape modification. Among the purpose-by-size interactions, Bio ($p < 0.05$, $\beta = 0.017$), Gen ($p < 0.01$, $\beta = 0.031$), and Hist ($p < 0.01$, $\beta = 0.055$) showed significant positive interactions, indicating that the negative relationship between easement size and HMI was attenuated for these categories relative to Ag easements (Table 3, Fig 7); for Hist, the relationship reversed, with HMI increasing as size increased. Dev showed a slightly negative interaction estimate ($\beta = -0.018$), Rec a positive but non-significant estimate ($\beta = 0.037$), and Sce a near-zero estimate ($\beta = 0.002$); none were significant. Figure 8 shows predicted HMI across the observed range of CE size for each purpose category, bounded by the minimum and maximum CE size within each purpose, with the Ag reference slope included for comparison.

Hist had the largest positive interaction estimate ($\beta = 0.055$) and increasing predicted HMI with increasing CE size, contrary to the negative size–HMI relationship seen for all other purposes. This is likely driven by the limited size range of Hist easements (0.12 to 229.14 acres, median = 5.12) and the small sample ($n = 30$), and suggests that many Hist CEs are located in more urban landscapes, with predicted HMI values between 0.6 and 0.8, consistent with more modified settings. Bio ($\beta = 0.017$) and Gen ($\beta = 0.031$) also had small but significant positive interaction estimates. Bio had the second widest CE size range after Sce, with predicted HMI decreasing from over 0.6 to less than 0.4 for very large CEs. Gen showed a small decrease in predicted HMI across its size range, from approximately 0.6 to 0.5.

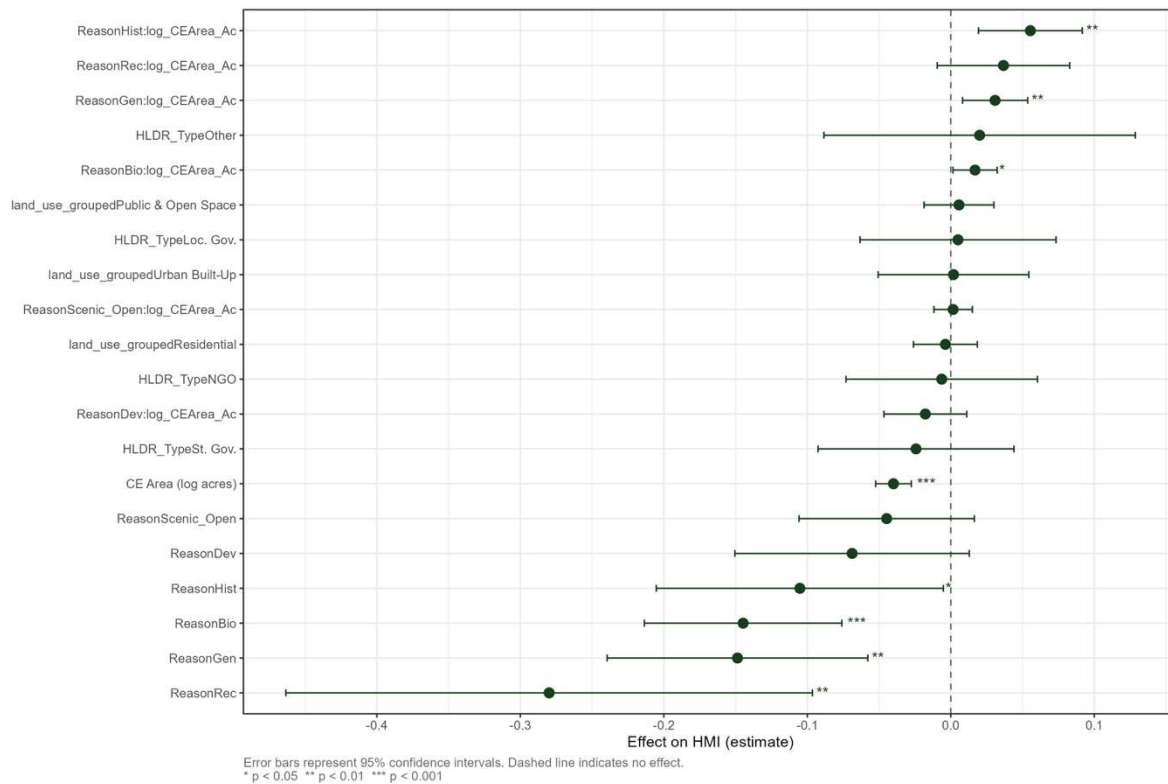


Fig 7 Fixed effects estimates from linear mixed-effects model. Error bars represent 95% CI. Dashed line indicates no effect. * p < 0.05 ** p < 0.01 *** p < 0.001

Although Rec was not significant as an interaction term, it was a significant main effect with the largest negative estimate of any purpose category ($\beta = -0.280$), suggesting that these CEs were located in areas with relatively low anthropogenic modification, though this estimate is based on only 14 easements. Rec showed a relatively flat modeled relationship, with predicted HMI between 0.4 and 0.5 and a slightly positive but non-significant interaction estimate. Sce had the widest CE size range (0.01 to 10,622.44 acres, median = 41.26, n = 1,069), with predicted HMI ranging from 0.9 to less than 0.4 and a near-zero interaction estimate that closely followed the slope of the Ag reference.

Discussion

Linear mixed-effects model results indicate that CE purpose was a significant predictor of HMI, with Hist, Bio, Gen, and Rec CEs all having significantly lower HMI than Ag CEs, while Dev and Sce did not differ significantly. This pattern is notable given Flynn's (2021) observation that biological or ecological preservation CEs are not required to align with governmental conservation policy under current Section 170(h) rules. Despite this lack of statutory alignment, the findings suggest that Bio CEs nonetheless tend to correspond with lower human modification than Ag, Sce, and Dev CEs. Sce CEs tended toward higher raw HMI values, which, though not statistically significant, may reflect regulatory requirements under 26 C.F.R. § 1.170A-14(d)(1)(iii) that scenic easements be visually accessible to the general public, often achieved through proximity to public roadways. Road proximity is consequential because HMI explicitly incorporates transportation networks as a stressor layer, including a traffic-volume stressor applied within a 1 km buffer (Theobald, 2013). As a result, Sce CEs on or near road networks are more likely to have higher HMI beyond the immediate road footprint.

CE size was also a significant predictor of HMI, with smaller CEs exhibiting higher HMI across most purpose categories, though the strength of this relationship varied by purpose (see below). This pattern is consistent with well-established landscape-ecology theory showing that smaller habitat parcels have proportionally larger edge-to-area ratios and are therefore more exposed to the conditions of the surrounding landscape (Murcia, 1995). Smaller CEs in fragmented landscapes are also more likely to be surrounded by denser road networks (Jaeger et al., 2009). Because HMI captures human modification both within and around a parcel, smaller CEs tend to show higher

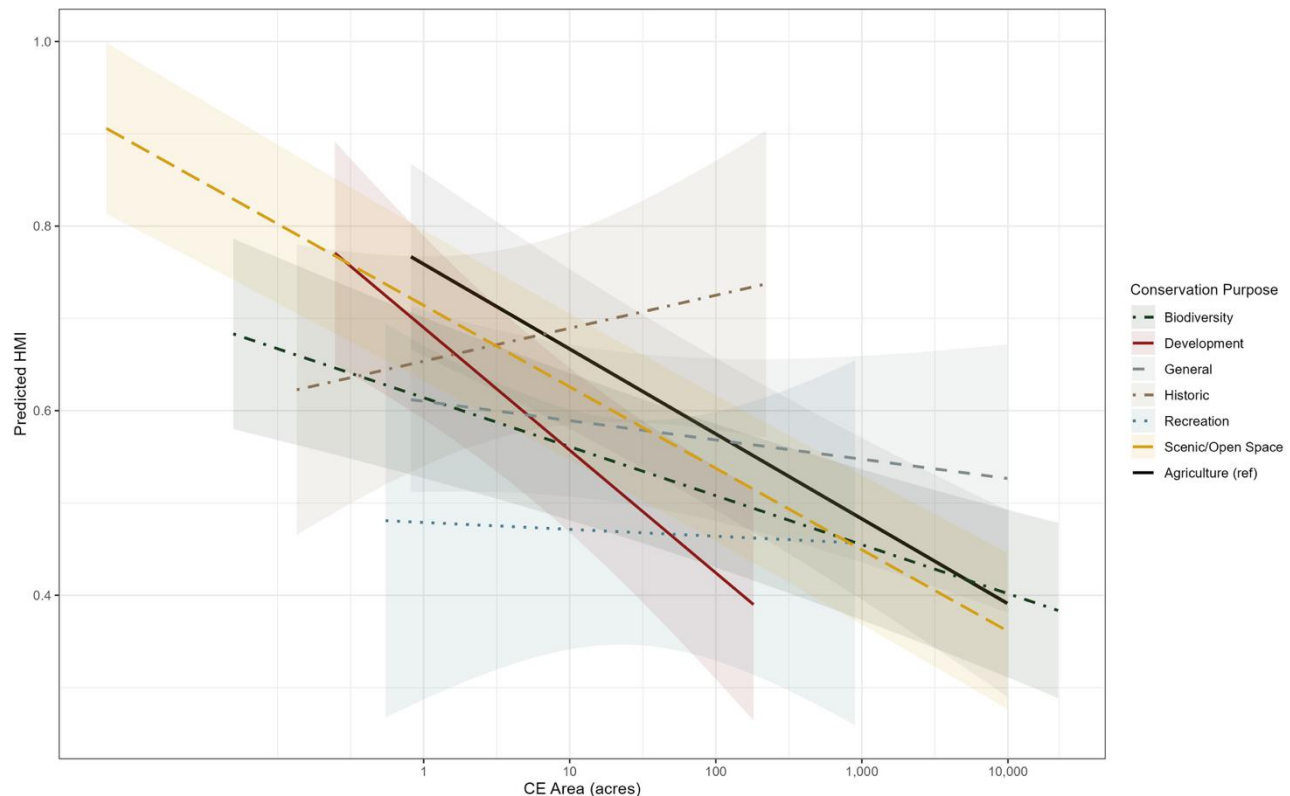


Fig 8 Predicted HMI by CE Size (log acres) and CE Purpose. Shaded bands represent 95% CI. Lines clipped to observed CE Size range within each conservation purpose category.

landscape modification, due in part to proximity to road networks and overall modification of the surrounding landscape.

The significant interaction between CE size and purpose for Bio and Gen CEs suggests that property owners are likely more deliberate in identifying larger, less modified lands to support conservation planning objectives. This contrasts with historic CEs, which showed higher HMI as size increased, suggesting these culturally important areas occur in more developed landscapes. CE holder type and LUD were not significant predictors of HMI, indicating that neither the organizational entity responsible for overseeing the CE nor the formal LUD of the parcel meaningfully affects the level of human modification. Although LUDs can shape ownership costs through taxation, signal permissible or aspirational land uses, and reflect local planning priorities, these administrative classifications do not reliably identify ecological condition.

Regional HMI variation aligns with documented patterns of historical population density and land use across the United States. Bounoua et al. (2018) found that the West had the lowest proportion of impervious surface, followed by the Midwest, South, and Northeast, consistent with regional HMI values reported here. However, WAS (mean HMI = 0.71) contains the most heavily modified county in the dataset, suggesting regional exceptions to broad trends. Residential dominance in the Southeast and agricultural dominance in the West reflect decades of land use change, with research from 1950 to 2000 showing extensive exurban growth and agricultural conversion in the Southeast and Northeast, versus relatively stable cropland and rangeland in the West (Brown et al., 2005; Bigelow & Borchers, 2017). The Northeast has long been the most densely populated region, holding approximately one-fifth of the US population within one-twentieth of the country's land area (U.S. Census Bureau, 2002), which reflects the longest history of urban and agricultural conversion at a continental scale (Homer et al., 2020; Li et al., 2023).

The prevalence of Sce designations reflects flexibility that accommodates working lands over strict biological preservation, consistent with Rissman et al. (2007), who found that 85% of sampled easements allowed residences, new structures, commercial use, or subdivision. The significance of the Bio category in our modeling likely reflects explicit conservation objectives, with alignment between landowner and holder motivations strongest when directed toward specific management purposes (Stroman & Kreuter, 2015). However, our global mean for the Bio category

was 0.54, far above Theobald's crosswalk value of 0.0 for unmodified natural land. This discrepancy suggests that truly unmodified natural landscapes are increasingly rare in regions such as the Southeast, experiencing rapid urban development (Terando et al., 2014); the Northeast, characterized by high population density (Gottmann, 1961); and the Midwest, dominated by extensive agricultural lands (Ye et al., 2021). This pattern is consistent with a global study of protected area effectiveness, which found that 73% of 160,000 protected areas exhibited some form of landscape alteration between 2003 and 2019 (Li et al., 2024).

Although holder type was not significant in the overall LMM model, county-level patterns reveal important conservation trends. BLD's local government holdings accounted for 39% of all local government CEs study-wide and 96% of all CEs in BLD, reflecting its long-standing open space program formalized through the 1978 Boulder County Comprehensive Plan. The county currently holds approximately 40,000 acres across nearly 850 properties (Boulder County, 2024) through donations, developer set-asides, tax funding, and a Transferable Development Rights program (Boulder County Parks & Open Space, 2022), led by Ag (22%), Bio (19%), and Dev (15%). WAS shows similar concentration, with 82% of CEs held by local government through the Land and Water Legacy Program, established via a voter-approved referendum in 2006, which has protected approximately 1,300 acres (Washington County, MN, n.d.). However, 73% of WAS CEs are classified as Sce, reflecting a narrowly focused strategy in contrast to BLD's diverse distribution. NGOs, present in all 12 counties, represented 39% of all CE holders and were dominant in CHS (98%). CHS uses county tax funds through the Greenbelt Program to support NGO partners (Charleston County, 2024), where 80% of CEs have biological purposes. The Lowcountry Land Trust, established in 1986, has protected over 165,000 acres across South Carolina's 17-county coastal plain and serves as a primary partner (Lowcountry Land Trust, 2024). CE purposes in YRK and LEB were dominated by Ag (70% and 99% respectively), accounting for 73% of all state government CEs, reflecting Pennsylvania's county-administered Agricultural Conservation Easement Purchase Program (Pennsylvania Department of Agriculture, 2025).

Study limitations include our inability to measure in-situ conservation attributes, which may have revealed additional ecological values not captured by HMI. This is especially salient given the measured importance of CE size in predicting mean HMI, which could suggest that smaller CEs have lower conservation value than larger ones. This interpretation should be made cautiously as research demonstrates that small protected areas can contribute meaningfully to conservation outcomes, particularly in fragmented landscapes (Lindenmayer, 2019). Future research incorporating fine-scale ecological assessments will be essential to evaluate these contributions more directly.

Conclusions

Our analysis provides the first empirical evidence that CE purpose and size, and their interaction, are associated with meaningful differences in HMI across US CEs, giving empirical context to ongoing policy discussions regarding the conservation purposes section of 170(h). Although our analysis does not directly measure species richness or conservation outcomes, lower HMI in larger CEs suggests these lands experience less intense human modification, which may create conditions more conducive to maintaining ecological integrity.

CEs are a flexible policy tool whose local implementation varies considerably. Owley (2011) notes that local governments increase CE adoption by passing supporting laws, funding programs, and requiring easements for development permits. CE size varied dramatically across counties, from 25,945 acres in GVL (Gen, held by The Nature Conservancy to protect Greenville's drinking water watershed from 1990s housing development) to 0.01 acres in LDN (Sce). Small easements in LDN likely reflect local development-approval requirements, where municipalities condition permits on permanent green space protection. This practice embodies exactions, whereby governments transfer environmental mitigation costs to developers as a condition of approval. A similar pattern emerges in CHS and GVL, where small CEs (0.02–0.04 acres) carried Bio purposes despite mean HMI values of 0.7 and 1.0, indicating that CE purpose designations may not reflect on-the-ground ecological conditions in developed areas. Despite this, the flexibility of CEs has allowed diverse jurisdictions to tailor programs to local conservation priorities and constraints, as evident in county-level implementation patterns.

The use of CEs and other non-traditional privately protected lands is not limited to the United States, and private ownership-based conservation tools to protect biological and ecological integrity are accelerating globally. The International Union for Conservation of Nature (IUCN) has released guidance supporting the role of private lands within Target 3, commonly referred to as "30 x 30," which aims to conserve 30 percent of the planet's lands and waters by 2030 (World Wildlife Fund and IUCN World Commission on Protected Areas, 2023). Yet research

evaluating their effectiveness at continental scales remains limited, particularly how documented CE purposes and land use restrictions shape management practices and, ultimately, conservation outcomes. A better understanding of how these lands contribute to conservation goals at local, regional, and national levels is needed.

Data Availability

These data will initially be made accessible, where county agreements do not preclude sharing, via a request to the authors. Within a year from publication, the data sets will be made available through a portal at Clemson University.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used Claude (Anthropic) to assist with copyediting, prose tightening, checking the internal consistency of statistical results against tables and figures, and R coding assistance. The author(s) reviewed and edited the output as needed and take full responsibility for the content of the published article.

Competing Interests

Authors do not have any financial or non-financial interests related to this work.

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