# Biodiversity Co-Benefits in Carbon Markets? Evidence from Voluntary Offset Projects

Zoey Yiyuan Zhou* and Douglas Almond‡

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**Abstract**

The current Holocene Extinction marks the fastest rate of species loss in human history. In the absence of effective public policies, market-based approaches and carbon offsets in particular may generate valuable biodiversity co-benefits. This study provides the first comprehensive evidence on how voluntary carbon offsets — which regularly promote biodiversity benefits to investors — impact habitat quality. We compile the largest extant dataset of voluntary carbon offset projects and merge these to finely-resolved data on local ecosystems derived from satellite measures of habitat integrity. Contrary to asserted co-benefits, we find carbon offset projects are associated with a 3.7% <u>increase</u> in habitat disturbance, as measured by the Human Influence Index (HII). Analyzing land-use data, we show that carbon projects spurred conversion of biodiverse habitats—particularly shrublands and less-dense forest ecosystems—into pasture and simplified landscapes, and thereby ecological trade-offs. We examine impact heterogeneity by ecosystem condition, certifications, stated co-benefits, protected area overlap, registry, and rating status, but still find no evidence of improved habitats. Nor do alternative habitat measures, the Bioclimate Ecosystem Resilience Index and the Biodiversity Habitat Index, show improvement following offset projects.

**Keywords:** Biodiversity, Nature-based Solutions, Voluntary Carbon Offset, Carbon

*Zhou (yz2851@columbia.edu, corresponding): Columbia Climate School, Columbia University

†Almond (da2152@columbia.edu): Department of Economics and SIPA, Columbia University and NBER

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Farming, Additionality.

# 1 Introduction

> Governments have never met a single target in the history of UN biodiversity agreements.
>
> (The Guardian, February 2025 - citing a 2020 United Nations report)

International policy responses to rapid biodiversity loss are fragmented and inadequate. Among the 137 countries that submitted national biodiversity strategies, more than half fail to propose any concrete action toward protecting 30% of their land and sea areas — despite formally adopting this target at the 2022 COP15 summit (The Guardian, 2025). Recent empirical evidence further underscores this shortfall. Reynaert et al. 2024 examine the ecological effects of protected area expansions under the "30 by 30" framework and find no significant improvements in biodiversity, as proxied by satellite-derived measures such as the Normalized Difference Vegetation Index (NDVI). Thus, headline conservation pledges have consistently lacked follow through.

The voluntary carbon market (VCM) is an emergent mechanism for channeling private capital into climate mitigation and, increasingly, biodiversity conservation. It allows firms to voluntarily offset emissions by investing in low-cost sequestration activities elsewhere, many of which involve forestry or land use changes – so-called "nature-based solutions." Forestry and land use offsets — comprising roughly half of all credits issued — frequently operate in ecologically sensitive locations. These projects often explicitly claim biodiversity co-benefits alongside their "mainline" carbon reductions. The VCM was valued at $2 billion in 2021 and is projected to reach $50 billion by 2030 (McKinsey & Company, 2021), growth driven by corporate net-zero commitments and investor interest in nature-based solutions (Taskforce on Scaling Voluntary Carbon Markets, 2021). Over 980 million metric tons of $CO_2$ have already been retired by the VCM.

The biodiversity claims of nature-based offset developers do have scientific support, at least in principle. As noted by Huston and Marland, 2003,

> *...carbon sequestration in living plants and soils, either through long-term protection of currently mature forests, or long-term protection of re-growing forests, is likely to have an immediate net positive effect on atmospheric carbon dioxide, plus a positive effect on biodiversity and other ecosystem services.*

Chausson et al., 2020, Griscom et al., 2017, and Osuri et al., 2020 likewise highlight the potential complementarities of carbon sequestration and biodiversity. Within the offset context specifically, Freedman et al. 2009 also emphasize the possibility of complementarities. But at present, there is no systematic evidence on whether biodiversity co-benefits actually exist in the VCM.

Indeed, even evidence on the carbon impacts of the VCM remains limited. Existing offset studies typically rely on small-sample case studies or theoretical models, leaving a critical gap in our understanding of VCM impacts at scale. For example, West et al. 2020, 2023 analyze 12 and 26 projects (respectively). Despite expansive framing,[1] Calel et al. 2025 do not consider any nature-based offset projects, focusing exclusively on wind turbine projects in India.

The low trading prices for carbon offsets underscore both the promise and potential dubiousness of the VCM. Based on our data, voluntary carbon offsets trade at an average price of approximately $6 per ton. The purported offset cost is often an order of magnitude (or more) lower than the U.S. government's most scientific estimate of the social cost of carbon: $190 per ton from the Interagency Working Group on the Social Cost of Greenhouse Gases (2023). For example, Singapore Airlines allows passengers to purchase offsets for one metric ton of $CO_2$ (roughly that from a RT economy flight from New York to East Asia) for $10 USD.[2] If these projects are indeed delivering on their stated carbon and biodiversity objectives, they represent an exceptionally low-cost and likely scalable avenue for advancing global conservation goals.

Our study addresses this research gap by providing the first comprehensive evidence on biodiversity impacts of the VCM. We compile a new dataset of detailed project-level data from major carbon registries which we combine with satellite-based biodiversity metrics of habitat. We analyze data on 1,703 geocoded VCM projects featuring nature-based solutions with five years of data before and after their implementation. We measure habitat pressure through the Human Influence Index (HII), a satellite-derived measure of human pressure on local ecosystems. While this does not count individual species, habitat loss is typically found to be the primary threat to biodiversity, e.g. 2024 Living Planet Report, World Wildlife Fund.

Our primary empirical analysis is an interrupted time series design. We establish that the baseline trends in HII prior to the start of offset projects are very steady and indeed flat. This simplifies the empirical analysis and lends credence to interpreting deviations after projects commence. Our analysis yields several key findings. Contrary to expectations based on claimed co-benefits, we document that carbon offset projects are associated with a prompt 3.7% increase in HII, i.e. an increase in human pressure reflecting compromised habitats. These increases in HII persist when we restrict comparisons to be entirely within and not across projects (i.e., including 2,701 project FE as controls).

This average impact may gloss over subcategories of projects with stronger biodiversity provisions. We assess heterogeneity across several project dimensions, including baseline ecosystem condition, certification status, stated biodiversity co-benefits, overlap with formally protected areas, registry affiliation, third-party rating status, and implementation timing relative to the 2014 IPBES assessment. Across all dimensions, we find no consistent

[1] Calel et al. 2025 titled their paper: "Do Carbon Offsets Offset Carbon?"

[2] One featured voluntary carbon offset project, *Rainforest Preservation*, is the Katingan Mentaya initiative in Indonesia, which claims to prevent over 7.5 million tonnes of greenhouse gas emissions annually. According to its description, the project "secures vital habitat for five critically endangered species including the Bornean Orangutan, Proboscis Monkey, and Southern Bornean Gibbon": https://businesscarbonoffset.singaporeair.com.sg/offset-projects

evidence of ecological improvement—no empirical "silver lining". Thus we cannot point to particular types of projects that definitely improve habitat. In addition, analyses using alternative satellite-derived habitat indicators—the Bioclimate Ecosystem Resilience Index and the Biodiversity Habitat Index—likewise reveal no measurable gains following project initiation. Our findings raise concerns about the reliability of biodiversity claims in the VCM and point to potential gaps in delivering promised environmental co- benefits.

To shed light on potential mechanisms behind habitat degradation, we examine satellite-based Land Use and Land Cover (LULC) data to track changes in surface composition before and after VCM project initiation. Specifically, we calculate net shifts in land cover categories associated with each project. On average, carbon offset projects are associated with an average increase of 45.9 square meters of pasture per project. These gains appear to come primarily from conversions of shrubland and certain forest types—land cover types typically associated with higher ecological complexity. The increase in pastureland may reflect land clearing for agroforestry or mixed-use farming consistent with project designs.

While such land-use transitions may store carbon, they do not necessarily promote biodiversity. In many cases, these conversions reflect a shift from structurally and compositionally diverse habitats to more simplified landscapes. This homogenization can reduce habitat connectivity, erode species richness, and undermine ecosystem resilience. In this sense, our findings reinforce a broader concern: carbon sequestration through land-use change, even if successful in reducing/offsetting emissions, may come at the cost of ecological integrity. Likewise, in afforestation projects, planting monocultures and "tree engineering" may store carbon at the cost of biodiversity. While it might be plausible *prima facie* that promoting forests would assist biodiversity, this does not appear to be the case empirically.

Our sobering finding contributes to the ongoing debate about the effectiveness of market-based approaches to biodiversity conservation (Salzman et al., 2018) and informs policy discussions on the appropriate regulation of voluntary carbon markets (Taskforce on Scaling Voluntary Carbon Markets, 2021). Our analysis of the spatial relationship between offset projects and protected areas contributes to the literature on conservation effectiveness and additionality in ecosystem service markets (Pattanayak et al., 2010; Jayachandran et al., 2017; Aspelund and Russo, 2024). By quantifying the extent of overlap and examining its implications, we provide insights into the potential for carbon finance to expand or reinforce existing conservation efforts. That biodiversity-carbon "win-wins" appear unlikely from the VCM underscores the urgent need for alternative means of slowing biodiversity loss.

The remainder of our paper is organized as follows. Section 2 provides institutional background on the biodiversity-related voluntary carbon offset market and details our hypotheses. Section 3 describes our data and empirical strategy. Section 4 presents our main results and additional analyses. Section 5 discusses the implications of our findings for policymakers, investors, and corporate decision-makers. Section 6 concludes.

## 2 Related Literature

Broadly speaking, economists agree on first-best policies to address climate change through GHG mitigation. The failure to implement such policies to date is stark. Even in the more progressive policy environments, average carbon prices implicit in existing governmental policies are well below that required to limit warming to 1.5 degrees Celsius (Allen et al. 2023). Capital markets may offer avenues for large and cost-effective reductions in GHG emissions even in the absence of first-best governmental policies policies.[3] This promise has helped drive growth in the marketplace for voluntary carbon offsets, projected to reach $50 billion in 2030 (McKinsey & Company 2021). Fortunately, these are just one potentially-promising tool in the absence of sufficient political support for the adoption of carbon cap and trade or carbon taxes of sufficient ambition.[4] Furthermore, capital markets have the financial heft to leverage the requisite investments in mitigation. Indeed, the market for sustainable debt securities totalled nearly $6,000 billion in 2020 (Allen et al., 2023).

Forests – through reforestation and avoided forest conversion, and better forest management – are central to nature-based climate solutions. Griscom et al. 2017 find that forests provide over two thirds of the nature-based mitigation needed to keep warming below 2 degrees Celsius. Franklin and Pindyck 2024 focus on marginal costs, estimating a supply curve for forest-based removal of CO2 in South America, factoring both land opportunity costs as well as direct forest costs. They find that more than 1 billion tons of CO2 can be removed each year via forestation at a cost up to $45 per ton, well below current estimates of the social cost of carbon.

Huston and Marland 2003 highlight the general issues surrounding the ecosystem-dependence of environmental benefits and in the case of forests, Huston and Marland 2003 come to a positive view (as the passage from the Introduction conveys). Freedman et al. 2009 advance a similarly sanguine view in the context of growing market for carbon offsets. Across a variety of land uses, benefits in both GHG offsetting and biodiversity are found (Freedman et al., 2009, Figure 1). Freedman et al. 2009 state: “Many kinds of land-management actions that are undertaken to engage ecological carbon sequestration or to protect existing reservoirs will also help to conserve biodiversity, and vice versa.”

On a more cautionary note, Seddon et al. 2020 note that reforestation through commercial plantations often involve single tree species, i.e. monocultures. Dooley et al. 2024’s study of Paris Climate Agreement pledges notes their heavy reliance on land use change and that: “establishing new plantations or expanding forest areas requires a land use change, which is also the leading driver of global biodiversity loss”, referencing this 2019 report. Horn 2022 studies tree planting programs funded by voluntary carbon market and verified according to guidelines of Verified Carbon Standards (VCS), the “market leader” of voluntary carbon standards. A particular focus is on the number of tree species planted, which Horn 2022 finds tends to reduce carbon sequestration – mono-culture commercial forestry stored more

[3] Meanwhile a budding literature in political economy considers obstacles to first-best GHG policies, e.g. Besley and Persson 2023; Longuet-Marx 2024.

[4] Allen et al. 2023 argue that carbon contingent securities might improve welfare by enabling wealthier countries to finance major reductions in carbon emissions.

carbon. In this vein, Huston and Marland 2003 likewise noted: "...the diversity of plants generally declines at high levels of productivity and is low in high productivity forests with massive trees. This counter-intuitive pattern is caused by competition among plants, which is most intense when plants are growing rapidly and achieving large sizes." Seddon et al. 2020; Horn 2022 both note that such monocultures are not supportive of biodiversity.

Flammer et al. 2023 approach the question of biodiversity preservation directly from the perspective of biodiversity finance and private capital, either on its own or "blended" with public of philanthropic capital. Using data from a leading biodiversity institution on deals from 2020 to 2022, Flammer et al. 2023 find that blended finance projects are most common and support large-scale biodiversity projects with moderate risk, but also moderate returns. Underscoring the novelty of the research area that lags substantially behind investor practice, Flammer et al. 2023 is likely the first academic paper to focus specifically on biodiversity finance.

Song et al. 2025 compare carbon storage measure following improved forest management projects in voluntary carbon markets and California's compliance market. Applying their own "business as usual" baselines, which they argue are more realistic, Song et al. 2025 find that "[compliance] market projects are non-additional and voluntary market projects also issue about three times more offset credits than our business-as-usual baselines can justify". Grupp et al. 2023 conduct the empirical analysis most similar to our own in the broadness of its scope and in deploying a large-sample, event study design. Grupp et al. 2023 find that the European Union's Protected Area Policy did not generate any additional benefits in terms of improved vegetative cover or reduced night lights, and therefore are unlikely to have promoted biodiversity as intended.

Finally, work-in-progress by Kotchen and Vogt 2024 highlights the theoretical complexities of offset markets, stressing that they go well beyond asymmetric information between buyers and sellers in the "market for lemons" (Akerlof 1970). Their model allows for buyers to have differing preferences over the additionality of the offset they purchase (modeled as a probability), nor is it revealed to buyers whether their purchased offset was indeed additional. Because of offset reputation effects, all buyers will care about the *collective* additionality of offsets. Results include that the quality of offsets depends on features of the seller and perhaps most troubling, there can be a tradeoff between additionality and the price of the offset.

# 3 Data and Methodology

## 3.1 Data Sources

Our analysis draws on a unique combination of datasets that allow us to examine the intersection of carbon offset markets, biodiversity, and corporate behavior. The primary components of our data are as follows:

### 3.1.1 Voluntary Carbon Offset Data

We construct a novel dataset of voluntary carbon offset projects by hand-collecting information from all major carbon registries. The data cover the period from January 2000 to December 2023 and include 29,974 distinct projects. Project-level information was extracted from publicly available registry records using a combination of automated scraping and manual processing, given the absence of standardized formats across registries.

For each project, we compile detailed metadata, including project identifiers, type, country location, developer information, crediting start date and period, and the volume of credits issued annually and cumulatively. We also document whether projects make biodiversity-related claims or hold certifications for environmental co-benefits.

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A critical component of our data collection involves obtaining precise geographic boundaries for spatial analysis. Project boundary shapes are obtained directly from carbon credit registries as part of their project documentation. We construct our geodatabase by cleaning these existing shapefiles through a two-step verification process. First, we identify and correct technically invalid geometric features, such as overlapping vertices and self-intersecting polygons. Second, we conduct manual visual inspection to identify obviously implausible boundaries that appear incorrectly georeferenced or extremely large relative to typical project types. Projects that fail verification are cross-referenced with original project design documents when available. If reliable boundaries cannot be established, we exclude such projects to avoid measurement error.

On the demand side, we collect credit retirement transactions, recording the retirement date, number of credits retired, credit vintage, and the identity of the retiring entity. Where possible, retiring entities are matched to firm-level identifiers to enable downstream analysis.

This unique dataset contains over 29,974 offset projects and 419,267 credit retirement records from 2000 to 2023, linked to 13,664 firms across 46 countries. Our primary analysis focuses on the subset of projects offering nature-based solutions with precise geolocation of project area boundaries, which are in total 2,701 offset projects. Among these 2,701 projects, 1,730 projects have 5 years of both pre-implementation and post- implementation data, i.e. an 11 year balanced panel.

This dataset offers a comprehensive view of both the supply and demand sides of the voluntary carbon market and enables a large-scale empirical evaluation of the ecological implications of carbon offsetting activities.

### 3.1.2 Biodiversity Metric

In evaluating the biodiversity impacts of carbon offset projects, the Human Influence Index (HII) is employed as the principal indicator of anthropogenic pressure on ecosystems. The selection of HII is motivated by its comprehensive integration of multiple human-driven factors that directly affect biodiversity, making it a suitable and rigorous metric for analyzing the potential ecological consequences of carbon offset activities.

**Human Influence Index (HII)** Developed by Venter et al., 2016, HII is a global, high-resolution metric designed to quantify the cumulative human pressure on natural ecosystems. The HII integrates multiple anthropogenic drivers, including population density, land use intensity (e.g., urban areas, agricultural land), accessibility to natural areas (e.g., distance to roads and railways), and infrastructure development (e.g., powerlines, navigable waterways). By incorporating these diverse variables, the HII provides a robust, temporally consistent measure of the extent and intensity of human impact on biodiversity (Sanderson et al., 2022).

The HII dataset is constructed using satellite-derived data at a 1km spatial resolution, offering a granular view of human influence on ecosystems. This spatial resolution is sufficiently fine to capture localized human impacts, which is essential for the assessment of carbon offset projects that often operate in heterogeneous landscapes with varying degrees of human interference. The temporal scope of the HII (2001-2020) also permits longitudinal analysis, allowing for both spatial and temporal evaluation of changes in human pressure over time, particularly in areas targeted for carbon offset interventions.

The HII assigns values on a scale from 0 to 64, where 0 represents areas with no detectable human influence (pristine ecosystems), and 64 represents areas subjected to maximal human pressure. The index captures the gradient of human impact, making it particularly useful for identifying regions where biodiversity is most at risk from anthropogenic disturbance. Areas with high HII values are typically characterized by significant habitat fragmentation, ecosystem degradation, and diminished biodiversity (See Sanderson et al. 2022).

wcshumanfootprint.org notes differences in how HII is calculated between its 1st and 2nd generation versions. To understand how these changes may impact our results, we plan to restrict the sample and reproduce the main results using 2nd generation only measures of HII from 2015-2020. Unfortunately, this will necessarily mean we are only analyzing the more recent projects established around 2017-2018. While the Human Influence Index (HII) offers broad spatial and temporal coverage and captures key dimensions of anthropogenic pressure, wcshumanfootprint.org has also disclosed the potential for "false negatives" that make HII an imperfect metric of biodiversity habitat. We acknowledge that its relationship with biodiversity is context-dependent and may not always align perfectly with on-the-ground ecological outcomes.

**Rationale for Using HII in Carbon Offset Project Evaluation** The use of HII aligns with how biodiversity is framed in many project documents. Offset developers often emphasize "habitat protection" or "ecosystem restoration" as co-benefits of their interventions, rather than specifying conservation outcomes for individual species. HII thus provides a conceptually coherent and policy-relevant proxy for assessing whether these habitat-oriented claims are realized in practice.

A growing body of ecological research emphasizes that habitat condition—not simply species counts or richness—is the most important determinant of biodiversity outcomes. Habitat loss, degradation, and fragmentation are consistently identified as the primary global drivers of biodiversity decline. The World Wildlife Fund writes that: “Habitat degradation and loss, driven primarily by our food system, is the most reported [biodiversity] threat in each region, followed by overexploitation, invasive species and disease.” (WWF, 2024) As such, any credible evaluation of biodiversity impacts must include an assessment of how interventions affect habitat quality and human pressure on ecosystems.

Carbon offset projects—particularly those involving land-use changes such as reforestation, afforestation, or avoided deforestation—are often promoted as yielding co-benefits for biodiversity. Yet these projects can vary widely in their ecological consequences. Some may restore degraded habitats or reconnect fragmented landscapes, while others—such as those relying on monoculture plantations or road-building—may degrade existing habitat or introduce new pressures.

In this context, the Human Influence Index (HII) offers a rigorous, spatially explicit, and globally consistent measure of anthropogenic pressure on habitat. HII captures factors such as infrastructure density, land accessibility, and population intensity—each of which directly contributes to habitat loss and fragmentation. By measuring changes in HII within project boundaries over time, we can assess whether carbon offset projects reduce or intensify human pressure on ecosystems.

Finally, HII allows for ecological heterogeneity across project contexts. In already degraded landscapes, a reduction in HII may signal successful ecological stabilization or recovery. In contrast, an increase in HII in previously undisturbed areas may indicate newly introduced pressure and potential habitat degradation. By embedding HII into our evaluation framework, we place habitat—the foundational layer of biodiversity—at the center of our empirical assessment of carbon offset project impacts.

**Limitations of the HII in Biodiversity Assessment** While the HII is a robust metric for capturing human pressures, it is important to acknowledge its limitations in biodiversity assessment. The HII primarily reflects human activities and does not directly measure species richness, ecosystem health, or conservation status. Therefore, it should ideally be complemented by additional biodiversity-specific indicators, such as species distribution models, habitat suitability assessments, or biodiversity intactness indices, to obtain a more complete understanding of biodiversity impacts.

However, to the best of our knowledge, no widely available open-source database currently offers biodiversity-specific indicators with the same level of geo-spatial precision and time-series coverage as the HII. This lack of comprehensive, high-resolution biodiversity data poses a significant limitation for biodiversity assessments, particularly in large-scale projects where localized and time-sensitive biodiversity outcomes are essential for accurate evaluation.

As a robustness check, we incorporate the Bioclimate Ecosystem Resilience Index (BERI) and the Biodiversity Habitat Index (BHI). However, these measures are only available for the years 2000, 2005, 2010, 2015, and 2020, limiting their ability to provide continuous temporal coverage across the full study period.

We also attempted to replicate the methodology of the Biodiversity Intactness Index (BII) study, as outlined by De Palma et al. 2021. However, we found that the publicly available data sources required to calculate BII are limited, which constrains the feasibility of generating a comprehensive and comparable BII measure for our study. As a result, our analysis relies primarily on HII, supplemented by BERI and BHI, to assess biodiversity impacts.

Despite these limitations, the HII remains a critical tool in the evaluation of biodiversity outcomes associated with carbon offset projects, particularly when used in conjunction with other ecological metrics. Its capacity to integrate spatial and temporal dimensions of human impact makes it uniquely suited for identifying areas where human activities have the most pronounced effects on ecosystems, and for tracking how these pressures evolve in response to conservation or offset interventions.

In summary, the Human Influence Index (HII) provides a rigorous, geographically comprehensive, and spatially resolved means for understanding the anthropogenic pressures on biodiversity. Its application in this study enables a systematic evaluation of the biodiversity risks and benefits associated with carbon offset projects, ensuring that the ecological outcomes of these interventions are assessed systematically in light of the broader landscape of human disturbance.

We also acknowledge that our sample is restricted to projects from 2000-2020 with adequate geographic documentation suitable for spatial analysis on HII, which may not be representative of the broader population of VCM projects. Projects lacking detailed boundary information were necessarily excluded from our analysis, and these excluded projects might exhibit different biodiversity outcomes than those we can analyze. Our temporal focus means we cannot assess whether more recent projects, potentially developed under improved standards or with better biodiversity planning, might show different patterns from the projects in our sample.

#### 3.1.3 Satellite-based Land Use Land Cover (LULC) Data

We complement the HII with additional satellite-based measures of Land Use Land Cover (LULC) Classification. We employ the ESA CCI Land Cover product, which provides annual global land cover maps at 300m resolution from 2000 to 2020, allowing us to track changes in ecosystem types over time.

#### 3.1.4 Protected Area Data

To assess the additionality of carbon offset projects and their relationship to existing conservation efforts, we use the World Database on Protected Areas (WDPA; UNEP-WCMC and IUCN, 2023). The WDPA is the most comprehensive global database of marine and terrestrial protected areas, offering critical insights into the existing conservation landscape. Key features of this dataset include both spatial (polygonal and point) data and attribute information for each protected area.

We incorporate spatial data on protected areas—sourced from the World Database on Protected Areas (WDPA)—to investigate the interaction between carbon offset projects and pre-existing conservation efforts. First, we calculate the spatial overlap between each offset project and officially designated protected areas. This analysis allows us to assess whether carbon projects are primarily extending protection into previously unprotected landscapes or instead concentrated in areas already under formal conservation management. Substantial overlap with protected areas may raise concerns about additionality, particularly if ecosystem integrity would have been preserved in the absence of carbon finance.

We further stratify our analysis by the International Union for Conservation of Nature (IUCN) classification of overlapping protected areas. This enables us to evaluate whether the stringency or category of existing protection is associated with different ecological outcomes post-project. For example, overlap with high-restriction zones (e.g., IUCN Category Ia) may suggest a lower marginal impact of carbon offsets, while overlap with lower-tier categories (e.g., VI) could imply complementarity between carbon and biodiversity goals.

Taken together, these applications of protected area data allow us to assess not only the additionality of biodiversity benefits from carbon finance but also the potential for voluntary carbon markets to complement, substitute for, or extend existing protected area networks. Our approach sheds light on how carbon finance interacts with traditional conservation tools in shaping land-use and habitat outcomes.

#### 3.1.5 Biodiversity Awareness and Regulatory Events

To capture exogenous shocks to biodiversity awareness and regulatory pressures, we have collected data on major IPBES report releases. (see Giglio et al., 2023). These data allow us to implement difference-in-differences and event study analyses to identify causal effects of information shocks on market behavior.

### 3.2 Empirical Strategy

Our empirical analysis consists of several complementary approaches designed to address our research questions and test our hypotheses.

#### 3.2.1 Raw Event Study Analysis

Before turning to regression analysis, we present raw unadjusted event study plots to examine whether human impact on ecosystems changes following offset project implementation. Using our balanced panel of 1,730 projects with complete 11-year coverage (5 years before and after project establishment), we plot average HII levels relative to project inception.

If the pre-implementation trend in HII is flat, this provides strong support for the parallel trends assumption underlying our difference-in-differences identification strategy. The raw event study visualization allows us to assess this assumption and provides initial evidence on treatment effects before controlling for potential confounders.

This raw data analysis motivates our formal regression specifications, which aggregate across post-implementation periods to estimate average treatment effects while controlling for various confounding factors.

### 3.2.2 Primary Specification

Our main analysis uses a difference-in-differences approach comparing biodiversity outcomes before and after project establishment within the same project areas:

$$HII_{i,j,k,t} = \alpha + \beta PostEstablishment_{i,j,k,t} + \gamma X_{i,j,k,t} + \delta_i + \eta_t + \rho_j + \sigma_k + \epsilon_{i,j,k,t} \quad (1)$$

where $HII_{i,j,k,t}$ represents the Human Influence Index for project $i$ in country $j$, registry $k$, and year $t$. $PostEstablishment_{i,j,k,t}$ is an indicator equal to 1 for the years following project establishment. $X_{i,j,k,t}$ denotes a vector of time-varying control variables. $\delta_i$, $\eta_t$, $\rho_j$, and $\sigma_k$ represent project fixed effects, year fixed effects, country fixed effects, and registry fixed effects, respectively.

By including fixed effects for every project $\delta_i$, we isolate variation in HII coming entirely over time within each individual VCM project. This allows us to remove unobserved differences across projects and their implementations that could otherwise confound variation identifying our primary ($\beta$) coefficients of interest.

### 3.2.3 Temporal Dynamics of Biodiversity Impact

To capture the evolving impact of projects over time, we estimate:

$$HII_{i,j,k,t} = \alpha + \sum_{m=-5}^{5} \beta_m I(t - t^*_{i,j,k} = m) + \gamma X_{i,j,k,t} + \delta_i + \eta_t + \rho_j + \sigma_k + \epsilon_{i,j,k,t} \quad (2)$$

where $I(t - t^*_{i,j,k} = m)$ are indicators for years relative to project establishment, allowing us to trace out dynamic treatment effects.

### 3.2.4 Heterogeneity Analysis

We extend this base specification to examine heterogeneity across project characteristics:

$$\begin{aligned} HII_{i,j,k,t} = {} & \alpha + \beta_1 PostEstablishment_{i,j,k,t} + \beta_2 (PostEstablishment_{i,j,k,t} \times Characteristic_{i,j,k,t-1}) \\ & + \gamma X_{i,j,k,t} + \delta_i + \eta_t + \rho_j + \sigma_k + \epsilon_{i,j,k,t} \end{aligned} \quad (3)$$

where $Characteristic_{i,j,k,t-1}$ represents Project-specific features measured in the year prior to the current observation, such as lagged HII levels, biodiversity requirements, or location in protected areas.

We also exploit the 2017 release of major report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as exogenous shocks to biodiversity awareness, allowing us to identify causal effects on market behavior. by examining market responses to exogenous shocks in biodiversity awareness, we contribute to the literature on information disclosure and market efficiency in environmental markets (Krueger et al., 2020). To the extent we observe increased development of biodiversity-focused projects in the post-release periods, this would suggest that the market is responsive to heightened awareness of biodiversity issues, though the effectiveness of these projects in delivering biodiversity benefits remains open to question. Our findings will have implications for how scientific information is incorporated into market decisions and corporate strategies.

# 4 Results

## 4.1 Temporal Dynamics and Spatial Patterns

Figure 1 illustrates the temporal and geographical distribution of carbon offset projects. The data reveal several notable patterns in market development. Panels A and B demonstrate steady growth in project establishment over time, with particularly pronounced acceleration after 2010. Projects explicitly promoting biodiversity co-benefits (Panel B) follow similar temporal trends but represent a substantial subset of the overall market, suggesting widespread integration of biodiversity claims in project marketing.

The geographic distribution (Panels C and D) shows concentration in specific regions—North America, Europe, and Asia—with notable clustering in areas that may offer favorable regulatory environments or lower implementation costs. This spatial pattern raises important questions about whether projects are targeting locations with the greatest biodiversity conservation potential or those with the most favorable economic conditions.

Figure 2 depicts similar trends for carbon offset credits, showing a rapid increase in credit issuance, especially for biodiversity-related projects. Table 2 focuses on the buyers of carbon offset credits, indicating a growing market with an increasing number of participants over time.

Figure 3 provides a visual representation of the relationship between carbon offset projects and the Human Influence Index. While the spatial patterns are not easily discernible at this map resolution shown in the paper, our preliminary reading of the underlying data suggests a concerning pattern: the comparison between 2001 (Panel A) and 2020 (Panel B) indicates that many carbon offset projects may be established in areas that have experienced increases in habitat disturbance over time. This suggestive spatial-temporal relationship motivates our formal econometric analysis to rigorously test whether projects are successfully reversing or inadvertently accelerating habitat degradation trends.

## 4.2 Impact of Carbon Offsetting Projects on Biodiversity

We begin our analysis by examining the impact of carbon offsetting projects on biodiversity, as measured by the Human Influence Index (HII). Our primary empirical design focuses on the most policy-relevant counterfactual: what would have happened to biodiversity outcomes in specific project locations had no VCM intervention occurred at that time and place. This temporal identification strategy leverages the clearly exogenous variation in project timing, while the remarkable stability of pre-treatment HII trends provides compelling evidence for our identifying assumptions.

Figure 4 presents the core empirical evidence for our analysis, displaying raw data plots from our balanced panel of approximately 1,800 projects tracked over 11 years (five years before and after establishment). Several key patterns emerge from these event study plots. First, the pre-implementation trend in HII is remarkably flat across both panels, providing strong support for the parallel trends assumption underlying our difference-in-differences approach. Second, the change following project inception is, if anything, perverse in direction—moving opposite to what biodiversity co-benefit claims would predict. Panel A, encompassing all projects, shows a clear increase in HII following project establishment, indicating rising human pressure on local ecosystems. Panel B, focusing on projects in areas with initially low human impact, reveals an even more pronounced deterioration in habitat conditions, suggesting that projects may be particularly harmful when implemented in previously undisturbed areas.

Importantly, our analysis addresses the counterfactual of "no VCM project in this particular area" rather than broader questions about geographic or sectoral substitution effects. The flat pre-treatment trends we observe represent one of the strongest starting points imaginable for credible causal identification in applied microeconomics, providing clear support for the parallel trends assumption underlying our difference-in-differences approach.

Whether we consider these raw event study plots or our regression-adjusted tabular estimates that include fixed effects for each project, the basic qualitative patterns remain consistent—a finding that strengthens confidence in our results across different analytical approaches.

Building on the visual evidence from Figure 4, Table 3 presents our baseline findings using average HII as the dependent variable. Column (1) shows that in the full sample, project establishment is associated with a statistically significant 1.297-point increase in HII. This effect attenuates but remains significant when we include comprehensive fixed effects in Column (2), suggesting the relationship is robust to controlling for country-level policies, temporal shocks, and registry-specific practices.

Our most conservative specifications focus on a balanced panel spanning five years before to five years after project establishment (Columns 3-7). Even with project fixed effects that control for all time-invariant characteristics of specific locations, we find that project establishment increases HII by 0.187 points—a 3.7% increase relative to the sample mean of 5.68 (Column 6). This effect size is both statistically significant and economically meaningful, representing a substantive deterioration in habitat conditions.

Column (7) reveals important temporal dynamics in biodiversity impacts. The increase in human pressure is not immediate but develops gradually over time. The coefficient on the EstablishmentYear dummy is positive and significant (0.243), and the effect continues to grow in subsequent years, reaching 0.159 three years after establishment. This pattern suggests that biodiversity impacts may worsen over time as project activities intensify or expand within the designated boundaries.

To account for the skewed distribution of HII and potential non-linear effects, we re-estimate our models using the log of average HII as the dependent variable in Table 4. The results are qualitatively similar, with the coefficient on PostEstablishment in our preferred specification (Column 6) indicating a 5% increase in HII following project establishment, confirming the robustness of our findings to alternative functional forms.

These findings represent a failure to realize the theoretical potential for win-win outcomes that exists in the ecological literature. While high-quality work by Griscom et al. 2017, Huston and Marland 2003, Osuri et al. 2020, and Freedman et al. 2009 demonstrates clear potential for complementarity between carbon sequestration and biodiversity preservation, our results suggest that current VCM implementation fails to harness these potential synergies. Particularly relevant is Osuri et al. 2020's natural experiment in Western Ghats, which shows that monoculture plantations are significantly less stable than natural forests for long-term carbon storage, favoring regeneration of natural forest ecosystems and multi-species plantations for both carbon and biodiversity objectives.

Our interpretation follows the concept of "local average treatment effects." In principle, given the existing ecological literature, VCMs have the potential to simultaneously increase both carbon sequestration and biodiversity preservation. However, realizing this potential would require specific types of land use transitions—such as the regeneration of natural forests in previously degraded areas, or the replacement of monoculture systems with diverse agroforestry—that we do not observe occurring systematically across the projects in our sample. What we document empirically represents the "local average treatment effect" of VCMs as they are currently designed and implemented, which appears to be largely neutral or negative for biodiversity outcomes.

We acknowledge that biodiversity benefits may manifest over longer time horizons than our current analysis captures, particularly for outcomes like species recovery, ecosystem restoration, or forest succession that may require decades to fully realize. However, our findings suggest that any such longer-term benefits would need to overcome the initial habitat degradation doc‘umented in our analysis.

These results have important practical implications for carbon market participants. Current VCM projects may expose investors to "hidden ecological risks" in assets marketed as "green," indicating that investors should not take biodiversity co-benefit claims at face value. At the same time, these findings also present an opportunity for investors to drive positive change by demanding greater transparency in ecological impact assessment. Ideally, investors engaged in active ownership can use this evidence to question carbon offset practices, encourage greater biodiversity disclosure, push for independent ecological impact assessments, and promote projects that demonstrate measurable co-benefits.

## 4.3 Heterogeneity Across Project Characteristics

Having established that carbon offset projects increase human pressure on average, we next examine whether this pattern varies across different project characteristics and implementation contexts.

We are interested in whether specific project characteristics might deliver better biodiversity outcomes, testing for heterogeneous treatment effects across multiple dimensions. This analysis is motivated by the possibility that certain project types, certification standards, or implementation contexts might successfully deliver the biodiversity co-benefits that the average effect obscures.

**Baseline Ecosystem Condition** Projects in areas with initially lower human impact show somewhat smaller increases in human pressure relative to projects in more disturbed areas. However, both groups experience statistically significant increases in HII following implementation. This suggests that baseline conditions influence the magnitude but not the direction of biodiversity impacts.

**Self-Reported Biodiversity Benefits** Projects that explicitly disclose biodiversity benefits in their documentation show modestly smaller increases in HII compared to those that do not make such claims, though this difference is not statistically significant in our pooled analysis. Both categories of projects continue to experience increases in human pressure, indicating that self-reported biodiversity intentions may not consistently translate to measurable habitat improvements on the ground.

**Registry-Mandated Biodiversity Requirements** Projects subject to specific biodiversity requirements set by carbon offset registries show similar patterns to those without such requirements. While the interaction effects suggest some differential impacts, both categories show statistically significant increases in HII following project implementation. This pattern may reflect challenges in designing effective biodiversity safeguards or limitations in their implementation and monitoring across different registry systems.

**Protected Area Location** Projects located within formally protected areas do not show systematically different biodiversity outcomes compared to those outside protected areas. Both groups experience increases in HII, which raises questions about the additional conservation value provided by carbon projects in already protected landscapes. This finding could reflect the complex interactions between carbon finance and existing conservation frameworks, or it might suggest that protected area designation alone is insufficient to prevent habitat degradation when combined with intensive carbon project activities.

**Registry and Rating Heterogeneity** Our analysis across different carbon registries reveals limited systematic heterogeneity in biodiversity outcomes, though statistical power is constrained by relatively small sample sizes for some individual registries (Table 6). While a few registries show patterns that might suggest differential impacts, these effects are generally modest and statistically imprecise. The limited variation across registries may reflect either genuinely similar performance or insufficient statistical power to detect meaningful differences.

Similarly, we find no statistically significant differences between projects that have received external carbon offset ratings and those that remain unrated. This suggests that existing rating systems, which typically focus on carbon integrity and additionality, do not systematically capture biodiversity-related outcomes. The finding highlights a potential gap in current market oversight mechanisms.

**Temporal Patterns: Pre- vs. Post-IPBES** We examine whether project outcomes differ before and after the release of the first IPBES Global Assessment Report in 2014, which heightened global awareness of biodiversity loss. Interestingly, projects established after 2014 show larger increases in human pressure following implementation compared to pre-2014 projects. While this temporal pattern is notable, multiple factors could contribute to this difference, including changes in project types, locations, or implementation approaches over time.

**Synthesis of Heterogeneity Findings** Across all dimensions analyzed—baseline ecosystem condition, certification status, stated biodiversity co-benefits, overlap with formally protected areas, registry affiliation, third-party rating status, and implementation timing—we find limited evidence of ecological improvement. We do not identify clear categories of projects that consistently deliver positive biodiversity outcomes.

This consistent pattern across all dimensions suggests that while effect magnitudes vary across subgroups, the direction of impact remains generally neutral or negative. Our analysis does not reveal a clear category of projects that systematically delivers biodiversity improvements. This finding indicates that current biodiversity safeguards and certification standards may be insufficient to ensure positive habitat outcomes in most contexts.

The variation we observe in effect magnitudes suggests that project design, location, and implementation approach may influence the degree of biodiversity impact. However, the limited evidence of positive outcomes indicates that achieving biodiversity co-benefits may require more fundamental changes to how carbon projects are designed, implemented, and monitored.

These findings suggest the need for developing more targeted approaches to carbon project design and more sophisticated monitoring frameworks that explicitly account for biodiversity outcomes alongside carbon objectives.

## 4.4 Robustness Checks and Additional Analyses

To ensure the reliability of our findings, we conduct several robustness checks using alternative biodiversity metrics and different specifications of our primary HII measure.

First, we test on alternative biodiversity metrics. For each project, we calculate zonal summaries of the HII by overlaying the project boundaries with the HII data, producing key statistics — minimum, and maximum—of HII values within each project's area. We re-estimate our main specifications using the minimum, maximum, and standard deviation of HII as dependent variables (Table A2). The results are qualitatively similar to our main findings, with project establishment associated with increases in all three measures of HII.

To address potential concerns about relying solely on HII as a proxy for biodiversity outcomes, we conduct sensitivity analyses using two complementary satellite-derived measures: the Bioclimatic Ecosystem Resilience Index (BERI) and the Biodiversity Habitat Index (BHI). BERI measures the capacity of ecosystems to maintain biodiversity in the face of human pressures and environmental changes, while BHI quantifies the intactness of natural habitats. These measures provide complementary perspectives to the HII, allowing us to capture different aspects of biodiversity impact.

However, as discussed in Sub-Section Biodiversity Metric, it is important to note that BERI and BHI are only available for the years 2000, 2005, 2010, 2015, and 2020, which limits their ability to provide continuous temporal coverage across our full study period. To address this limitation, we employ a long-difference approach in our analysis, comparing changes in these metrics between the closest available time points before and after project establishment. As shown in Table 8, the results are qualitatively similar to our main findings, showing no evidence of biodiversity improvements following project implementation.

The convergent evidence across multiple independent satellite-derived measures strengthens our conclusion that current VCM projects are not delivering measurable biodiversity co-benefits. The satellite-derived measures provide objective assessment that does not rely on project developer claims or certification processes, offering a reliable basis for evaluating actual environmental outcomes.

Second, we also replicate our heterogeneity analysis using the alternative HII specifications (Table A3). The results largely confirm our main findings, with some variations in effect sizes and statistical significance that do not alter our primary conclusions.

Figures A1, A2, A3 provide visual representations of the robustness checks. These measures consistently reveal patterns in the biodiversity impact of carbon offsetting projects across various HII metrics and project characteristics.

And should treatment effect heterogeneity appear more pronounced, we can look to effect heterogeneity[5] to ascertain where biodiversity improvements might be maximized through carbon markets.

## 4.5 Mechanisms: Land Use Change and Biodiversity Trade-Offs

With our main findings robust to alternative specifications and biodiversity metrics, we turn to understanding the mechanisms behind these biodiversity impacts.

To illuminate the pathways through which VCM projects affect local ecosystems and explain the increases in HII documented above, we examine systematic changes in land cover composition within project boundaries. These results provide our strongest evidence on the specific mechanisms driving the biodiversity impacts we observe.

We use high-resolution satellite-derived Land Use and Land Cover (LULC) data to track land cover categories annually at the project level. These data classify each cell of Earth's surface into ecologically meaningful vegetation and land use types. We aggregate this information across each project's fixed geographic boundary to measure the total area covered by ten mutually exclusive land cover categories. These include evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, mixed forest, a residual "other forest" category, shrubland, pasture, urban land, and an "other" class for transitional or uncategorized terrain.

[5] Systematically, using the approach of Chernozhukov et al., 2018.

To identify the effects of project implementation on land composition, we estimate the following project-level panel regression for each land cover type $l$:

$$\Delta Area^l_{i,j,k,t} = \alpha + \beta \cdot PostEstablishment_{i,j,k,t} + \delta_i + \eta_t + \rho_j + \sigma_k + \epsilon^l_{i,j,k,t}, \quad (4)$$

where $\Delta Area^l_{i,j,k,t}$ is the change in the area (in square meters) of land cover type $l$ in project $i$, located in country $j$, registry $k$, and year $t$. The variable $PostEstablishment$ is a binary indicator equal to one for all years following the project's establishment. Project fixed effects ($\delta_i$) absorb all time-invariant heterogeneity across project sites. Year fixed effects ($\eta_t$), country fixed effects ($\rho_j$), and registry fixed effects ($\sigma_k$) control for temporal shocks, national land use trends, and protocol-specific practices. Standard errors are clustered at the project level.

This specification identifies whether the establishment of an offset project is associated with systematic within-project changes in land composition over time. By modeling first differences in area, we isolate deviations in land use dynamics attributable to project activity, net of underlying trends or fixed site characteristics.

Table 9 presents the results. We find that, on average, offset project implementation is associated with a statistically significant increase in pasture area of approximately 45.9 square meters per year. This gain appears to be offset primarily by reductions in shrubland (–35.4 square meters) and in "other forest" cover (–4.6 square meters). No statistically significant changes are observed across the other forest types or in urban land.

These findings reveal a particularly concerning pattern: VCM project implementation is systematically associated with the conversion of natural and semi-natural vegetation—particularly shrubland and less-dense forest ecosystems—into pasture and related low-diversity land use types. Rather than protecting or restoring natural habitats as might be expected from conservation-oriented carbon projects, we observe systematic conversion toward more intensive land uses that support fewer species and provide diminished ecosystem services.

The ecological implications of shrubland conversion deserve particular attention. Shrubland ecosystems, while perhaps less charismatic than old-growth forests, often support remarkably high biodiversity and provide critical ecological services disproportionate to their modest appearance. These systems frequently serve as biodiversity hotspots, supporting specialized plant communities adapted to specific soil, moisture, and disturbance regimes that cannot survive in other habitat types. Many shrubland systems exhibit exceptional plant diversity, often exceeding that of adjacent forest areas in terms of species richness per unit area, and provide critical habitat for numerous wildlife species, including many that are rare or endemic.

The systematic conversion of shrubland to pasture likely reflects several factors in current carbon project development. First, shrubland areas may be targeted because they are perceived as "underutilized" land that can be "improved" through more intensive management, failing to recognize the ecological value of these natural systems. Second, conversion to pasture may be driven by economic needs of VCM project development, as converting shrubland to pasture can provide immediate income through livestock grazing while potentially claiming carbon sequestration benefits from grass establishment and soil carbon accumulation. However, this approach prioritizes short-term economic returns over longer-term ecological integrity.

These findings indicate that offset project implementation may involve conversion of natural or semi-natural vegetation—particularly shrubland and less-dense forest ecosystems—into pasture or related low-diversity land types. Such transitions are consistent with protocols that allow for agroforestry, managed grazing, or other land uses designed to store carbon but not necessarily to enhance ecological integrity. From a biodiversity perspective, these land use changes are unlikely to constitute habitat improvements and may in fact degrade structural and compositional diversity within the landscape.

Our results suggest that carbon-oriented land management may be effective in enhancing above-ground biomass but can simultaneously reduce habitat quality. These ecological trade-offs are typically unmeasured within current carbon accounting frameworks, which focus on emissions rather than biodiversity outcomes. As such, the voluntary carbon market may incentivize land use transitions that enhance carbon sequestration while eroding the ecological complexity required to support species diversity.

These findings reinforce the importance of incorporating biodiversity-relevant metrics—such as land cover composition and habitat heterogeneity—into monitoring, reporting, and verification (MRV) systems for nature-based climate solutions. Without such safeguards, carbon offset projects may unintentionally promote ecological simplification under the guise of restoration.

## 4.6 Interpretation and Limitations

Several important considerations affect the interpretation of our empirical findings. Our analysis focuses specifically on treated project areas as defined by project developers, meaning our results reflect environmental outcomes within areas that developers designate as treated rather than capturing potential spillover effects in surrounding regions. Since we rely primarily on developer-disclosed project boundaries, our interpretation reflects what developers intend to treat rather than necessarily capturing the full ecological footprint of project activities.

Our sample is restricted to nature-based VCM projects from 2000-2020 that have disclosed detailed geo-boundary data suitable for spatial analysis. This sample restriction means our findings are limited to projects with sufficient geographic documentation, which may not be representative of the broader population of VCM projects. Projects lacking detailed boundary information were necessarily excluded from our analysis, and it is possible that these excluded projects might exhibit different biodiversity outcomes than those we can analyze.

Treatment assignment in our primary analysis depends on whether observations fall within the defined project boundaries. While we implement verification procedures to ensure boundary reliability, imprecise boundaries could introduce measurement error that affects our treatment effect estimates. Boundary precision varies considerably across projects depending on the quality of registry documentation, and some degree of measurement error in boundary definition is likely unavoidable given the heterogeneous nature of our data sources. Additionally, our verification process relies partly on subjective assessments that could introduce inconsistencies across projects.

Our findings should therefore be interpreted as evidence about the observable impacts within developer-defined areas of a specific subset of nature-based VCM projects with adequate spatial documentation, rather than definitive conclusions about all carbon offset programs. The temporal scope of our analysis means our conclusions apply to the generation of VCM projects developed through 2020, and more recent projects operating under evolved standards may show different patterns. Future research with longer time series, ground-based verification, and more comprehensive project coverage would help validate and extend these findings while addressing the limitations of our current approach.

# 5 Discussion and Conclusion

Biodiversity preservation is a plausible potential side benefit of nature-based carbon offsets. Not only is it frequently claimed by project developers, but high quality work by Griscom et al. 2017; Huston and Marland 2003; Osuri et al. 2020; Freedman et al. 2009, etc. leans toward the potential for complementarity with carbon storage (in general). Osuri et al. 2020 leverages a natural experiment in Western Ghats that argues that monoculture plantations are less stable than natural forests in storing carbon, favoring regeneration of natural forest and multi-species plantations for the purposes of sequestering *carbon*. In not finding evidence of this complementarity with VCMs, we see an analogy to the "local average treatment effect" concept [Angrist and Pischke 2009]. In principle given the existing literature, VCMs could increase both carbon and biodiversity. But achieving that would likely require a specific set of land use transitions that we do not observe in any pervasive way. That is, we are not arguing that there is a fundamental or universal incompatibility between carbon sequestration through nature based solutions and biodiversity preservation.[6]

Our strongest empirical evidence speaks to what would have happened to habitat in the project area had the project not occurred. Not only is this empirical test robust to fixed effects for every project (and identified purely by project timing), but it is also robust to measurement error in the satellite-based proxy for habitat. Classical measurement error in the *dependent* variable (as we use HII) is relatively benign, and indeed the "estimated slope parameter will be unbiased...and consistent" [Pindyck and Rubinfeld 1998]. Our heterogeneity analysis implicitly considers the counterfactual of the offset project having occurred in a different context. That said, we have the least to say about how the occurrence of a project in one area affects the likelihood of projects in other areas. Clearly, a broader set of VCM counterfactuals may be addressed in future structural work that builds and estimates general equilibrium models.

In failing to find biodiversity co-benefits, our work reinforces existing doubt spurred by the

[6] Zhou and Almond 2025 consider VCM impacts on carbon storage using Net Primary Product measures.

empirical literature that considered narrow subcategories of VCM projects, e.g. West et al. 2020, 2023; Calel et al. 2025. Additionally, our finding resonates with more conceptually focussed work on VCMs by Kotchen and Vogt 2024. They stress that market failures go go well beyond asymmetric information between buyers and sellers in the "market for lemons" (Akerlof 1970), and that buyers may have differing preferences over the additionality of the offset they purchase (modeled as a probability). Nor is it even revealed to buyers whether their purchased offset was indeed additional. In such a unique and complex market, unintended "surprises" are to be expected, e.g. the potential for tradeoff between additionality and the price of the offset Kotchen and Vogt 2024.

More constructively, our study highlights a benefit of rapid improvements in satellite-based measures of local ecology and habitats. Their broad geographic coverage enables more comprehensive and representative impact evaluations than previously conducted. Particularly as they are free of strategic misreporting, they may provide policymakers opportunities to strengthen the regulatory architecture and MVR governing biodiversity performance in carbon markets. Expanded use of improved satellite-derived measures, in tandem with more traditional ground-based measures, should be explored as part of emerging international frameworks such as the Convention on Biological Diversity (CBD) and the Taskforce on Nature-related Financial Disclosures (TNFD). Meanwhile, investors weighing the veracity of co-benefit claims currently face unpriced ecological risk that might be reduced through greater reliance on high-resolution, satellite data, e.g. to assess the past performance by specific offset developers. Rapid improvements in satellite-derived measures of both carbon sequestration and biodiversity should be leveraged to steer VCMs toward more effective performance.

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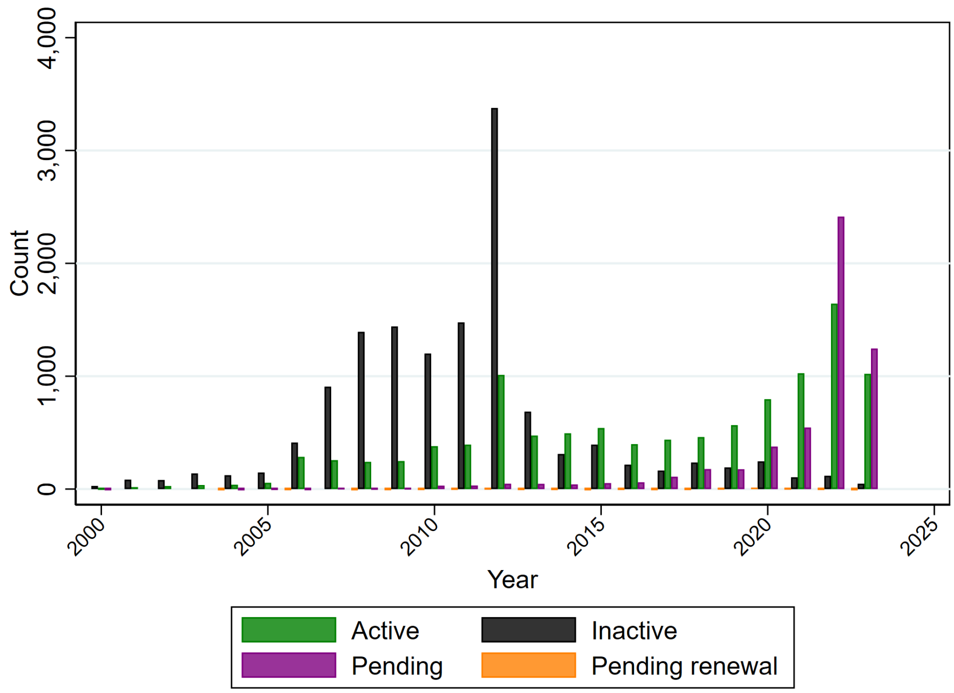
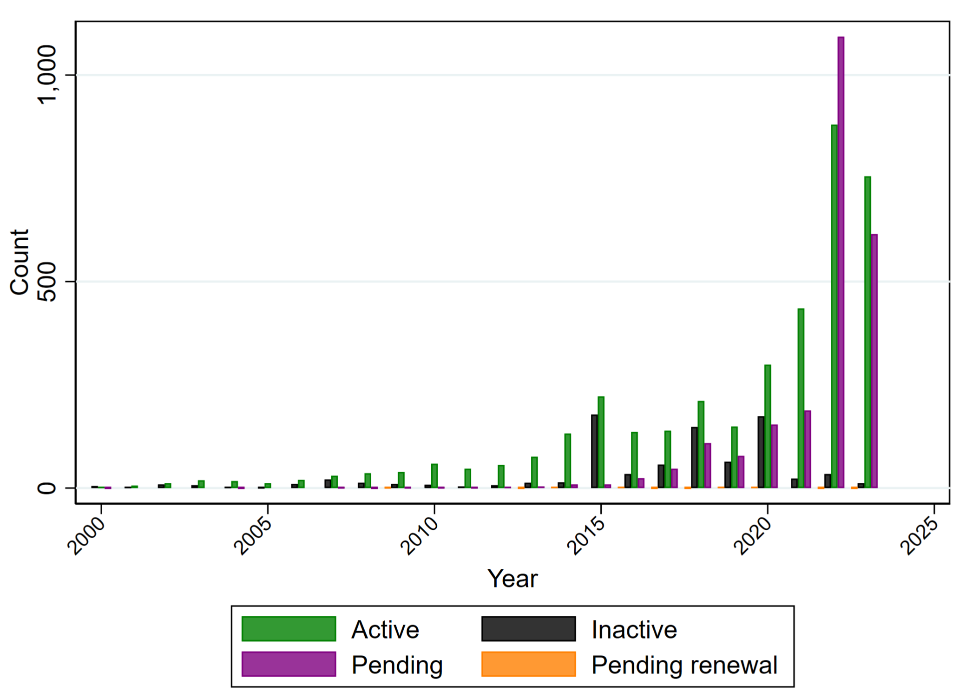
Figure 1: Trends in Carbon Offset Projects

These figures illustrate the time and geographical distributions of carbon offset projects, with a focus on those related to biodiversity.

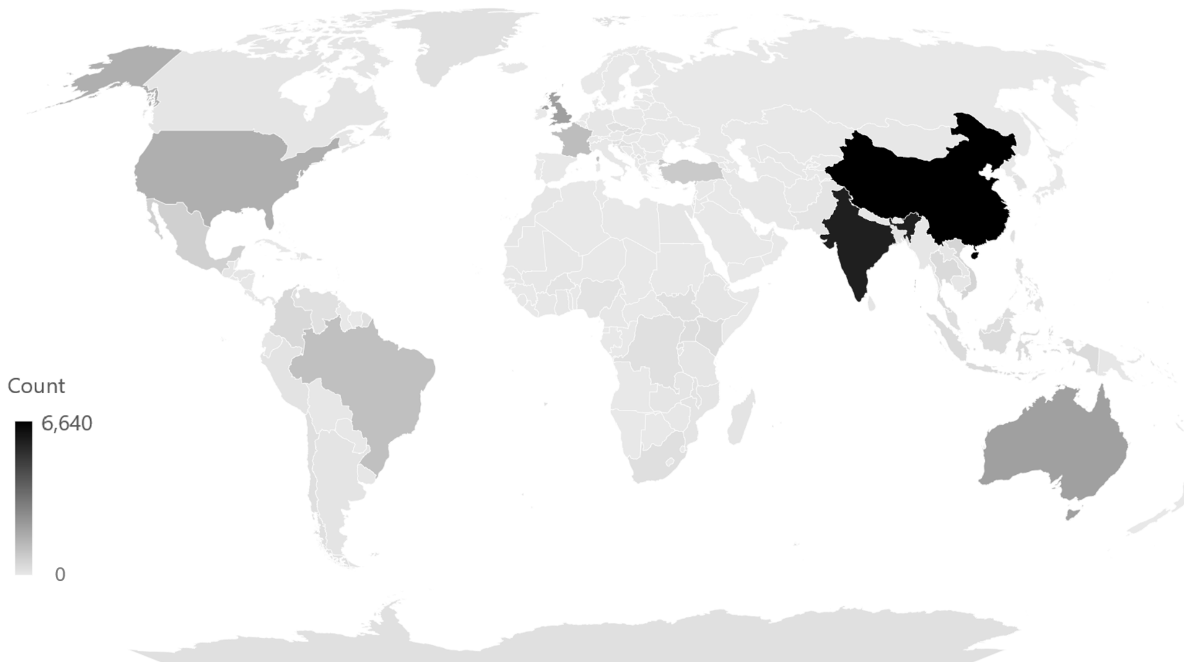
Panel A Carbon Offset Projects




Panel B Carbon Offset Projects Related to Biodiversity



Panel C Carbon Offset Projects




Panel D Carbon Offset Projects Related to Biodiversity

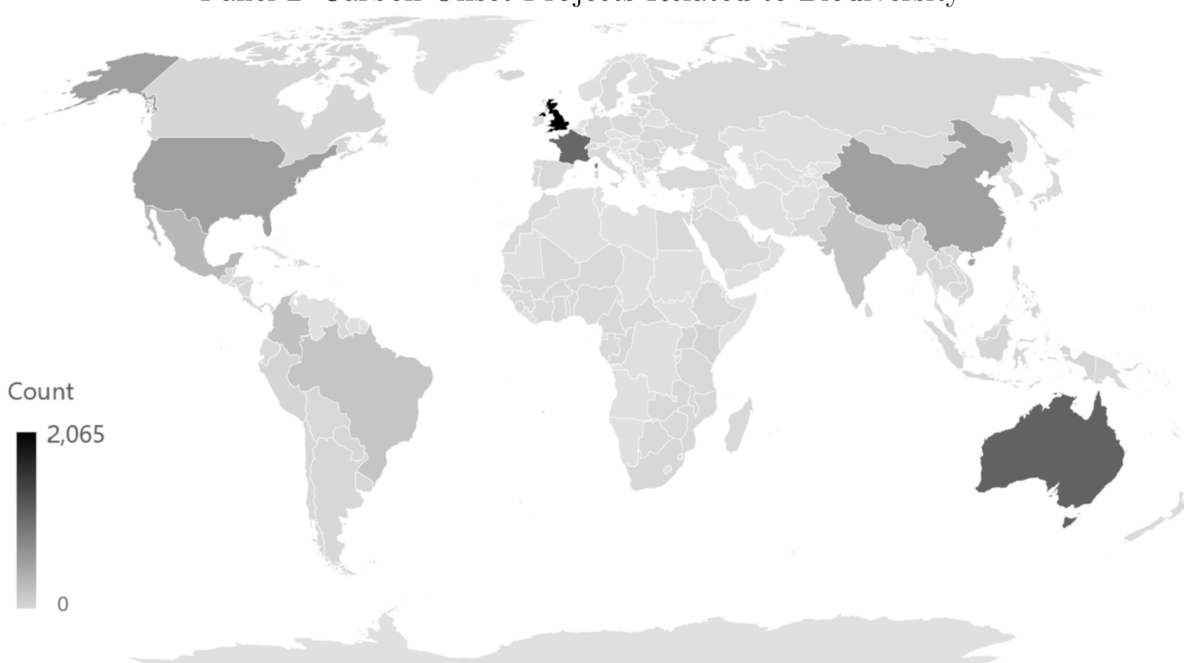
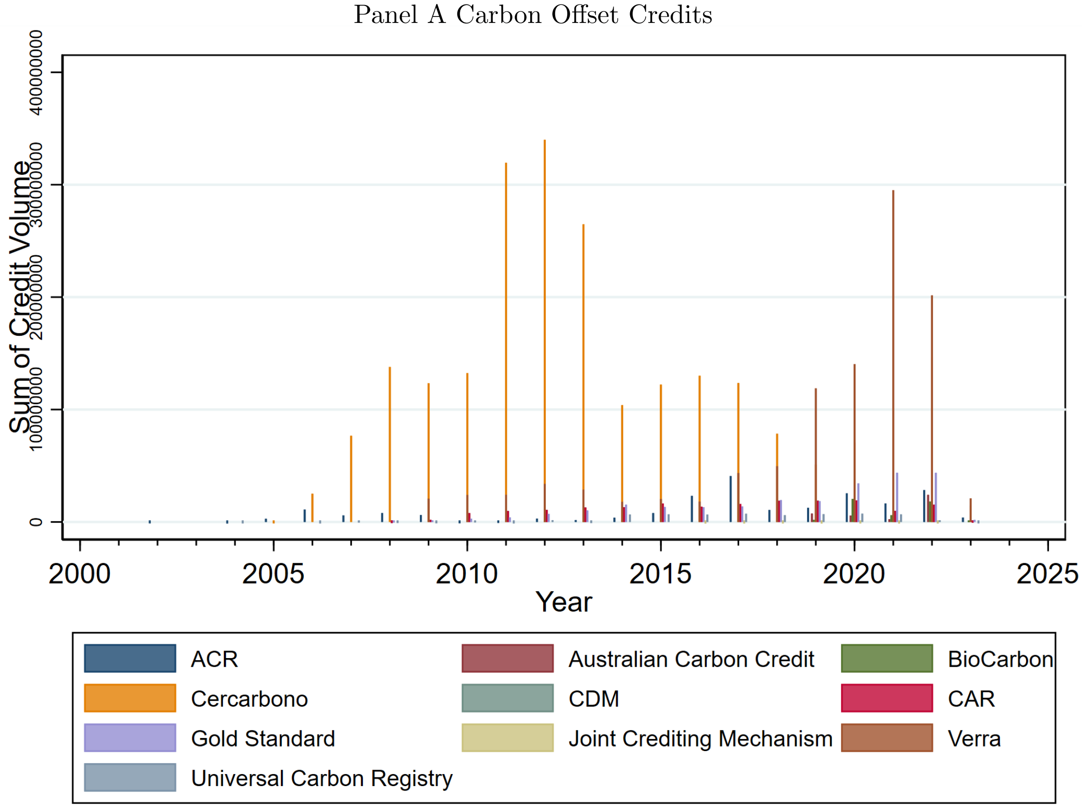


Figure 2: Trends in Carbon Offset Credits

These figures illustrate the time and geographical distributions of carbon offset insurance credits, with a focus on those related to biodiversity. Each unit along the Y-axis corresponds to one metric ton of CO-equivalent emissions offset.

Panel A Carbon Offset Credits




Panel B Carbon Offset Credits Related to Biodiversity

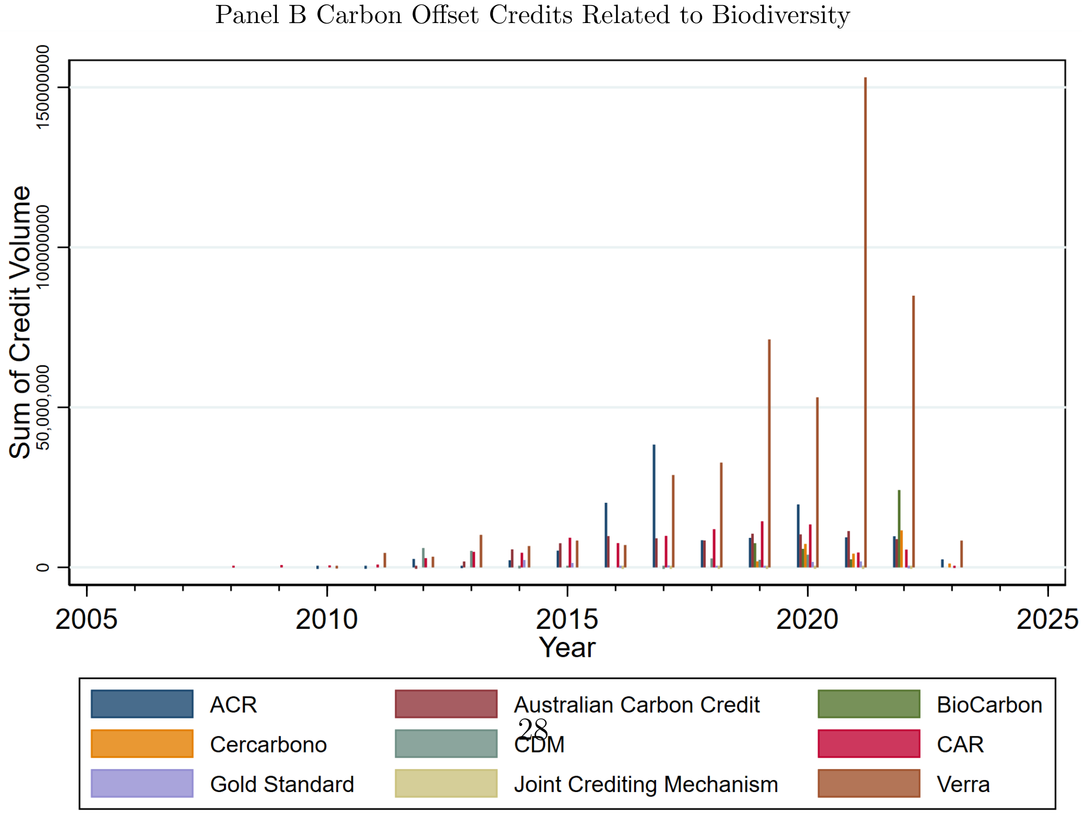
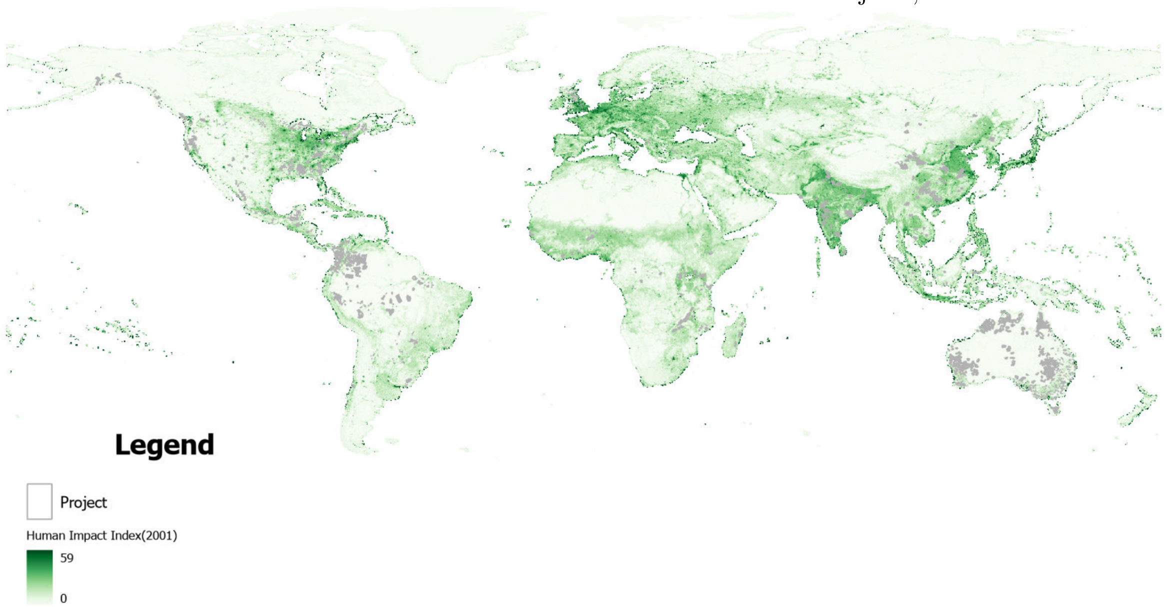


Figure 3: Carbon Offset Projects and Human Influence Index (HII)
This figure shows the relationship between carbon offset projects and the Human Influence Index (HII). Greener areas indicate regions with higher HII, representing greater human impact. The outlined polygons represent the locations of carbon offset projects. Panel A shows the map for the year 2001, and Panel B shows the map for 2020, allowing for a comparison of changes in HII and carbon offset project locations over time.

Panel A Human Influence Index and Carbon Offset Projects, 2001




Panel B Human Influence Index and Carbon Offset Projects, 2020

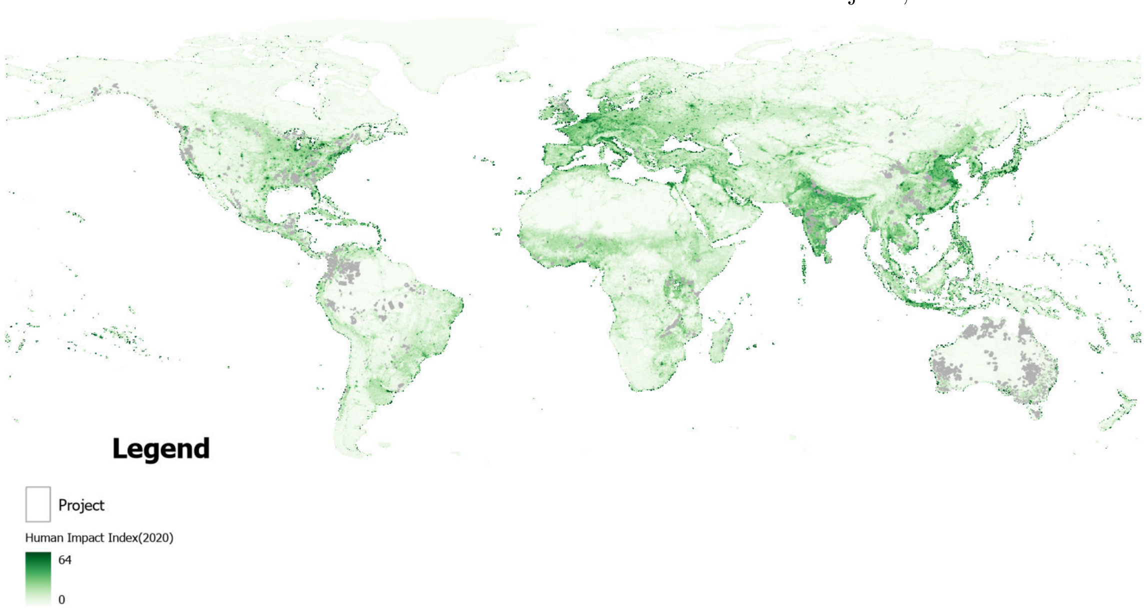


Figure 4: Biodiversity Impact of Carbon Offsetting Projects
This figure shows the impact of carbon offsetting projects on biodiversity using the Human Influence Index (HII). Panel A shows the average treatment effect on the HII for all carbon offsetting projects in the study. Panel B shows the average treatment effect on HII for projects located in areas with initially low human impact, determined by using the median HII value from the year before project establishment. The x-axis represents years relative to project establishment, spanning from t-5 to t+5. The y-axis shows the mean HII values. Shaded areas depict the 10th to 90th percentile range of HII values for each project type. The vertical dashed line at t=0 marks the project establishment year. Higher HII values indicate greater human impact on local ecosystems.

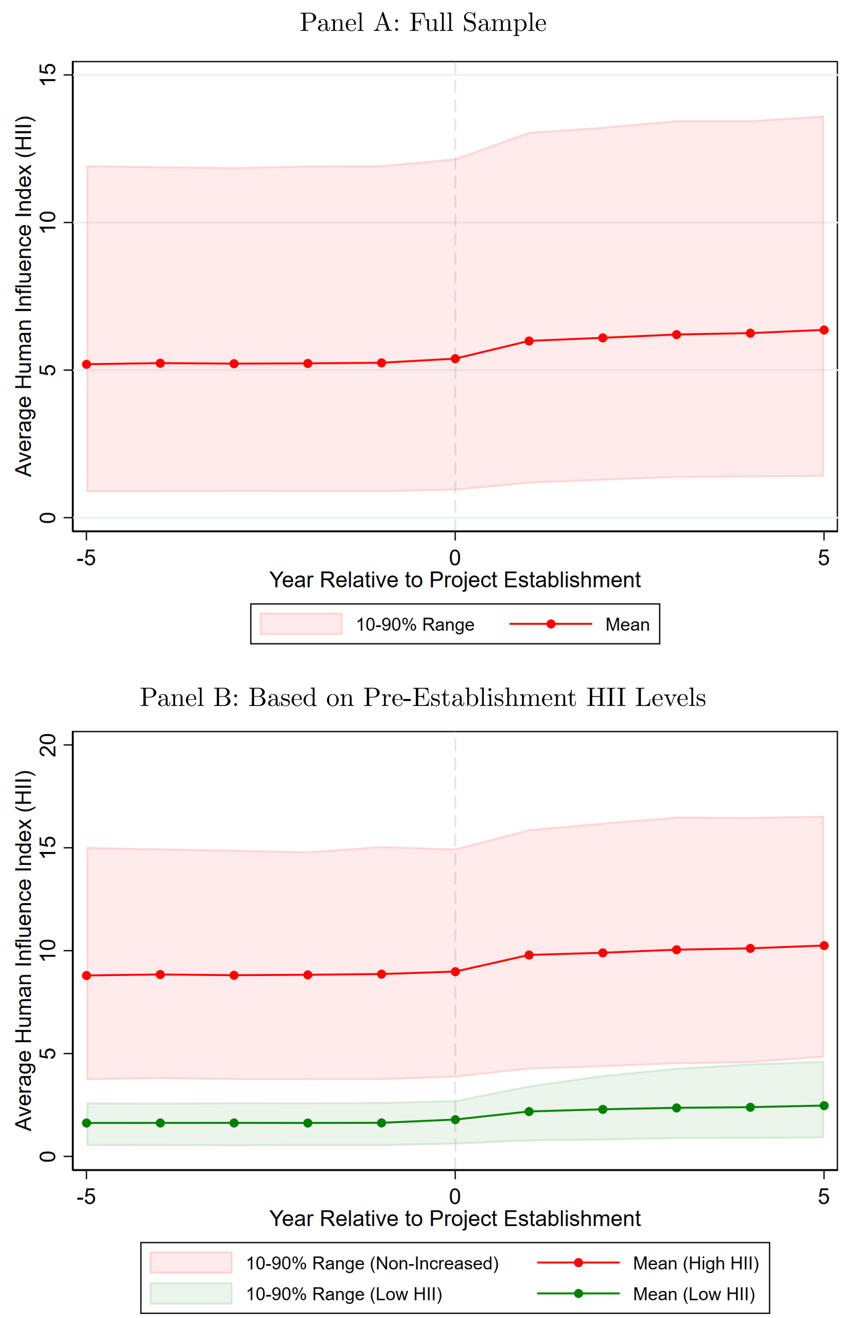
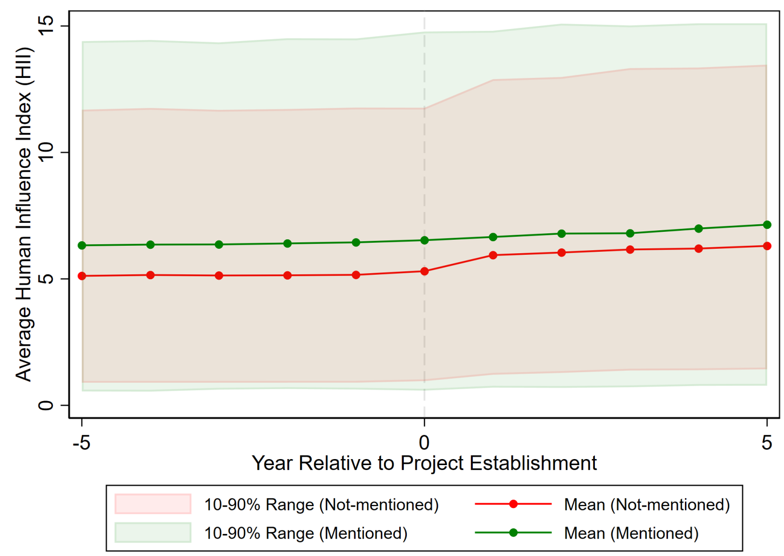


Figure 5: Biodiversity Impact of Carbon Offsetting Projects Based on Project Self-disclosure and Registry Requirements

This figure illustrates the biodiversity impact of carbon offsetting projects, categorized by project characteristics. Panel A presents the average treatment effect on the HII for projects that self-disclose biodiversity benefits in their documentation. Panel B presents the average treatment effect on the HII for projects that are subject to specific biodiversity and conservation requirements set by carbon offset registries. The x-axis represents years relative to project establishment, spanning from t-5 to t+5. The y-axis shows the mean HII values. Shaded areas depict the 10th to 90th percentile range of HII values for each project type. The vertical dashed line at t=0 marks the project establishment year. Higher HII values indicate greater human impact on local ecosystems.

Panel A: Projects Disclosing Biodiversity Benefits




Panel B: Projects with Biodiversity and Conservation Requirements

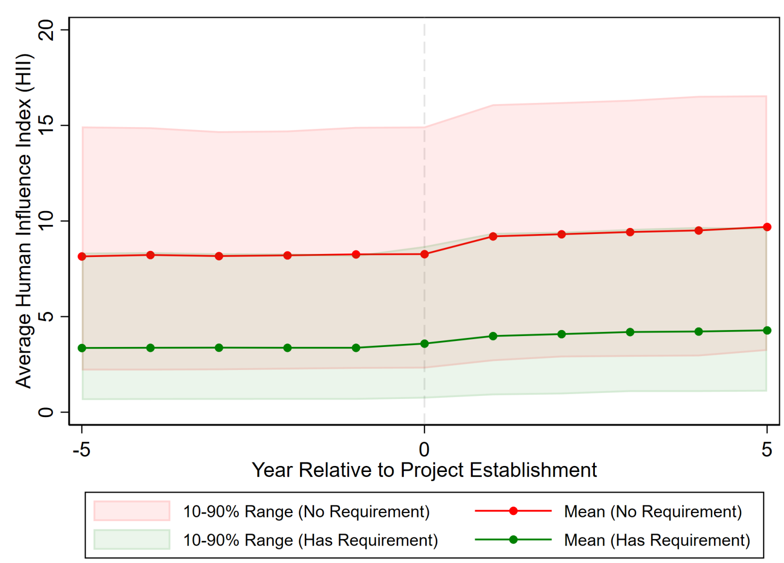


Figure 6: Biodiversity Impact of Carbon Offsetting Projects Based on Protected Area Location

This figure indicates how the location of carbon offsetting projects in relation to protected areas influences their impact on biodiversity, as measured by changes in the HII. Protected areas are defined according to the World Database on Protected Areas (WDPA) classification as the "Strict Nature Reserve". The x-axis represents years relative to project establishment, spanning from t-5 to t+5. The y-axis shows the mean HII values. Shaded areas depict the 10th to 90th percentile range of HII values for each project type. The vertical dashed line at t=0 marks the project establishment year. Higher HII values indicate greater human impact on local ecosystems.

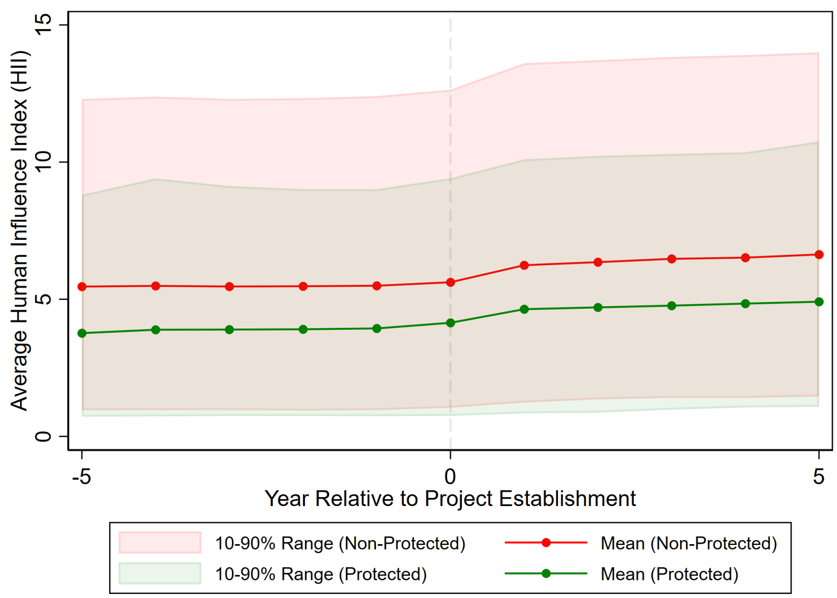


Table 1: Summary Statistics

This table presents summary statistics for the Human Influence Index (HII) across individual carbon offsetting projects. For each project, we calculate zonal summaries of the HII by overlaying the project boundaries with the HII data, producing key statistics—mean, minimum, maximum, and standard deviation—of HII values within each project's area. Panel A shows these summary statistics for the full sample, while Panel B presents the statistics for a balanced subsample, restricted to projects observed consistently from five years before to five years after their establishment.

Panel A: Original Sample

| | count | mean | sd | min | p25 | p50 | p75 | max |
|---|---|---|---|---|---|---|---|---|
| Average of HII | 40,480 | 5.989 | 5.632 | 0.000 | 1.840 | 3.894 | 8.829 | 48.184 |
| Minimum of HII | 40,480 | 2.744 | 4.308 | 0.000 | 0.110 | 0.875 | 3.300 | 47.190 |
| Maximum of HII | 40,480 | 15.184 | 9.968 | 0.000 | 8.070 | 13.245 | 18.550 | 63.000 |
| Standard Deviation of HII | 40,480 | 2.380 | 1.481 | 0.000 | 1.548 | 2.107 | 3.118 | 13.258 |

Panel B: Balanced Sample

| | count | mean | sd | min | p25 | p50 | p75 | max |
|---|---|---|---|---|---|---|---|---|
| Average of HII | 19,022 | 5.676 | 5.223 | 0.000 | 1.872 | 3.516 | 8.464 | 48.184 |
| Minimum of HII | 19,022 | 2.635 | 4.194 | 0.000 | 0.120 | 0.860 | 3.110 | 47.190 |
| Maximum of HII | 19,022 | 14.396 | 8.722 | 0.000 | 8.080 | 13.140 | 17.950 | 61.650 |
| Standard Deviation of HII | 19,022 | 2.327 | 1.388 | 0.000 | 1.607 | 2.093 | 3.018 | 13.258 |

Table 2: Summary of Top Buyers and their Credit Volumes

Panel A: All the credit volumes

| Buyer | Industry | Sum of Credit Volume |
|---|---|---|
| Delta | Aviation | 40,537,111 |
| Shell | Energy | 30,492,007 |
| Toucan Token | Technology and Telecommunication | 22,119,936 |
| PRIMAX COLOMBIA | Energy | 20,654,016 |
| Eni | Energy | 13,406,656 |
| Chevron | Energy | 11,945,963 |
| Takeda | Healthcare | 11,116,338 |
| easyJet | Aviation | 11,088,274 |
| Volkswagen | Industrials | 10,957,763 |
| Hu-Chems Fine Corp | Materials | 10,167,493 |
| Biofix Consultoría | Professional Services Firms | 9,984,218 |
| Banco Votorantim | Financial Services | 9,899,219 |
| Biomax Biocombustibles | Energy | 9,520,524 |
| LSB Industries | Industrials | 7,951,096 |
| Telstra | Technology and Telecommunication | 7,625,653 |
| AUDI | Ground and Maritime Transportation | 7,091,586 |
| Terpel | Energy | 6,966,156 |
| Disney | Consumer Services | 6,210,483 |
| Interface | Industrials | 5,972,412 |
| Petróleos del Milenio | Energy | 5,832,221 |

Panel B: Credits Related to Biodiversity

| Buyer | Industry | Sum of Credit Volume |
|---|---|---|
| Shell | Energy | 25,550,670 |
| PRIMAX COLOMBIA | Energy | 16,469,884 |
| Delta | Aviation | 15,128,050 |
| Eni | Energy | 11,809,160 |
| Biofix Consultoría | Professional Services Firms | 9,984,218 |
| Chevron | Energy | 7,880,886 |
| easyJet | Aviation | 7,202,146 |
| Volkswagen | Industrials | 7,107,138 |
| Disney | Consumer Services | 5,274,148 |
| ENTEGA | Energy | 4,877,217 |
| Greenchoice | Energy | 4,714,574 |
| Gucci | Fashion | 4,385,010 |
| AUDI | Ground and Maritime Transportation | 4,063,253 |
| Terpel | Energy | 3,892,003 |
| PetroChina | Energy | 3,772,096 |
| Takeda | Healthcare | 3,338,971 |
| Petróleos del Milenio | Energy | 3,103,821 |
| Zeuss Petroleum | Energy | 2,680,090 |
| Tokyo Gas | Energy | 2,446,956 |
| Toucan Token | Technology and Telecommunication | 2,308,886 |

Table 3: Effects of Carbon Offset Project Implementation on Habitat Condition

This table reports the effects of carbon offsetting projects on the Human Influence Index (HII). The dependent variable across all specifications is the average HII. Columns (1)–(2) present the average treatment effects for the full sample of carbon offsetting projects, while Columns (3)–(7) restrict the analysis to a balanced subsample, limited to observations from five years before to five years after project establishment. In Columns (1)–(4) and (6), the key independent variable is PostEstablishment, a dummy variable that takes the value of 1 if the project has been established. In Columns (5) and (7), the independent variables include a set of time-period dummy variables. Standard errors, clustered at the project level, are reported in parentheses. Statistical significance is denoted by ***, **, and * for the 1%, 5%, and 10% levels, respectively.

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| VARIABLES | Dependent variable: *Average HII* | | | | | | |
| PostEstablishment | 1.297*** | 0.648*** | 0.822*** | 0.663* | | 0.187*** | |
| | (0.093) | (0.232) | (0.032) | (0.386) | | (0.050) | |
| 5YearBeforeEstablishment | | | | | -0.499 | | -0.114* |
| | | | | | (0.483) | | (0.067) |
| 4YearBeforeEstablishment | | | | | -0.413 | | -0.063 |
| | | | | | (0.360) | | (0.046) |
| 3YearBeforeEstablishment | | | | | -0.295 | | -0.033 |
| | | | | | (0.236) | | (0.034) |
| 2YearBeforeEstablishment | | | | | -0.133 | | -0.024 |
| | | | | | (0.112) | | (0.021) |
| EstablishmentYear | | | | | 0.414*** | | 0.243*** |
| | | | | | (0.120) | | (0.041) |
| 1YearAfterEstablishment | | | | | 0.351 | | 0.017 |
| | | | | | (0.232) | | (0.058) |
| 2YearAfterEstablishment | | | | | 0.543 | | 0.072 |
| | | | | | (0.346) | | (0.057) |
| 3YearAfterEstablishment | | | | | 0.868* | | 0.159*** |
| | | | | | (0.468) | | (0.053) |
| 4YearAfterEstablishment | | | | | 0.863 | | 0.089** |
| | | | | | (0.590) | | (0.040) |
| 5YearAfterEstablishment | | | | | 0.696 | | |
| | | | | | (0.706) | | |
| Observations | 40,480 | 40,480 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 |
| Adjusted R-squared | 0.012 | 0.337 | 0.006 | 0.220 | 0.220 | 0.973 | 0.973 |
| Country FE | N | Y | N | Y | Y | Y | Y |
| Year FE | N | Y | N | Y | Y | Y | Y |
| Registry FE | N | Y | N | Y | Y | Y | Y |
| Project FE | N | N | N | N | N | Y | Y |

Table 4: Robustness: Effects of Carbon Offset Project Implementation on Habitat Condition

This table reports the effects of carbon offsetting projects on the Human Influence Index (HII). The dependent variable across all specifications is the log of the average HII. Columns (1)–(2) present the average treatment effects for the full sample of carbon offsetting projects, while Columns (3)–(7) restrict the analysis to a balanced subsample, limited to observations from five years before to five years after project establishment. In Columns (1)–(4) and (6), the key independent variable is PostEstablishment, a dummy variable that takes the value of 1 if the project has been established. In Columns (5) and (7), the independent variables include a set of time-period dummy variables. Standard errors, clustered at the project level, are reported in parentheses. Statistical significance is denoted by ***, **, and * for the 1%, 5%, and 10% levels, respectively.

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| VARIABLES | Dependent variable: *log(Average HII)* | | | | | | |
| PostEstablishment | 0.323*** | 0.175*** | 0.222*** | 0.091 | | 0.050*** | |
| | (0.019) | (0.047) | (0.011) | (0.069) | | (0.019) | |
| 5YearBeforeEstablishment | | | | | -0.060 | | -0.040 |
| | | | | | (0.083) | | (0.024) |
| 4YearBeforeEstablishment | | | | | -0.050 | | -0.020 |
| | | | | | (0.062) | | (0.016) |
| 3YearBeforeEstablishment | | | | | -0.032 | | -0.010 |
| | | | | | (0.042) | | (0.011) |
| 2YearBeforeEstablishment | | | | | -0.017 | | -0.009 |
| | | | | | (0.022) | | (0.007) |
| EstablishmentYear | | | | | 0.094*** | | 0.071*** |
| | | | | | (0.027) | | (0.018) |
| 1YearAfterEstablishment | | | | | 0.033 | | 0.000 |
| | | | | | (0.044) | | (0.020) |
| 2YearAfterEstablishment | | | | | 0.058 | | 0.010 |
| | | | | | (0.062) | | (0.020) |
| 3YearAfterEstablishment | | | | | 0.088 | | 0.025 |
| | | | | | (0.081) | | (0.017) |
| 4YearAfterEstablishment | | | | | 0.078 | | 0.020 |
| | | | | | (0.101) | | (0.013) |
| 5YearAfterEstablishment | | | | | 0.022 | | |
| | | | | | (0.120) | | |
| Observations | 40,430 | 40,430 | 19,002 | 19,002 | 19,002 | 19,002 | 19,002 |
| Adjusted R-squared | 0.017 | 0.242 | 0.010 | 0.146 | 0.146 | 0.932 | 0.932 |
| Country FE | N | Y | N | Y | Y | Y | Y |
| Year FE | N | Y | N | Y | Y | Y | Y |
| Registry FE | N | Y | N | Y | Y | Y | Y |
| Project FE | N | N | N | N | N | Y | Y |

Table 5: Heterogeneity: Effects of Carbon Offset Project Implementation on Habitat Condition

This table reports the cross-sectional effects of carbon offsetting projects on the Human Influence Index (HII). The dependent variable across all specifications is the average HII. Panels A–D present results from split-sample analyses: Panel A examines projects with low versus high HII prior to establishment; Panel B focuses on projects that disclose biodiversity benefits versus those that do not; Panel C evaluates projects with biodiversity requirements versus those without; and Panel D considers projects located in protected areas versus those not located in such areas. In Columns (1)–(4) and (7)–(8), the key independent variable is PostEstablishment, a dummy variable that takes the value of 1 if the project has been established. In Columns (5)–(6) and (9)–(10), the independent variables include a set of time-period dummy variables. Panel E tests all the above variables separately in the pooled sample. The analysis is conducted in a balanced subsample, limited to observations from five years before to five years after project establishment. Standard errors, clustered at the project level, are reported in parentheses. Statistical significance is denoted by ***, **, and * for the 1%, 5%, and 10% levels, respectively.

Panel A: Low HII Before Establishment

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| VARIABLES | Dependent variable: *Average HII* | | | | | | | | | |
| LowHIIBeforeEstablishment: | Y | N | Y | N | Y | N | Y | N | Y | N |
| PostEstablishment | 0.620*** | 1.020*** | -0.261** | 0.854* | | | 0.140 | 0.223*** | | |
| | (0.037) | (0.051) | (0.122) | (0.474) | | | (0.112) | (0.055) | | |
| 5YearBeforeEstablishment | | | | | 0.252* | -0.572 | | | -0.302* | -0.060 |
| | | | | | (0.148) | (0.589) | | | (0.164) | (0.072) |
| 4YearBeforeEstablishment | | | | | 0.271** | -0.455 | | | -0.134 | -0.055 |
| | | | | | (0.108) | (0.442) | | | (0.112) | (0.052) |
| 3YearBeforeEstablishment | | | | | 0.172** | -0.325 | | | -0.098 | -0.029 |
| | | | | | (0.075) | (0.290) | | | (0.078) | (0.040) |
| 2YearBeforeEstablishment | | | | | 0.067 | -0.166 | | | -0.070 | -0.015 |
| | | | | | (0.041) | (0.140) | | | (0.046) | (0.025) |
| EstablishmentYear | | | | | 0.251*** | 0.358** | | | 0.378*** | 0.150*** |
| | | | | | (0.074) | (0.145) | | | (0.090) | (0.045) |
| 1YearAfterEstablishment | | | | | -0.525*** | 0.623** | | | -0.266** | 0.196*** |
| | | | | | (0.112) | (0.280) | | | (0.133) | (0.062) |
| 2YearAfterEstablishment | | | | | -0.586*** | 0.850** | | | -0.215* | 0.231*** |
| | | | | | (0.129) | (0.418) | | | (0.122) | (0.063) |
| 3YearAfterEstablishment | | | | | -0.563*** | 1.267** | | | -0.063 | 0.276*** |
| | | | | | (0.145) | (0.570) | | | (0.094) | (0.065) |
| 4YearAfterEstablishment | | | | | -0.602*** | 1.226* | | | 0.057 | 0.094* |
| | | | | | (0.186) | (0.719) | | | (0.068) | (0.050) |
| 5YearAfterEstablishment | | | | | -0.823*** | 1.233 | | | | |
| | | | | | (0.258) | (0.855) | | | | |
| Observations | 9,514 | 9,508 | 9,514 | 9,508 | 9,514 | 9,508 | 9,514 | 9,508 | 9,514 | 9,508 |
| Adjusted R-squared | 0.068 | 0.010 | 0.240 | 0.205 | 0.249 | 0.205 | 0.682 | 0.962 | 0.688 | 0.962 |
| Country FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Year FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Registry FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Project FE | N | N | N | N | N | N | Y | Y | Y | Y |

Panel B: Disclose Biodiversity Benefit

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| VARIABLES | Dependent variable: *Average HII* | | | | | | | | | |
| DiscloseBiodiversityBenefit: | Y | N | Y | N | Y | N | Y | N | Y | N |
| PostEstablishment | 0.441*** | 0.850*** | -0.700 | 1.229** | | | 0.115* | 0.189*** | | |
| | (0.075) | (0.033) | (0.524) | (0.485) | | | (0.060) | (0.066) | | |
| 5YearBeforeEstablishment | | | | | 1.029 | -1.153* | | | -0.109* | -0.139 |
| | | | | | (0.695) | (0.619) | | | (0.063) | (0.093) |
| 4YearBeforeEstablishment | | | | | 0.765 | -0.889* | | | -0.078* | -0.074 |
| | | | | | (0.525) | (0.461) | | | (0.046) | (0.064) |
| 3YearBeforeEstablishment | | | | | 0.482 | -0.593** | | | -0.069** | -0.032 |
| | | | | | (0.353) | (0.301) | | | (0.033) | (0.047) |
| 2YearBeforeEstablishment | | | | | 0.238 | -0.280** | | | -0.032 | -0.033 |
| | | | | | (0.182) | (0.143) | | | (0.022) | (0.028) |
| EstablishmentYear | | | | | -0.262 | 0.620*** | | | 0.039 | 0.305*** |
| | | | | | (0.184) | (0.148) | | | (0.030) | (0.053) |
| 1YearAfterEstablishment | | | | | -0.485 | 0.602** | | | 0.112 | -0.078 |
| | | | | | (0.383) | (0.292) | | | (0.072) | (0.076) |
| 2YearAfterEstablishment | | | | | -0.733 | 1.018** | | | 0.167** | -0.024 |
| | | | | | (0.553) | (0.435) | | | (0.074) | (0.074) |
| 3YearAfterEstablishment | | | | | -1.175 | 1.657*** | | | 0.058 | 0.135* |
| | | | | | (0.737) | (0.589) | | | (0.064) | (0.069) |
| 4YearAfterEstablishment | | | | | -1.603* | 1.854** | | | 0.049 | 0.078 |
| | | | | | (0.930) | (0.739) | | | (0.045) | (0.049) |
| 5YearAfterEstablishment | | | | | -2.097* | 1.881** | | | | |
| | | | | | (1.137) | (0.875) | | | | |
| Observations | 1,295 | 17,727 | 1,295 | 17,727 | 1,295 | 17,727 | 1,295 | 17,727 | 1,295 | 17,727 |
| Adjusted R-squared | 0.001 | 0.007 | 0.710 | 0.200 | 0.713 | 0.201 | 0.989 | 0.972 | 0.989 | 0.972 |
| Country FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Year FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Registry FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Project FE | N | N | N | N | N | N | Y | Y | Y | Y |

Panel C: Has Biodiversity Requirement

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| VARIABLES | | | | | Dependent variable: *Average HII* | | | | | |
| HasBiodiversityRequirement: | Y | N | Y | N | Y | N | Y | N | Y | N |
| PostEstablishment | 0.690*** | 1.033*** | -0.642* | 0.088 | | | 0.265*** | 0.141** | | |
| | (0.038) | (0.054) | (0.329) | (0.445) | | | (0.077) | (0.061) | | |
| 5YearBeforeEstablishment | | | | | 0.869** | 0.075 | | | -0.305** | -0.035 |
| | | | | | (0.434) | (0.646) | | | (0.122) | (0.079) |
| 4YearBeforeEstablishment | | | | | 0.594* | 0.048 | | | -0.207** | -0.004 |
| | | | | | (0.323) | (0.478) | | | (0.086) | (0.060) |
| 3YearBeforeEstablishment | | | | | 0.377* | -0.001 | | | -0.122* | -0.015 |
| | | | | | (0.206) | (0.322) | | | (0.063) | (0.046) |
| 2YearBeforeEstablishment | | | | | 0.167* | 0.010 | | | -0.078** | -0.000 |
| | | | | | (0.095) | (0.162) | | | (0.037) | (0.029) |
| EstablishmentYear | | | | | 0.125 | 0.029 | | | 0.381*** | 0.046 |
| | | | | | (0.109) | (0.195) | | | (0.066) | (0.040) |
| 1YearAfterEstablishment | | | | | -0.557*** | 0.071 | | | -0.025 | 0.140* |
| | | | | | (0.194) | (0.363) | | | (0.087) | (0.081) |
| 2YearAfterEstablishment | | | | | -0.808*** | 0.093 | | | 0.010 | 0.222*** |
| | | | | | (0.288) | (0.519) | | | (0.084) | (0.080) |
| 3YearAfterEstablishment | | | | | -0.947** | 0.210 | | | 0.169** | 0.176** |
| | | | | | (0.382) | (0.719) | | | (0.075) | (0.079) |
| 4YearAfterEstablishment | | | | | -1.339*** | -0.026 | | | 0.148*** | 0.022 |
| | | | | | (0.482) | (0.898) | | | (0.050) | (0.073) |
| 5YearAfterEstablishment | | | | | -1.905*** | -0.227 | | | | |
| | | | | | (0.592) | (1.089) | | | | |
| Observations | 11,711 | 7,311 | 11,711 | 7,311 | 11,711 | 7,311 | 11,711 | 7,311 | 11,711 | 7,311 |
| Adjusted R-squared | 0.007 | 0.009 | 0.387 | 0.283 | 0.390 | 0.282 | 0.963 | 0.970 | 0.964 | 0.970 |
| Country FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Year FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Registry FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Project FE | N | N | N | N | N | N | Y | Y | Y | Y |

Panel D: Located In Protective Area

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| VARIABLES | Dependent variable: *Average HII* | | | | | | | | | |
| LocatedInProtectiveArea: | Y | N | Y | N | Y | N | Y | N | Y | N |
| PostEstablishment | 0.869*** | 0.807*** | -0.698* | 1.366** | | | 0.236*** | 0.167** | | |
| | (0.064) | (0.036) | (0.379) | (0.591) | | | (0.072) | (0.074) | | |
| 5YearBeforeEstablishment | | | | | 0.993** | -1.175 | | | -0.234*** | -0.002 |
| | | | | | (0.439) | (0.780) | | | (0.088) | (0.097) |
| 4YearBeforeEstablishment | | | | | 0.710** | -0.942 | | | -0.158** | 0.023 |
| | | | | | (0.330) | (0.574) | | | (0.063) | (0.066) |
| 3YearBeforeEstablishment | | | | | 0.460** | -0.673* | | | -0.089* | 0.018 |
| | | | | | (0.215) | (0.375) | | | (0.046) | (0.049) |
| 2YearBeforeEstablishment | | | | | 0.176* | -0.328* | | | -0.072** | 0.024 |
| | | | | | (0.105) | (0.182) | | | (0.029) | (0.028) |
| EstablishmentYear | | | | | 0.025 | 0.650*** | | | 0.256*** | 0.247*** |
| | | | | | (0.128) | (0.188) | | | (0.059) | (0.061) |
| 1YearAfterEstablishment | | | | | -0.419* | 0.832** | | | 0.098 | -0.018 |
| | | | | | (0.235) | (0.367) | | | (0.079) | (0.085) |
| 2YearAfterEstablishment | | | | | -0.682** | 1.241** | | | 0.138* | 0.043 |
| | | | | | (0.343) | (0.541) | | | (0.074) | (0.083) |
| 3YearAfterEstablishment | | | | | -0.951** | 1.929*** | | | 0.192*** | 0.152* |
| | | | | | (0.452) | (0.734) | | | (0.069) | (0.079) |
| 4YearAfterEstablishment | | | | | -1.376** | 2.190** | | | 0.135*** | 0.068 |
| | | | | | (0.567) | (0.931) | | | (0.052) | (0.061) |
| 5YearAfterEstablishment | | | | | -1.954*** | 2.307** | | | | |
| | | | | | (0.694) | (1.113) | | | | |
| Observations | 4,790 | 14,232 | 4,790 | 14,232 | 4,790 | 14,232 | 4,790 | 14,232 | 4,790 | 14,232 |
| Adjusted R-squared | 0.009 | 0.005 | 0.361 | 0.228 | 0.365 | 0.229 | 0.965 | 0.975 | 0.965 | 0.975 |
| Country FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Year FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Registry FE | N | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Project FE | N | N | N | N | N | N | Y | Y | Y | Y |

Panel E: All

| VARIABLES | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Dependent variable: *Average HII* | | | |
| PostEstablishment | 0.388*** | 0.204*** | 0.444*** | 0.149*** |
| | (0.057) | (0.053) | (0.062) | (0.056) |
| LowHIIBeforeEstablishment x PostEstablishment | -0.479*** | | | |
| | (0.063) | | | |
| DiscloseBiodiversityBenefit x PostEstablishment | | -0.121 | | |
| | | (0.082) | | |
| HasBiodiversityRequirement x PostEstablishment | | | -0.430*** | |
| | | | (0.065) | |
| LocatedInProtectedArea x PostEstablishment | | | | 0.110 |
| | | | | (0.072) |
| Observations | 19,022 | 19,022 | 19,022 | 19,022 |
| Adjusted R-squared | 0.974 | 0.973 | 0.974 | 0.973 |
| Country FE | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y |

Table 6: Registry and Rating Heterogeneity: Effects of Carbon Offset Project Implementation on Habitat Condition

This table reports the estimated effects of carbon offset project implementation on habitat condition, proxied by the Human Influence Index (HII). The dependent variable is the average HII within each project polygon in a given year. Panel A presents results disaggregated by project registry, including ACCU (Australian Carbon Credit Units), ACR (American Carbon Registry), CAR (Climate Action Reserve), CDM (Clean Development Mechanism), Gold Standard, Verra, and a residual "Other" category. Odd-numbered columns (1), (3), (5), etc., report baseline single-difference estimates of the post-project change in HII. Even-numbered columns report event-study specifications, capturing dynamic effects from five years before to four years after project establishment. Panel B presents analogous estimates, disaggregated by whether the project has ever been covered by an external carbon offset rating agency. Columns (1) and (3) report single-difference effects for rated and unrated projects, respectively; columns (2) and (4) present corresponding event-study results. All specifications include project, year, country, and registry fixed effects. Standard errors, clustered at the project level, are reported in parentheses. Statistical significance is denoted by ***, **, and * for the 1%, 5%, and 10% levels, respectively.

Panel A: Heterogeneous Effects by Project Registry

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| VARIABLES: | Dependent variable: *Average HII* | | | | | | |
| Registry: | ACCU | ACR | CAR | CDM | Gold | Verra | Others |
| PostEstablishment | 0.068 | -0.438* | 0.029 | 0.071 | 0.399* | 0.019 | -0.044 |
| | (0.097) | (0.247) | (0.162) | (0.057) | (0.213) | (0.047) | (0.195) |
| Observations | 14,245 | 616 | 1,188 | 108 | 107 | 1,744 | 1,010 |
| Adjusted R-squared | 0.971 | 0.941 | 0.982 | 0.998 | 0.996 | 0.992 | 0.971 |
| Country FE | Y | Y | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y | Y | Y | Y |

Panel B: Heterogeneous Effects by Rating Status

| | (1) | (2) |
|---|---|---|
| VARIABLES | Dependent variable: *Average HII* | |
| Has Carbon Offset Rating or Not: | Rated | Non-Rated |
| PostEstablishment | 0.378*** | 0.174*** |
| | (0.099) | (0.065) |
| Observations | 1,957 | 17,065 |
| Adjusted R-squared | 0.971 | 0.974 |
| Country FE | Y | Y |
| Year FE | Y | Y |
| Registry FE | Y | Y |
| Project FE | Y | Y |

Table 7: Heterogeneous Effects of Carbon Offset Projects Before and After the 2014 IPBES Report

This table presents the estimated effects of carbon offset project implementation on habitat condition, proxied by the Human Influence Index (HII), separately for projects established before and after the release of the first Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment in 2014. The dependent variable is the average HII within each project polygon in a given year. The key independent variable is *PostEstablishment*, a binary indicator equal to one in all years following project initiation. Column (1) reports results for projects established after 2014; Column (2) for those established before 2014. All specifications include country, year, registry, and project fixed effects. Standard errors, clustered at the project level, are reported in parentheses. Statistical significance is denoted by ***, **, and * for the 1%, 5%, and 10% levels, respectively.

| | (1) | (2) |
|---|---|---|
| VARIABLES | Dependent variable: *Average HII* | |
| IPBES Report in 2014: | After | Before |
| PostEstablishment | 1.573*** | 0.090*** |
| | (0.202) | (0.025) |
| | | |
| Observations | 9,284 | 9,699 |
| Adjusted R-squared | 0.979 | 0.997 |
| Country FE | Y | Y |
| Year FE | Y | Y |
| Registry FE | Y | Y |
| Project FE | Y | Y |

Table 8: Robustness: Effects of Carbon Offset Project Implementation on Biodiversity

This table reports the effects of carbon offsetting projects on the Biodiversity Habitat Index (BHI) and the Bioclimatic Ecosystem Resilience Index (BERI). BHI estimates the level of species diversity expected to be retained within any given spatial reporting unit as a function of the unit's area, connectivity and integrity of natural ecosystems across it. BHI can be measured in both portion of species and portion of habitats. BERI measures the capacity of natural ecosystems to retain species diversity in the face of climate change, as a function of ecosystem area, connectivity and integrity - it assesses the extent to which any given spatial configuration of natural habitat across a landscape would promote or hinder climate-induced shifts in biological distributions. The key independent variable is *PostEstablishment*, a dummy variable that takes the value of 1 if the project has been established. Standard errors, clustered at the project level, are reported in parentheses. Statistical significance is denoted by ***, **, and * for the 1%, 5%, and 10% levels, respectively.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| VARIABLES | Dependent variable: *Average BERI* | | Dependent variable: *Average BHI* | |
| PostEstablishment | -0.003*** | | -0.001*** | |
| | (0.001) | | (0.000) | |
| 5-1YearsBeforeEstablishment | | -0.001 | | 0.001 |
| | | (0.001) | | (0.001) |
| 0-4YearssAfterEstablishment | | -0.005*** | | -0.001 |
| | | (0.002) | | (0.001) |
| 5-10YearsAfterEstablishment | | -0.011*** | | -0.006*** |
| | | (0.003) | | (0.002) |
| Observations | 6,940 | 6,940 | 6,940 | 6,940 |
| Adjusted R-squared | 0.996 | 0.996 | 0.999 | 0.999 |
| Country FE | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y |

Table 9: Land Cover Change Following Carbon Offset Project Implementation

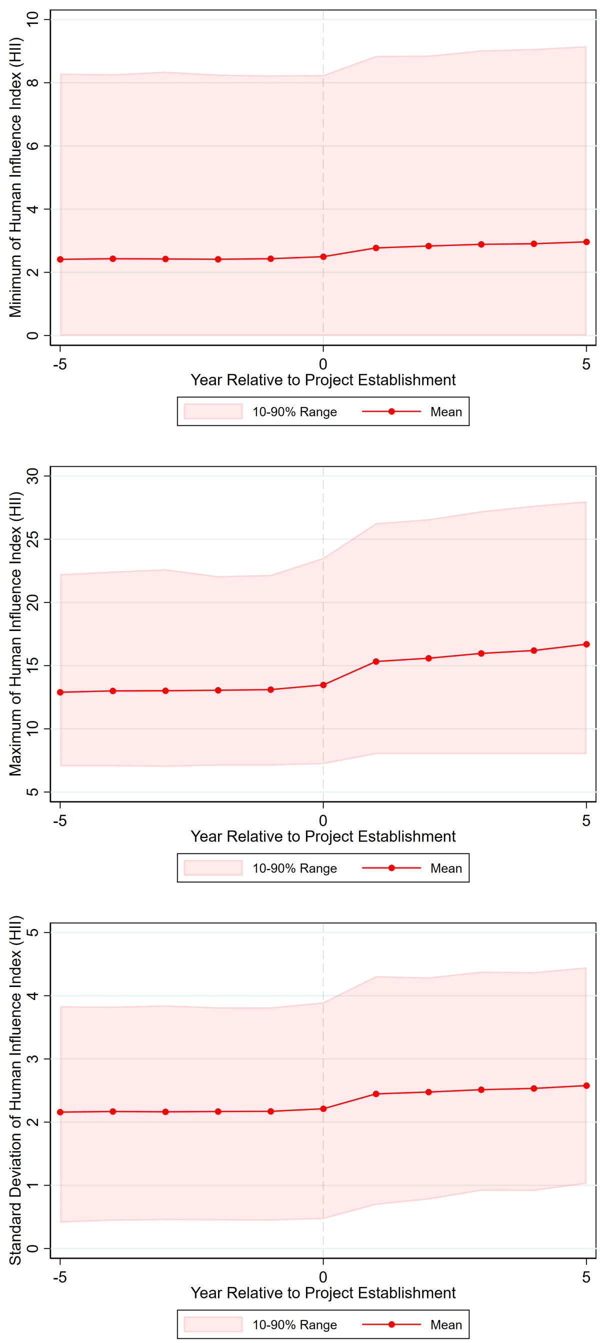
This table reports the estimated effects of carbon offset project implementation on land cover composition, using annual panel data derived from satellite-based Land Use and Land Cover (LULC) maps. The dependent variable in each column is the year-on-year change in area (square meters) of a specific land cover type within the fixed geographic boundary of each project. We estimate separate regressions for each of ten mutually exclusive land cover categories: pasture, shrubland, evergreen needle leaf forest, evergreen broadleaf forest, deciduous needle leaf forest, deciduous broadleaf forest, mixed forest, other forest, urban land, and a residual "other" category. The key explanatory variable is *PostEstablishment*, a binary indicator equal to one for all years following the year in which a project is established. All regressions include project, year, country, and registry fixed effects. Standard errors, clustered at the project level, are reported in parentheses. Statistical significance is denoted by ***, **, and * for the 1%, 5%, and 10% levels, respectively.

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| VARIABLES | $\triangle Pasture$ | $\triangle Shrubland$ | $\triangle EverNeedle$ | $\triangle EverBroad$ | $\triangle DeciNeedle$ | $\triangle DeciBroad$ | $\triangle MixForest$ | $\triangle OtherForest$ | $\triangle Urban$ | $\triangle Other$ |
| PostEstablishment | 45.913*** | -35.418*** | -1.270 | -0.647 | -0.010 | 0.060 | -0.012 | -4.627** | -0.096 | -0.089 |
| | (5.495) | (5.808) | (0.864) | (1.335) | (0.009) | (0.493) | (0.024) | (2.223) | (0.086) | (0.606) |
| Observations | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 |
| Adjusted R-squared | 0.066 | 0.047 | 0.061 | 0.017 | -0.065 | 0.123 | 0.020 | 0.188 | 0.182 | 0.052 |
| Country FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |

## Appendix

Figure A1: Robustness of Figure 4: Biodiversity Impact of Carbon Offsetting Projects
This figure shows the impact of carbon offsetting projects on the Human Influence Index (HII). Panel A shows the minimum, maximum, and standard deviation of HII for all carbon offsetting projects across time in the study. Panel B shows the minimum, maximum, and standard deviation of HII for projects located in areas with initially low human impact, determined by using the median of HII value from the year before project establishment. The x-axis represents years relative to project establishment, spanning from t-5 to t+5. The y-axis shows the maximum HII values. Shaded areas depict the 10th to 90th percentile range of maximum HII values for each project type. The vertical dashed line at t=0 marks the project establishment year. Higher HII values indicate greater human impact on local ecosystems.

Panel A: Full Sample



Panel B: Based on Pre-Establishment HII Levels

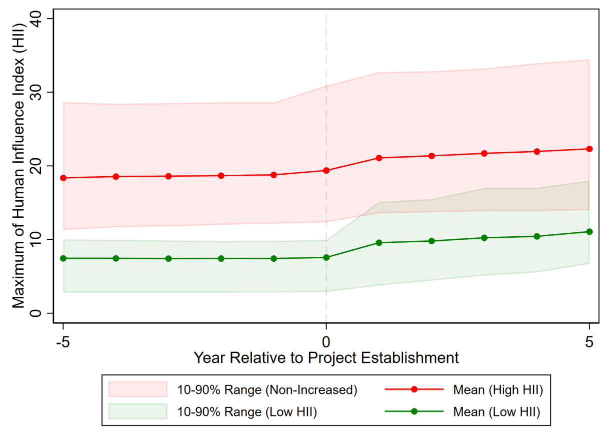
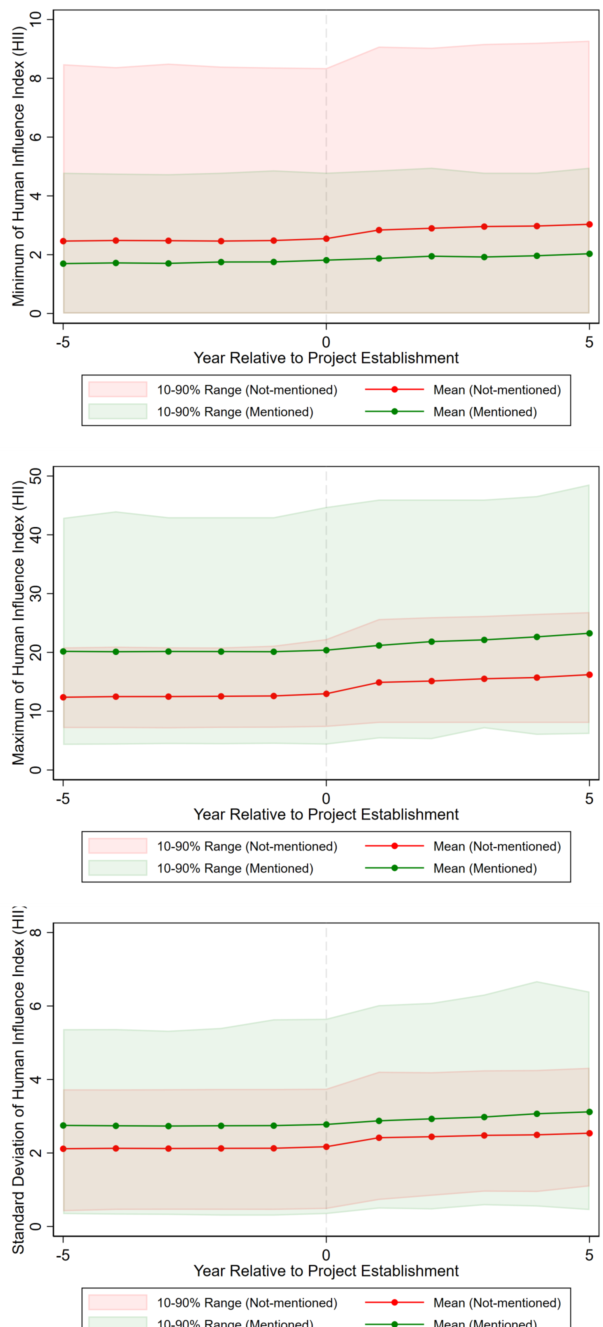




Figure A2: Robustness of Figure 5: Biodiversity Impact of Carbon Offsetting Projects Based on Project Self-disclosure and Registry Requirements

This figure illustrates the biodiversity impact of carbon offsetting projects, categorized by project characteristics. Panel A presents the minimum, maximum, and standard deviation of HII for projects that self-disclose biodiversity benefits in their documentation. Panel B presents the minimum, maximum, and standard deviation of HII for projects that are subject to specific biodiversity and conservation requirements set by carbon offset registries. The x-axis represents years relative to project establishment, spanning from t-5 to t+5. The y-axis shows the maximum HII values. Shaded areas depict the 10th to 90th percentile range of maximum HII values for each project type. The vertical dashed line at t=0 marks the project establishment year. Higher HII values indicate greater human impact on local ecosystems.

Panel A: Projects Disclosing Biodiversity Benefits



Panel B: Projects with Biodiversity and Conservation Requirements

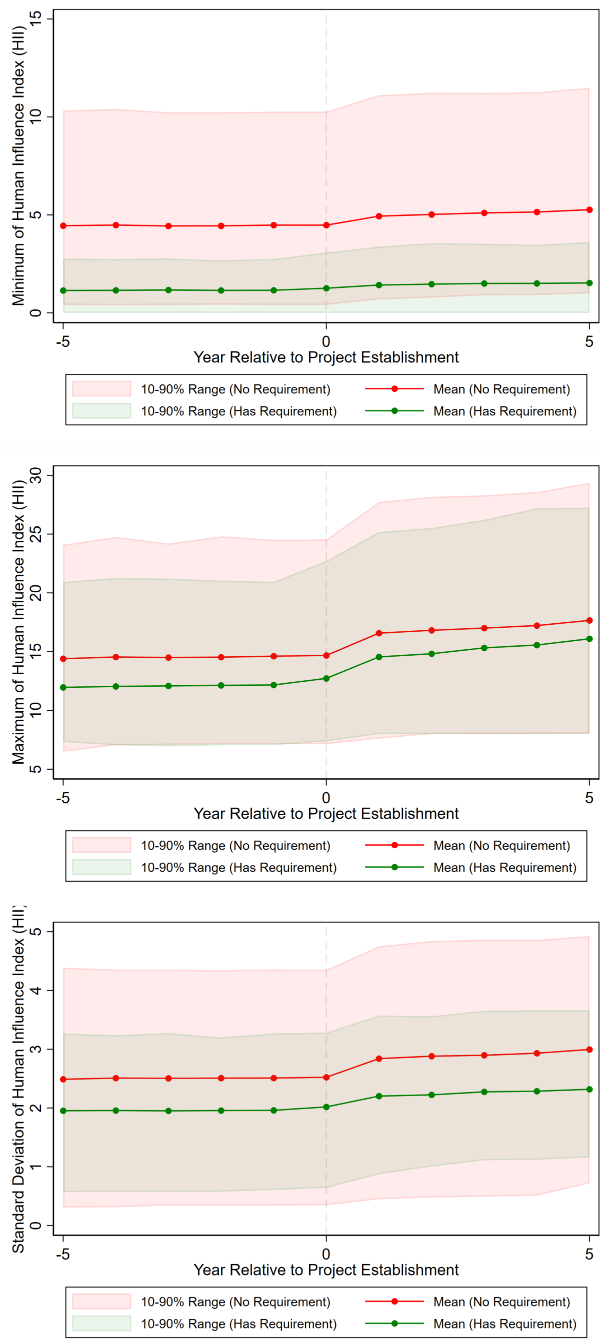


Table A1: Carbon Offset Project Types and Categories

| Project Category | Project Type |
|---|---|
| Agriculture | Fertilizer<br>Grassland/rangeland management<br>Livestock methane<br>No-till/low-till agriculture<br>Rice cultivation/management<br>Sustainable agricultural land management<br>Other - Agriculture |
| Chemical Processes/Industrial Manufacturing | Nitric Acid<br>Ozone-depleting substances<br>Carbon capture and storage<br>Coal mine methane<br>Other - Chemical Processes/Industrial Manufacturing |
| Energy Efficiency/Fuel Switching | Energy efficiency - community-focused (targeting individuals, communities, etc.)<br>Energy efficiency - industrial-focused (targeting corporations)<br>Fuel switching<br>Waste heat recovery<br>Other - Energy Efficiency/Fuel Switching |
| Forestry and Land Use | Afforestation/reforestation<br>Agro-forestry<br>Avoided conversion<br>Improved forest management<br>REDD - Avoided planned deforestation<br>REDD - Avoided unplanned deforestation<br>Soil carbon<br>Urban forestry<br>Wetland restoration/management<br>Other - Forestry and land use |
| Household Devices | Clean cookstove distribution<br>Water purification device distribution<br>Other - Household Devices |
| Renewable Energy | Biogas<br>Biomass/biochar<br>Geothermal<br>Large hydro<br>Run-of-river hydro<br>Solar |

**Carbon Offset Project Types and Categories (continued)**

| Project Category | Project Type |
|---|---|
| | Wind<br>Other - Renewable Energy |
| Transportation | Transportation - private (cars/trucks)<br>Transportation - public (bikes/public transit)<br>Other - Transportation |
| Waste Disposal | Landfill methane<br>Waste water methane<br>Other - Waste Disposal |

Figure A3: Robustness of Figure 6: Biodiversity Impact of Carbon Offsetting Projects Based on Protected Area Location

This figure indicates how the location of carbon offsetting projects in relation to protected areas influences their impact on biodiversity, as measured by changes in the HII. Protected areas are defined according to the World Database on Protected Areas (WDPA) classification as the "Strict Nature Reserve". The x-axis represents years relative to project establishment, spanning from t-5 to t+5. The y-axis shows the minimum, maximum, and standard deviation of HII values. Shaded areas depict the 10th to 90th percentile range for each project type. The vertical dashed line at t=0 marks the project establishment year. Higher HII values indicate greater human impact on local ecosystems.

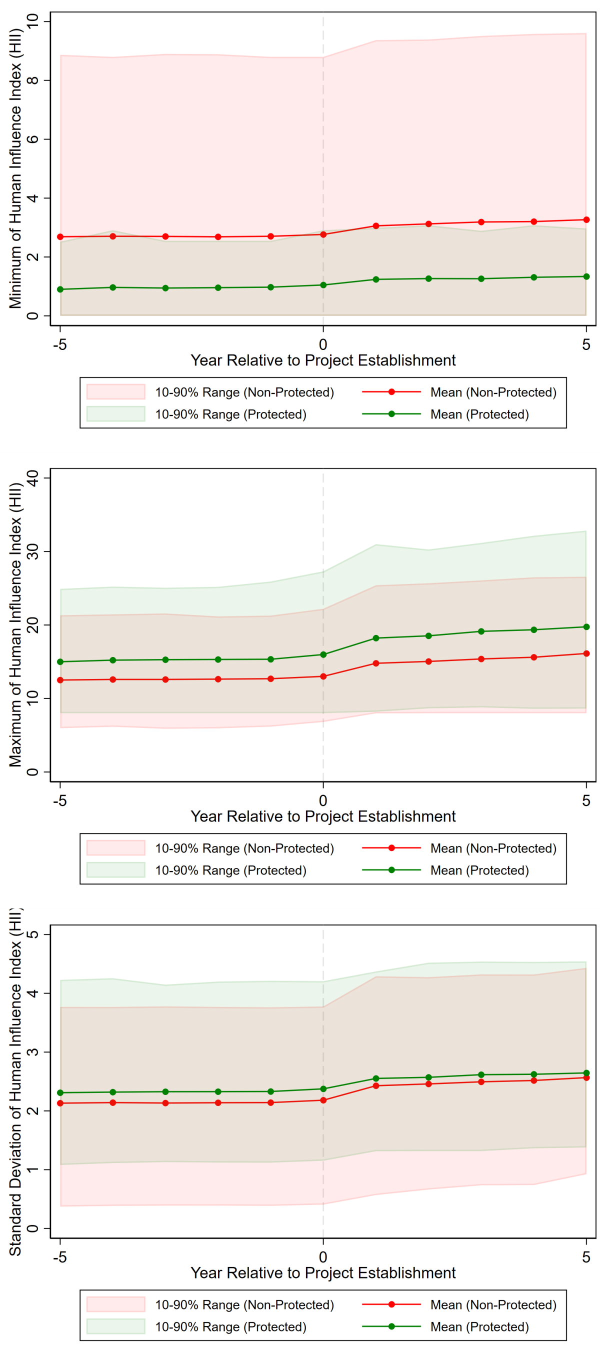


Table A2: Robustness of Table 3: Biodiversity Impact of Carbon Offsetting Projects

This table reports the effects of carbon offsetting projects on the Human Influence Index (HII). The dependent variables in Panels A, B, and C are the minimum, maximum, and standard deviation of HII values, respectively. Columns (1)–(2) present results for the full sample of carbon offsetting projects, while Columns (3)–(7) restrict the analysis to a balanced subsample, limited to observations from five years before to five years after project establishment. In Columns (1)–(4) and (6), the key independent variable is PostEstablishment, a dummy variable that takes the value of 1 if the project has been established. In Columns (5) and (7), the independent variables include a set of time-period dummy variables. Standard errors, clustered at the project level, are reported in parentheses. Statistical significance is denoted by ***, **, and * for the 1%, 5%, and 10% levels, respectively.

Panel A: Minimum of HII

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| VARIABLES | Dependent variable: *Minimum of HII* | | | | | | |
| PostEstablishment | 0.702*** | 0.708*** | 0.387*** | 0.828** | | 0.079** | |
| | (0.069) | (0.208) | (0.026) | (0.343) | | (0.039) | |
| 5YearBeforeEstablishment | | | | | -0.821* | | -0.029 |
| | | | | | (0.437) | | (0.067) |
| 4YearBeforeEstablishment | | | | | -0.585* | | 0.017 |
| | | | | | (0.326) | | (0.047) |
| 3YearBeforeEstablishment | | | | | -0.404* | | 0.016 |
| | | | | | (0.213) | | (0.035) |
| 2YearBeforeEstablishment | | | | | -0.182* | | 0.010 |
| | | | | | (0.101) | | (0.023) |
| EstablishmentYear | | | | | 0.356*** | | 0.115*** |
| | | | | | (0.105) | | (0.032) |
| 1YearAfterEstablishment | | | | | 0.475** | | -0.003 |
| | | | | | (0.206) | | (0.047) |
| 2YearAfterEstablishment | | | | | 0.724** | | 0.026 |
| | | | | | (0.306) | | (0.044) |
| 3YearAfterEstablishment | | | | | 1.113*** | | 0.064 |
| | | | | | (0.415) | | (0.042) |
| 4YearAfterEstablishment | | | | | 1.324** | | 0.018 |
| | | | | | (0.524) | | (0.029) |
| 5YearAfterEstablishment | | | | | 1.498** | | |
| | | | | | (0.617) | | |
| Observations | 40,480 | 40,480 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 |
| Adjusted R-squared | 0.006 | 0.258 | 0.002 | 0.208 | 0.210 | 0.970 | 0.970 |
| Country FE | N | Y | N | Y | Y | Y | Y |
| Year FE | N | Y | N | Y | Y | Y | Y |
| Registry FE | N | Y | N | Y | Y | Y | Y |
| Project FE | N | N | N | N | N | Y | Y |

Panel B: Maximum of HII

| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| | Dependent variable: *Maximum of HII* | | | | | | |
| PostEstablishment | 3.157*** | -0.509 | 2.527*** | -0.626 | | 0.472*** | |
| | (0.166) | (0.450) | (0.081) | (0.683) | | (0.110) | |
| 5YearBeforeEstablishment | | | | | 1.208 | | -0.398** |
| | | | | | (0.771) | | (0.160) |
| 4YearBeforeEstablishment | | | | | 0.790 | | -0.196* |
| | | | | | (0.579) | | (0.114) |
| 3YearBeforeEstablishment | | | | | 0.517 | | -0.093 |
| | | | | | (0.391) | | (0.081) |
| 2YearBeforeEstablishment | | | | | 0.255 | | -0.072 |
| | | | | | (0.200) | | (0.051) |
| EstablishmentYear | | | | | 0.255 | | 0.551*** |
| | | | | | (0.224) | | (0.095) |
| 1YearAfterEstablishment | | | | | -0.404 | | 0.188 |
| | | | | | (0.433) | | (0.123) |
| 2YearAfterEstablishment | | | | | -0.625 | | 0.302** |
| | | | | | (0.646) | | (0.124) |
| 3YearAfterEstablishment | | | | | -0.872 | | 0.435*** |
| | | | | | (0.863) | | (0.122) |
| 4YearAfterEstablishment | | | | | -1.704 | | 0.271*** |
| | | | | | (1.088) | | (0.100) |
| 5YearAfterEstablishment | | | | | -2.914** | | |
| | | | | | (1.341) | | |
| Observations | 40,480 | 40,480 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 |
| Adjusted R-squared | 0.023 | 0.422 | 0.021 | 0.311 | 0.313 | 0.935 | 0.935 |
| Country FE | N | Y | N | Y | Y | Y | Y |
| Year FE | N | Y | N | Y | Y | Y | Y |
| Registry FE | N | Y | N | Y | Y | Y | Y |
| Project FE | N | N | N | N | N | Y | Y |

Panel C: Standard Deviation of HII

| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| | Dependent variable: *Standard Deviation of HII* | | | | | | |
| PostEstablishment | 0.383*** | 0.044 | 0.294*** | -0.032 | | 0.059*** | |
| | (0.023) | (0.068) | (0.014) | (0.100) | | (0.019) | |
| 5YearBeforeEstablishment | | | | | 0.088 | | -0.042 |
| | | | | | (0.116) | | (0.029) |
| 4YearBeforeEstablishment | | | | | 0.044 | | -0.020 |
| | | | | | (0.087) | | (0.021) |
| 3YearBeforeEstablishment | | | | | 0.024 | | -0.015 |
| | | | | | (0.058) | | (0.016) |
| 2YearBeforeEstablishment | | | | | 0.017 | | -0.010 |
| | | | | | (0.029) | | (0.010) |
| EstablishmentYear | | | | | 0.033 | | 0.060*** |
| | | | | | (0.033) | | (0.016) |
| 1YearAfterEstablishment | | | | | -0.023 | | 0.034 |
| | | | | | (0.064) | | (0.024) |
| 2YearAfterEstablishment | | | | | -0.040 | | 0.045* |
| | | | | | (0.094) | | (0.023) |
| 3YearAfterEstablishment | | | | | -0.044 | | 0.065*** |
| | | | | | (0.126) | | (0.021) |
| 4YearAfterEstablishment | | | | | -0.137 | | 0.047*** |
| | | | | | (0.159) | | (0.018) |
| 5YearAfterEstablishment | | | | | -0.318 | | |
| | | | | | (0.198) | | |
| Observations | 40,480 | 40,480 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 |
| Adjusted R-squared | 0.016 | 0.204 | 0.011 | 0.136 | 0.136 | 0.922 | 0.922 |
| Country FE | N | Y | N | Y | Y | Y | Y |
| Year FE | N | Y | N | Y | Y | Y | Y |
| Registry FE | N | Y | N | Y | Y | Y | Y |
| Project FE | N | N | N | N | N | Y | Y |

Table A3: Robustness of Table A4: Heterogeneity: Biodiversity Impact of Carbon Offsetting Projects

This table reports the cross-sectional effects of carbon offsetting projects on the Human Influence Index (HII). The dependent variables in Panels A, B, and C are the minimum, maximum, and standard deviation of HII, respectively. LowHIIBeforeEstablishment is a dummy variable equal to 1 for projects with low HII prior to establishment and 0 for those with high HII. DiscloseBiodiversityBenefit is a dummy variable equal to 1 for projects that disclose biodiversity benefits and 0 otherwise. HasBiodiversityRequirement is a dummy variable equal to 1 for projects with biodiversity requirements and 0 for those without. LocatedInProtectedArea is a dummy variable equal to 1 for projects located in protected areas and 0 for those outside such areas. Standard errors, clustered at the project level, are reported in parentheses. Statistical significance is indicated by ***, **, and * for the 1%, 5%, and 10% levels, respectively.

Panel A: Minimum of HII

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| VARIABLES | Dependent variable: *Minimum of HII* | | | |
| PostEstablishment | 0.234*** | 0.090** | 0.248*** | 0.075* |
| | (0.047) | (0.041) | (0.051) | (0.043) |
| LowHIIBeforeEstablishment x PostEstablishment | -0.369*** | | | |
| | (0.053) | | | |
| DiscloseBiodiversityBenefit x PostEstablishment | | -0.075 | | |
| | | (0.063) | | |
| HasBiodiversityRequirement x PostEstablishment | | | -0.284*** | |
| | | | (0.056) | |
| LocatedInProtectiveArea x PostEstablishment | | | | 0.010 |
| | | | | (0.057) |
| Observations | 19,022 | 19,022 | 19,022 | 19,022 |
| Adjusted R-squared | 0.970 | 0.970 | 0.970 | 0.970 |
| Country FE | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y |

Panel B: Maximum of HII

| VARIABLES | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Dependent variable: *Maximum of HII* | | | |
| PostEstablishment | 0.429*** | 0.430*** | 0.245* | -0.027 |
| | (0.132) | (0.124) | (0.130) | (0.128) |
| LowHIIBeforeEstablishment x PostEstablishment | 0.103 | | | |
| | (0.158) | | | |
| DiscloseBiodiversityBenefit x PostEstablishment | | 0.287 | | |
| | | (0.283) | | |
| HasBiodiversityRequirement x PostEstablishment | | | 0.379** | |
| | | | (0.151) | |
| LocatedInProtectiveArea x PostEstablishment | | | | 1.464*** |
| | | | | (0.196) |
| Observations | 19,022 | 19,022 | 19,022 | 19,022 |
| Adjusted R-squared | 0.935 | 0.935 | 0.935 | 0.936 |
| Country FE | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y |

Panel C: Standard Deviation of HII

| VARIABLES | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Dependent variable: *Standard Deviation of HII* | | | |
| PostEstablishment | 0.104*** | 0.052** | 0.124*** | 0.059*** |
| | (0.024) | (0.021) | (0.025) | (0.021) |
| LowHIIBeforeEstablishment x PostEstablishment | -0.107*** | | | |
| | (0.029) | | | |
| DiscloseBiodiversityBenefit x PostEstablishment | | 0.046 | | |
| | | (0.046) | | |
| HasBiodiversityRequirement x PostEstablishment | | | -0.109*** | |
| | | | (0.031) | |
| LocatedInProtectiveArea x PostEstablishment | | | | 0.000 |
| | | | | (0.030) |
| Observations | 19,022 | 19,022 | 19,022 | 19,022 |
| Adjusted R-squared | 0.922 | 0.922 | 0.922 | 0.922 |
| Country FE | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y |

Table A4: Heterogeneity: Effects of Carbon Offset Project Implementation on Habitat Condition and Land Use Changes

This table reports the cross-sectional effects of carbon offsetting projects on the Human Influence Index (HII) and land use changes. The dependent variable across all specifications is the average HII. The analysis is conducted in a balanced subsample, limited to observations from five years before to five years after project establishment. Standard errors, clustered at the project level, are reported in parentheses. Statistical significance is denoted by ***, **, and * for the 1%, 5%, and 10% levels, respectively.

Panel A: Average HII

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VARIABLES | Dependent variable: *Average HII* | | | | | | | | | | | | |
| PostEstablishment | 0.387*** | 0.204*** | 0.444*** | 0.149*** | 0.645*** | 0.057 | 0.007 | 0.184*** | 0.185*** | 0.219*** | 0.219*** | 0.055 | 0.018 |
| | (0.059) | (0.053) | (0.062) | (0.056) | (0.079) | (0.049) | (0.054) | (0.051) | (0.051) | (0.055) | (0.056) | (0.057) | (0.048) |
| LowHIIBeforeEstablishment × *PostEstablishment* | -0.436*** | | | | | | | | | | | | |
| | (0.065) | | | | | | | | | | | | |
| DiscloseBiodiversityBenefit × *PostEstablishment* | | -0.121 | | | | | | | | | | | |
| | | (0.082) | | | | | | | | | | | |
| HasBiodiversityRequirement × *PostEstablishment* | | | -0.430*** | | | | | | | | | | |
| | | | (0.065) | | | | | | | | | | |
| LocatedInProtectiveArea × *PostEstablishment* | | | | 0.110 | | | | | | | | | |
| | | | | (0.072) | | | | | | | | | |
| ACCU × *PostEstablishment* | | | | | -0.999*** | | | | | | | | |
| | | | | | (0.122) | | | | | | | | |
| ACR × *PostEstablishment* | | | | | | 2.006*** | | | | | | | |
| | | | | | | (0.204) | | | | | | | |
| CAR × *PostEstablishment* | | | | | | | 1.398*** | | | | | | |
| | | | | | | | (0.147) | | | | | | |
| CDM × *PostEstablishment* | | | | | | | | 0.158 | | | | | |
| | | | | | | | | (0.186) | | | | | |
| Gold × *PostEstablishment* | | | | | | | | | 0.088 | | | | |
| | | | | | | | | | (0.140) | | | | |
| Verra × *PostEstablishment* | | | | | | | | | | -0.166*** | | | |
| | | | | | | | | | | (0.064) | | | |
| OtherRegistries × *PostEstablishment* | | | | | | | | | | | -0.270 | | |
| | | | | | | | | | | | (0.209) | | |
| Rated × *PostEstablishment* | | | | | | | | | | | | 0.604*** | |
| | | | | | | | | | | | | (0.114) | |
| AfterIPBES × *PostEstablishment* | | | | | | | | | | | | | 0.918*** |
| | | | | | | | | | | | | | (0.118) |
| Observations | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 | 19,022 |
| Adjusted R-squared | 0.974 | 0.973 | 0.974 | 0.973 | 0.974 | 0.974 | 0.974 | 0.973 | 0.973 | 0.973 | 0.973 | 0.973 | 0.973 |
| Country FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |

## Panel B: Changes in Pasture Area

| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dependent variable: $\triangle Pasture$ | | | | | | | | | | | | |
| PostEstablishment | 29.231*** | 47.938*** | 25.122*** | 60.732*** | 37.034*** | 47.022*** | 47.475*** | 45.973*** | 46.079*** | 48.374*** | 46.266*** | 49.106*** | 40.308*** |
| | (4.484) | (5.843) | (4.524) | (6.406) | (4.751) | (5.690) | (5.784) | (5.522) | (5.510) | (5.996) | (5.542) | (6.090) | (6.115) |
| LowHIIBeforeEstablishment $\times PostEstablishment$ | 33.974*** | | | | | | | | | | | | |
| | (6.930) | | | | | | | | | | | | |
| DiscloseBiodiversityBenefit $\times PostEstablishment$ | | -12.872** | | | | | | | | | | | |
| | | (5.374) | | | | | | | | | | | |
| HasBiodiversityRequirement $\times PostEstablishment$ | | | 33.590*** | | | | | | | | | | |
| | | | (6.269) | | | | | | | | | | |
| LocatedInProtectiveArea $\times PostEstablishment$ | | | | -41.416*** | | | | | | | | | |
| | | | | (12.944) | | | | | | | | | |
| ACCU $\times PostEstablishment$ | | | | | 19.305*** | | | | | | | | |
| | | | | | (6.285) | | | | | | | | |
| ACR $\times PostEstablishment$ | | | | | | -15.561*** | | | | | | | |
| | | | | | | (5.228) | | | | | | | |
| CAR $\times PostEstablishment$ | | | | | | | -12.536*** | | | | | | |
| | | | | | | | (3.853) | | | | | | |
| CDM $\times PostEstablishment$ | | | | | | | | -3.129 | | | | | |
| | | | | | | | | (8.318) | | | | | |
| Gold $\times PostEstablishment$ | | | | | | | | | -15.958*** | | | | |
| | | | | | | | | | (3.179) | | | | |
| Verra $\times PostEstablishment$ | | | | | | | | | | -11.843** | | | |
| | | | | | | | | | | (5.036) | | | |
| Others $\times PostEstablishment$ | | | | | | | | | | | -3.311 | | |
| | | | | | | | | | | | (5.888) | | |
| Rated $\times PostEstablishment$ | | | | | | | | | | | | -13.650*** | |
| | | | | | | | | | | | | (4.621) | |
| AfterIPBES $\times PostEstablishment$ | | | | | | | | | | | | | 28.274*** |
| | | | | | | | | | | | | | (10.286) |
| Observations | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 |
| Adjusted R-squared | 0.067 | 0.067 | 0.067 | 0.067 | 0.067 | 0.067 | 0.067 | 0.066 | 0.066 | 0.067 | 0.066 | 0.067 | 0.067 |
| Country FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |

## Panel C: Changes in Strubland Area

| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Dependent variable: $\triangle Shrubland$ | | | | | | | |
| PostEstablishment | -19.034*** | -38.036*** | -17.247*** | -47.775*** | -26.608*** | -36.163*** | -36.712*** | -35.634*** | -35.483*** | -38.757*** | -35.602*** | -39.600*** | -30.369*** |
| | (4.800) | (6.075) | (4.602) | (6.144) | (5.292) | (6.019) | (6.133) | (5.842) | (5.826) | (6.259) | (5.934) | (6.378) | (6.832) |
| LowHIIBeforeEstablishment $\times PostEstablishment$ | -33.367*** | | | | | | | | | | | | |
| | (6.728) | | | | | | | | | | | | |
| DiscloseBiodiversityBenefit $\times PostEstablishment$ | | 16.640* | | | | | | | | | | | |
| | | (9.447) | | | | | | | | | | | |
| HasBiodiversityRequirement $\times PostEstablishment$ | | | -29.358*** | | | | | | | | | | |
| | | | (6.073) | | | | | | | | | | |
| LocatedInProtectiveArea $\times PostEstablishment$ | | | | 34.537*** | | | | | | | | | |
| | | | | (12.319) | | | | | | | | | |
| ACCU $\times PostEstablishment$ | | | | | -19.155*** | | | | | | | | |
| | | | | | (7.090) | | | | | | | | |
| ACR $\times PostEstablishment$ | | | | | | 10.455** | | | | | | | |
| | | | | | | (4.967) | | | | | | | |
| CAR $\times PostEstablishment$ | | | | | | | 10.390*** | | | | | | |
| | | | | | | | (3.751) | | | | | | |
| CDM $\times PostEstablishment$ | | | | | | | | 11.321*** | | | | | |
| | | | | | | | | (3.321) | | | | | |
| Gold $\times PostEstablishment$ | | | | | | | | | 6.322 | | | | |
| | | | | | | | | | (6.115) | | | | |
| Verra $\times PostEstablishment$ | | | | | | | | | | 16.072** | | | |
| | | | | | | | | | | (7.943) | | | |
| Others $\times PostEstablishment$ | | | | | | | | | | | 1.726 | | |
| | | | | | | | | | | | (6.182) | | |
| P_HasRatings $\times PostEstablishment$ | | | | | | | | | | | | 17.876*** | |
| | | | | | | | | | | | | (6.349) | |
| AfterIPBES $\times PostEstablishment$ | | | | | | | | | | | | | -25.472** |
| | | | | | | | | | | | | | (10.408) |
| Observations | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 |
| Adjusted R-squared | 0.048 | 0.048 | 0.048 | 0.048 | 0.048 | 0.048 | 0.048 | 0.048 | 0.048 | 0.048 | 0.048 | 0.048 | 0.048 |
| Country FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |

## Panel D: Changes in Other Forest Area

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VARIABLES | Dependent variable: $\triangle ForestOthers$ | | | | | | | | | | | | |
| PostEstablishment | -3.239 | -4.414** | -2.254 | -7.023** | -4.282 | -5.091** | -4.835** | -4.786** | -4.635** | -4.116** | -4.378* | -4.479** | -5.312** |
| | (2.632) | (2.044) | (2.617) | (2.942) | (2.827) | (2.215) | (2.256) | (2.247) | (2.228) | (2.063) | (2.257) | (2.128) | (2.290) |
| LowHIIBeforeEstablishment $\times PostEstablishment$ | -2.827 | | | | | | | | | | | | |
| | (2.379) | | | | | | | | | | | | |
| DiscloseBiodiversityBenefit $\times PostEstablishment$ | | -1.355 | | | | | | | | | | | |
| | | (5.400) | | | | | | | | | | | |
| HasBiodiversityRequirement $\times PostEstablishment$ | | | -3.833* | | | | | | | | | | |
| | | | (2.104) | | | | | | | | | | |
| LocatedInProtectiveArea $\times PostEstablishment$ | | | | 6.697 | | | | | | | | | |
| | | | | (5.077) | | | | | | | | | |
| ACCU $\times PostEstablishment$ | | | | | -0.750 | | | | | | | | |
| | | | | | (2.572) | | | | | | | | |
| ACR $\times PostEstablishment$ | | | | | | 6.513** | | | | | | | |
| | | | | | | (2.578) | | | | | | | |
| CAR $\times PostEstablishment$ | | | | | | | 1.673 | | | | | | |
| | | | | | | | (1.582) | | | | | | |
| CDM $\times PostEstablishment$ | | | | | | | | 8.332 | | | | | |
| | | | | | | | | (7.648) | | | | | |
| Gold $\times PostEstablishment$ | | | | | | | | | 0.795 | | | | |
| | | | | | | | | | (2.357) | | | | |
| Verra $\times PostEstablishment$ | | | | | | | | | | -2.458 | | | |
| | | | | | | | | | | (4.207) | | | |
| Others $\times PostEstablishment$ | | | | | | | | | | | -2.328 | | |
| | | | | | | | | | | | (2.052) | | |
| Rated $\times PostEstablishment$ | | | | | | | | | | | | -0.631 | |
| | | | | | | | | | | | | (3.582) | |
| AfterIPBES $\times PostEstablishment$ | | | | | | | | | | | | | 3.459 |
| | | | | | | | | | | | | | (3.894) |
| Observations | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 | 17,682 |
| Adjusted R-squared | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 |
| Country FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Registry FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Project FE | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |