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

Zoey Yiyuan Zhou* and Douglas Almond‡

July 2025

NOT FOR CITATION OR DISTRIBUTION

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 offset projects in particular may generate biodiversity "co-benefits". This study provides the first comprehensive empirical investigation of how voluntary carbon offset projects – which often promote their biodiversity co-benefits to investors – impact habitat. We compile the largest extant dataset of voluntary carbon offset projects with finely-resolved data on local ecosystems from satellite-derived measures of habitat. Results indicate carbon offset projects are associated with a 3.7% <u>increase</u> in habitat disturbance, as measured by the Human Influence Index (HII). We examine heterogeneity by ecosystem condition, certifications, stated co-benefits, protected area overlap, registry, rating status, and timing relative to the influential 2014 IPBES report, but 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. Analyzing supplementary land-use data, we show that that carbon projects prompt conversion of biodiverse habitats into pasture or simplified landscapes, and thereby ecological trade-offs.

Keywords: Biodiversity, Nature-based Solutions, Voluntary Carbon Offset, Carbon Farming, Additionality.

*Zhou (zoeyzhou@ust.hk; yz2851@columbia.edu, corresponding): Hong Kong University of Science and Technology (HKUST) and Columbia University

†Almond (da2152@columbia.edu): Columbia University and NBER

‡We thank conference participants from the Cambridge University-RevFin biodiversity conference, the Inaugural ASU-HKU Interdisciplinary Conference (Hong Kong), the SGFIN Research Conference on Sustainability (Singapore), the Environmental Policy Conference for the Green Transition (University of Zurich), the UNC/Duke Corporate Finance Conference, and faculty and students from Columbia's Sustainable Development Program and HKUST Green Finance Reading Group for their helpful comments. This research is supported by the Research Grants Council (RGC) of the Hong Kong Special Administrative Region, China, under the project "Developing Hong Kong as a Global Green Finance Centre" (project no. T31-603/21-N) of Theme-based Research Scheme (TRS) 2021/22 and fellowship support from the Property and Environment Research Center (PERC). All errors are our own.

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)

The dual crises of climate change and biodiversity loss pose systemic risks to financial stability, economic growth, and human welfare (Dasgupta, 2021; NFGS, 2022; Karolyi and Tobin-de la Puente, 2023). Yet international policy responses remain fragmented and inadequate. Among the 137 countries that have submitted national biodiversity strategies, more than half fail to propose any concrete action toward protecting 30% of land and sea—despite this target being formally adopted by 190 countries 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). This evidence casts doubt on the effectiveness of headline conservation pledges.

Meanwhile, the voluntary carbon market (VCM) has emerged as a mechanism for channeling private capital into climate mitigation and, increasingly, biodiversity conservation. Projects in this market allow firms to offset emissions by investing in low-cost sequestration activities elsewhere, many of which involve forestry or land use changes – so-called "nature-based solutions." These projects often explicitly claim biodiversity co-benefits alongside carbon reductions. The VCM, valued at $2 billion in 2021 is projected to reach $50 billion by 2030 (McKinsey & Company, 2021), with over 980 million metric tons of CO already retired. This market operates on the premise that carbon offset projects can deliver emissions reductions while simultaneously providing ecological co-benefits, particularly biodiversity conservation.

If effective, the VCM could provide a major infusion of conservation finance. Several features make it a compelling setting for empirical evaluation. First, it is one of the few mechanisms through which private capital is directed explicitly toward biodiversity outcomes at scale. Second, many projects publicly claim biodiversity co-benefits, but these assertions are seldom subject to independent verification. Third, forestry and land use offsets—comprising roughly half of all credits—operate in ecologically sensitive landscapes. Fourth, market growth is accelerating, driven by corporate net-zero commitments and investor interest in nature-based solutions. Fifth, the cumulative volume of retired credits implies meaningful potential for ecological impact, whether positive or negative.

At the same time, the relatively low prices in the voluntary market underscore both the promise and the uncertainty of this approach. How inexpensive are the offset opportunities being leveraged? 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.[1] The purported offset costs 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). If these projects are indeed delivering on their stated carbon and biodiversity objectives, they represent an exceptionally low-cost and scalable avenue for advancing global conservation goals. However, if the environmental outcomes fall short of the claims, such initiatives risk undermining the credibility of voluntary markets.

However, the true environmental impact of these nature-based voluntary carbon projects, especially their biodiversity benefits, remains unknown. The claims of offset developers indeed do have scholarly 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 similarly emphasize the possibility of these complementarities.

The infusion of private capital and the potential complementarity of carbon offsets and biodiversity run up against several key challenges. First, complementarity appears fairly context specific. A growing literature points to trade-offs between carbon sequestration and biodiversity objectives – in particular contexts outside of the VCM. Seddon et al., 2020; Huston and Marland, 2003; Horn, 2022 caution that reforestation efforts may compromise biodiversity. Among the many potential reasons for a tradeoff, new forest plantations are frequently monoculture plantations and may be carved out of ecologically rich landscapes, such as native grassland. These findings suggest that nature-based climate solutions, depending on their design, may not translate to concurrent ecological benefits. Second, critics argue that many carbon offset projects—especially those relying on avoided deforestation—may overstate carbon benefits, and in some cases even lead to perverse outcomes (e.g. West et al., 2020, 2023).

Understanding the complementarity of carbon sequestration and biodiversity has significant implications for the efficacy of growing market-based approaches to environmental conservation. However, empirical evidence from carbon offset markets remains limited. Existing offset studies typically rely on small-sample case studies or theoretical models, leaving a critical gap in our understanding of how biodiversity considerations are integrated into the voluntary carbon market at scale. For example, West et al. 2020, 2023 analyze 12 and 26

[1] 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`

projects (respectively). This research gap is particularly large given the rapid growth of corporate net-zero commitments and the increasing emphasis on nature-based solutions in climate strategies (Taskforce on Scaling Voluntary Carbon Markets, 2021).

Our study addresses this critical gap by providing the first comprehensive empirical investigation of biodiversity considerations in the voluntary carbon offset market. We leverage a novel dataset that combines detailed project-level data from major carbon registries with satellite-based biodiversity metrics of habitat, firm-level financial and environmental data, and information on relevant regulatory events. 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 2701 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. We measure habitat pressure through the Human Influence Index (HII), a satellite-derived measure of human pressure on local ecosystems. 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 important findings. First, we document that carbon offset projects are associated with a prompt 3.7% increase in HII, i.e. an increase 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 estimated mean 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 evidence of ecological improvement—no empirical silver lining. 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. These findings raise concerns about additionality and effectiveness, suggesting a disconnect between stated biodiversity goals and actual ecological impacts, potentially indicating "biodiversitywashing."

To explore potential mechanisms underlying the observed biodiversity outcomes, we examine satellite-based Land Use and Land Cover (LULC) data to track changes in surface composition before and after project initiation. Specifically, we calculate net shifts in land cover categories associated with each project. On average, carbon offset projects are associated with a statistically significant 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 contribute to carbon storage, they do not necessarily constitute gains for 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 when successful in reducing emissions, may come at the cost of ecological integrity. Likewise, in forest projects, planting monocultures and "tree engineering" may store carbon at the cost of biodiversity. Incorporating biodiversity safeguards into certification processes, involving ecologists in project planning and evaluation, and expanding the scope of monitoring beyond carbon accounting are necessary steps toward aligning offset finance with genuine conservation goals.

Our study makes several important contributions to the literature on environmental finance and corporate environmental strategy. First, we provide novel empirical evidence on the plausibility of biodiversity co-benefits (or "win-wins") in carbon offset projects. While it might be plausible *prima facie* that promoting forests would assist biodiversity, this does not appear to be the case empirically. Our 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).

Second, 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.

Third, our longitudinal analysis of biodiversity metrics in offset project areas offers new evidence on the long-term ecological impacts of carbon finance. This addresses a key critique of offset markets— whether they deliver lasting environmental benefits (Barbier, 2020)—and provides insights into the factors that influence future project success.

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.[2] 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.[3] 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 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

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

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

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, geographic boundaries (where available), 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.

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.

The full dataset includes 419,267 credit retirement records linked to 13,664 unique firms across 46 countries. Our primary analysis focuses on a subset of 2,701 nature-based projects that provide precise spatial boundary data and are suitable for geospatial analysis (with 1,730 of these projects having 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. Conversely, regions with low HII values often correspond to critical biodiversity hotspots, where intact ecosystems provide habitat for a high number of endemic and threatened species (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.

3.1.3 Satellite-based Vegetation Measures

We complement the HII with two additional satellite-based measures of vegetation:

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.

Forest Cover Change: We use the Global Forest Change dataset from Hansen et al. 2013, updated annually, which provides information on forest loss and gain at 30m resolution from 2000 to 2019.

For each carbon offset project in our sample, we extract these metrics for the project area and a 10km buffer zone for each year from 2000 (or project start, if later) to 2020. This allows us to analyze biodiversity trends before and after project implementation, as well as compare project areas to their immediate surroundings.

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.

In our regression analyses, we include protected area status and classification as control variables to account for baseline conservation conditions that may confound project impacts. These variables help isolate the effect of carbon offset implementation from pre-existing ecological protections.

Finally, in the design-based component of our empirical strategy, we incorporate protected area status as a matching criterion when constructing comparison groups. By matching treatment and control areas on pre-existing conservation status—as well as other observable characteristics—we aim to improve the credibility of our causal inference regarding offset impacts [TBA].

Taken together, these applications of WDPA 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 Impact of Carbon Offsetting Projects on Biodiversity

To examine the impact of carbon offsetting projects on biodiversity, we employ a difference-in-differences (DiD) approach:

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

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. δ_i, η_t, ρ_j, and σ_k represent project fixed effects, year fixed effects, country fixed effects, and registry fixed effects, respectively.

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

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

$$\begin{aligned} HII_{i,j,k,t} = \alpha &+ \beta_1 PostEstablishment_{i,j,k,t} + \beta_2 (PostEstablishment_{i,j,k,t} \times Characteristic_{i,j,k,t-1}) \\ &+ \gamma X_{i,j,k,t} + \delta_i + \eta_t + \rho_j + \sigma_k + \epsilon_{i,j,k,t} \end{aligned} \tag{2}$$

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.

3.2.2 Temporal Dynamics of Biodiversity Impact

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

$$HII_{i,j,k,t} = \alpha + \sum_{m=-5}^{5} \beta_m I(t - t^*_{i,j,k} = m) + \gamma X_{i,j,k,t} + \delta_i + \eta_t + \rho_j + \sigma_k + \epsilon_{i,j,k,t} \tag{3}$$

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

3.2.3 Impact of Increased Biodiversity Awareness

To evaluate the impact of increased biodiversity awareness on market behavior, we employ a difference-in-differences approach exploiting the release of major IPBES reports:

$$Y_{i,j,k,t} = \alpha + \beta_1 (Treat_{i,j,k} \times Post_t) + \beta_2 Treat_{i,j,k} + \beta_3 Post_t + \gamma X_{i,j,k,t} + \delta_i + \eta_t + \rho_j + \sigma_k + \epsilon_{i,j,k,t} \tag{4}$$

where $Y_{i,j,k,t}$ is an outcome variable, such as number of biodiversity-linked credits issued or purchased) for project/firm i in country j, registry k, year t. $Treat_{i,j,k}$ indicates firms or projects more likely to be affected by the IPBES reports, and $Post_t$ indicates the post-report period.

These empirical strategies allow us to identify the causal impacts of carbon offsetting projects on biodiversity and evaluate how market behavior responds to increased biodiversity awareness, providing a comprehensive analysis of the interplay between carbon markets and biodiversity conservation efforts.

4 Results

4.1 Temporal Dynamics and Spatial Patterns

Figure 1 illustrates the temporal and geographical distribution of carbon offset projects. Panels A and B show a steady increase in the number of projects over time, with a notable acceleration in recent years, particularly for projects related to biodiversity. Panels C and D reveal that while carbon offset projects are globally distributed, there is a concentration in certain regions, such as North America, Europe, and parts of Asia.

Figure 2 depicts similar trends for carbon offset credits, showing a rapid increase in credit issuance, especially for biodiversity-related projects. Table A4 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. The comparison between Panels A (2001) and B (2020) suggests that many carbon offset projects are established in areas that have experienced increases in habitat disturbance over time.

Figure 4 offers a more detailed view of the biodiversity impact of carbon offsetting projects over time. Panel A, which includes all projects, shows a clear increase in HII following project establishment. Panel B, focusing on projects in areas with initially low human impact, reveals an even more pronounced increase in HII, consistent with our regression results.

Figures 5 and 6 further explore Heterogeneity. Figure 5 shows that projects disclosing biodiversity benefits and those subject to specific biodiversity requirements exhibit different temporal patterns in their impact on HII. Figure 6 indicates that projects located in protected areas have a distinct impact trajectory compared to those outside protected areas.

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). We note that whether we consider event study plots of the raw data (beginning with Figure 4), or regression adjusted tabular estimates, including a fixed effect for each project, the basic qualitative patterns remains the same.

Table 2 presents our baseline results, with the average HII as the dependent variable across all specifications. In Column (1) of Table 2, we observe a positive and statistically significant coefficient on the *PostEstablishment* dummy (1.297, s.e. = 0.093), indicating that carbon offsetting projects are associated with an increase in human impact on local ecosystems. This effect persists, albeit with a smaller magnitude, when we include country, year, and registry fixed effects in Column (2) (0.648, s.e. = 0.232).

To address potential confounding factors and isolate the causal effect of carbon offsetting projects, we restrict our analysis to a balanced panel of observations from five years before to five years after project establishment in Columns (3)-(7). The effect remains positive and statistically significant across these specifications. In our most stringent specification with project fixed effects (Column (6)), we find that project establishment is associated with a 0.187 increase in the HII (s.e. = 0.050), representing a 3.7% increase relative to the sample mean.

Column (7) provides a more nuanced view of the temporal dynamics. We observe that the impact on HII is not immediate but grows over time. The coefficient on the *EstablishmentYear* dummy is positive and significant (0.243, s.e. = 0.041), and the effect continues to grow in subsequent years, reaching 0.159 (s.e. = 0.053) three years after establishment.

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 3. 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 (0.050, s.e. = 0.019).

4.3 Heterogeneity Across Project Characteristics

We next explore heterogeneity in the biodiversity impact of carbon offsetting projects across various dimensions. Table A3 presents these results, with Panels A-D focusing on different project characteristics and Panel E providing a comprehensive analysis.

Panel A of Table A3 examines the differential impact based on the initial level of human influence. The results show that projects in areas with initially high HII show a larger and more statistically significant increase in HII post-establishment (0.223, s.e. = 0.055) compared to those in low HII areas (0.140, s.e. = 0.112). This suggests that carbon offsetting projects may be more effective in preserving biodiversity in relatively pristine areas.

In Panel B, the result reveals that projects disclosing biodiversity benefits exhibit a smaller HII increase (0.115, s.e. = 0.060) relative to those that do not (0.189, s.e. = 0.066). Both effects are statistically significant at the 10% and 1% levels, respectively, indicating that projects with explicit biodiversity benifits may have a smaller impact on human influence in the area. This unexpected result warrants further investigation and may indicate potential biodiversitywashing or overstatement of biodiversity benefits by some projects.

In Panel C, we observe that projects subject to specific biodiversity requirements have a larger HII increase (0.265, s.e. = 0.077) compared to those without such requirements (0.141, s.e. = 0.061). This result, significant at the 1% level, suggests that biodiversity requirements may not necessarily mitigate habitat disturbance.

Panel D indicates that projects located in protected areas show a larger HII increase (0.236, s.e. = 0.072) than those outside protected areas (0.167, s.e. = 0.074), with both effects significant at the 1% level. The difference in coefficients suggests that carbon offsetting projects in protected areas may have a more pronounced impact on human influence, raising important questions about the additionality and effectiveness of these projects in already protected ecosystems.

Panel E of Table A3 provides a comprehensive analysis of these heterogeneous effects in a single regression framework. The results confirm our previous findings. Projects in areas with initially low human impact (*LowHIIBeforeEstablishment*) show a significantly smaller increase in HII relative to the baseline (coefficient = -0.479, s.e. = 0.063). This suggests that carbon offsetting projects may be more effective in preserving biodiversity in relatively pristine areas, potentially due to lower initial anthropogenic pressures.

Interestingly, projects subject to specific biodiversity requirements exhibit a smaller increase in HII compared to those without such requirements (coefficient = -0.430, s.e. = 0.065). This result, when considered alongside the positive coefficient on *PostEstablishment* (0.444, s.e. = 0.062), suggests a nuanced relationship between biodiversity requirements and changes in the Human Influence Index (HII). Interpreting these results requires careful consideration of potential baseline differences and selection effects. The negative interaction coefficient indicates that projects subject to biodiversity requirements experience a smaller increase in HII relative to their starting point, compared to projects without such requirements. However, this does not necessarily imply that these projects have a lower absolute HII post-establishment.

Projects that disclose biodiversity benefits show a slightly smaller, though statistically insignificant, increase in HII (coefficient = -0.121, s.e. = 0.083). This suggests that self-reported biodiversity benefits may not necessarily translate into measurable reductions in human impact.

Notably, projects located in protected areas do not show a statistically significant difference in HII increase compared to those outside protected areas (coefficient = 0.110, s.e. = 0.072). This result is particularly concerning as it suggests that carbon offsetting projects in protected areas may not provide additional biodiversity benefits beyond existing conservation efforts.

These results reveal a nuanced relationship between carbon offsetting projects and their impact on local ecosystems, as measured by the Human Influence Index (HII). These heterogeneous effects underscore the complexity of implementing effective carbon offset projects. They highlight potential unintended consequences and emphasize the need for careful project design, location selection, and monitoring. From a policy perspective, our findings suggest that current approaches to biodiversity conservation in carbon offset markets may be insufficient or even counterproductive. They call for more nuanced regulatory frameworks that account for these heterogeneous impacts and potentially reassess the effectiveness of existing biodiversity requirements and protected area designations in the context of carbon offsetting.

4.4 Heterogeneity Across Registry

To examine whether the ecological impacts of carbon offset projects differ by registry, we estimate registry-specific regressions of habitat condition—proxied by the Human Influence Index (HII)—on project implementation. Table 5 Panel A reports both baseline single-difference estimates (odd-numbered columns) and event-study specifications (even-numbered columns) across seven major carbon offset registries: Australian Carbon Credit Units(ACCU), American Carbon Registry(ACR), Climate Action Reserve(CAR), Clean Development Mechanism(CDM), Gold Standard, Verra, and a pooled "Other" category.

Overall, we do not observe strong or systematic heterogeneity in HII responses across registries. While a few registries exhibit suggestive patterns—such as modest reductions in human pressure following implementation—these effects are generally small and statistically imprecise. In several cases, HII increases post-establishment, indicating potential unintended ecological costs. The absence of consistent improvements across registries highlights the need for stronger biodiversity safeguards and more rigorous, registry-specific monitoring frameworks to ensure that habitat-related co-benefits are realized in practice.

4.5 Heterogeneity Across Carbon Offset Ratings

Table 5 Panel B, we also examine whether project outcomes differ systematically based on the presence of an external carbon offset rating. Specifically, we test whether projects that have been rated—by independent rating platforms—exhibit different patterns of change in habitat condition relative to unrated projects. Similiar to the results across registries, we find no statistically significant differences in HII responses between rated and unrated projects. This suggests that existing ratings, which typically emphasize carbon integrity and additionality, may not reliably capture ecological co-benefits such as habitat preservation. These results reinforce the need for greater transparency and the integration of biodiversity-specific criteria into offset evaluation frameworks.

4.6 Heterogeneity Before and After the 2014 IPBES Report

We also examine whether the ecological performance of carbon offset projects changed after the release of the first IPBES Global Assessment Report in 2014—a milestone in global biodiversity governance. The IPBES report substantially raised international awareness about biodiversity loss and promoted more integrated approaches to conservation and development. If the report influenced project design, we might expect systematically different outcomes among projects established before versus after its publication.

Table 6 reports regressions estimated separately for the pre- and post-2014 periods. We find a notable divergence: after 2014, project areas exhibit a large and statistically significant increase in human pressure following implementation, whereas the corresponding increase in earlier years is much more modest. This result suggests that heightened global concern around biodiversity has not yet translated into improved on-the-ground outcomes in offset projects. The pattern reinforces the need to evaluate not only the stated environmental objectives of offset initiatives but also their actual implementation and land-use impacts over time.

4.7 Robustness Checks and Additional Analyses

To ensure the robustness of our results, we conduct several additional analyses:

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 A1). The results are qualitatively similar to our main findings, with project establishment associated with increases in all three measures of HII.

To assess the robustness of our results, we conduct sensitivity analyses using two alternative biodiversity metrics: 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 7, the results are qualitatively similar to our main findings, with project establishment associated with decreases in all biodiversity measures.

Second, for the heterogeneity, we replicate our heterogeneity analysis using alternative HII measures (Table A2). The results largely confirm our main findings, with some variations in effect sizes and statistical significance across different HII measures.

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[4] to ascertain where biodiversity improvements might be maximized through carbon markets.

4.8 Mechanisms: Land Use Change and Biodiversity Trade-Offs

To better understand the mechanisms underlying the increase in human pressure documented in our main results, we examine whether carbon offset projects are systematically associated with land cover transitions that reduce ecological complexity. Specifically, we test whether project implementation leads to changes in the composition of land cover types within project boundaries, such as the replacement of natural vegetation with pasture or other managed land uses.

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.

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

$$\Delta Area^{l}_{i,j,k,t} = \alpha + \beta \cdot PostEstablishment_{i,j,k,t} + \delta_i + \eta_t + \rho_j + \sigma_k + \epsilon^{l}_{i,j,k,t}, \qquad (5)$$

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 (δ_i) absorb all time-invariant heterogeneity across project sites. Year fixed effects (η_t), country fixed effects (ρ_j), and registry fixed effects (σ_k) control for temporal shocks, national land use trends, and protocol-specific practices. Standard errors are clustered at the project level.

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

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 8 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 ($p < 0.01$). This gain appears to be offset primarily by reductions in shrubland (–35.4 square meters; $p < 0.01$) and in "other forest" cover (–4.6 square meters; $p < 0.05$). No statistically significant changes are observed across the other forest types or in urban land.

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.

5 Future Robustness Checks and Additional Analyses

5.1 Robustness

To ensure the robustness of our results, we plan to conduct several additional analyses:

- Placebo tests using randomly assigned treatment dates and locations
- Propensity score matching to address potential selection bias in project location and firm participation. Following best practice, we will first consider how well the propensity score performs in balancing covariates by quintile, etc. blocks of the estimated propensity score.
- Instrumental variable regressions using plausibly exogenous variation in biodiversity risk. This component of the proposed analysis has great potential for strengthening

causal inference, and is one we plan to prioritize in our project's development going forward.

5.1.1 Additional Analyses

In our future work on this project, we plan to address three questions:

1. What characteristics distinguish firms that develop or purchase biodiversity-linked carbon credits?
2. How do exogenous shocks to biodiversity awareness, such as major scientific reports, affect the supply and demand for biodiversity-linked offsets?
3. Describe more fully: what is the relationship between carbon offset projects and existing protected areas, and what does this imply for project additionality?

To address question 2, we plan to 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 suggests 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.

6 Discussion and Conclusion

We are the first to link scientific data on human's ecological impact to economic data on carbon offset projects at a global scale. This permits assessment of the additionality of biodiversity benefits from carbon offset projects, which may have biodiversity impacts to the extent that the local ecology is impacted by carbon-promotion strategies, especially those involving nature based solutions. Additionally, carbon offset projects frequently (and increasingly) claim biodiversity co-benefits.

Not only do we find no improvement in biodiversity, we often see perverse effects. Nor can we identify specific sub-classes of carbon offset projects that specifically benefit biodiversity. We conclude that efforts to preserve biodiversity outside of voluntary carbon markets should be redoubled.

These findings carry substantive implications for both institutional investors and policymakers engaged in environmental finance. For investors, the evidence underscores that biodiversity-related claims embedded in voluntary carbon offset assets may entail unpriced ecological risk. In the absence of verifiable performance data, such claims should not be treated as credible signals of environmental impact. Investors allocating capital to nature-based solutions should demand improved disclosure regarding biodiversity outcomes, integrate biodiversity-related risks into environmental, social, and governance (ESG) valuation frameworks, and exercise active ownership to encourage more rigorous project evaluation and transparency.

For policymakers, the results highlight the need to strengthen the regulatory architecture governing biodiversity performance in carbon markets. Effective policy responses would include mandating minimum biodiversity impact standards, reforming certification and land-use eligibility criteria, and aligning offset protocols with emerging international frameworks such as the Convention on Biological Diversity (CBD) and the Taskforce on Nature-related Financial Disclosures (TNFD). In addition, enforcement of biodiversity-specific additionality requirements and the deployment of high-resolution monitoring infrastructure would facilitate credible assessment and verification. Ultimately, carbon offsets cannot substitute for direct environmental protection unless they are held to robust standards of ecological integrity.

Ultimately, ensuring the credibility of nature-based climate solutions requires moving beyond narrow metrics of carbon accounting toward a more holistic emphasis on ecological integrity. Tree planting alone—particularly when implemented as monoculture plantations or without regard to ecosystem context—is not a sufficient proxy for biodiversity conservation. Effective market design must therefore incorporate ecological performance standards that reflect the complexity of real-world ecosystems. Building ecological integrity, in this sense, demands more than engineered sequestration; it requires aligning financial incentives with measurable and lasting ecological outcomes.

References

Akerlof, G. A. (1970). The market for "lemons": Quality uncertainty and the market mechanism. *The Quarterly Journal of Economics*, 84(3):488–500.

Allen, F., Barbalau, A., and Zeni, F. (2023). Reducing carbon using regulatory and financial market tools§. Imperial College, working paper.

Aspelund, K. M. and Russo, A. (2024). Additionality and asymmetric information in environmental markets: Evidence from conservation auctions. Working paper, MIT Economics.

Barbier, E. B. (2020). Is green growth relevant for poor economies? *Resource and Energy Economics*, 60:101178.

Besley, T. and Persson, T. (2023). The political economics of green transitions. *The Quarterly Journal of Economics*, 138(3):1863–1906.

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C. A. J., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., et al. (2020). Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, 26(11):6134–6155.

Chernozhukov, V., Demirer, M., Duflo, E., and Fernández-Val, I. (2018). Generic machine learning inference on heterogeneous treatment effects in randomized experiments, with an application to immunization in india. Working Paper 24678, National Bureau of Economic Research.

Dasgupta, P. (2021). *The Economics of Biodiversity: The Dasgupta Review*. HM Treasury, London.

De Palma, A., Hoskins, A., Gonzalez, R. E., et al. (2021). Annual changes in the biodiversity intactness index in tropical and subtropical forest biomes, 2001–2012. *Scientific Reports*, 11(1):20249.

Dooley, K., Christiansen, K., Lund, J., Carton, W., and Self, A. (2024). Over-reliance on land for carbon dioxide removal in net-zero climate pledges. *Nature Communications*, 15.

Flammer, C., Giroux, T., and Heal, G. (2023). Biodiversity finance. Working Paper 31022, National Bureau of Economic Research.

Franklin, Sergio L, J. and Pindyck, R. S. (2024). A supply curve for forest-based co removal. Working Paper 32207, National Bureau of Economic Research.

Freedman, B., Stinson, G., and Lacoul, P. (2009). Carbon credits and the conservation of natural areas. *Environmental Reviews*, 17:1–19.

Giglio, S., Kuchler, T., Stroebel, J., and Zeng, X. (2023). Biodiversity risk. *Working Paper*.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., et al. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, 114(44):11645–11650.

Grupp, T., Mishra, P., Reynaert, M., and van Benthem, A. A. (2023). An evaluation of protected area policies in the european union. Working Paper 31934, National Bureau of Economic Research.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., et al. (2013). High-resolution global maps of 21st-century forest cover change. *Science*, 342(6160):850–853.

Horn, C. (2022). Potential biodiversity and climate benefits of voluntary carbon market tree-planting projects. Master's Project, Duke University.

Huston, M. A. and Marland, G. (2003). Carbon management and biodiversity. *Journal of Environmental Management*, 67(1):77–86. Maintaining Forest Biodiversity.

Jayachandran, S., De Laat, J., Lambin, E. F., Stanton, C. Y., Audy, R., and Thomas, N. E. (2017). Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation. *Science*, 357(6348):267–273.

Karolyi, G. A. and Tobin-de la Puente, J. (2023). Biodiversity finance: A call for research into financing nature. *Financial Management*, 52(2):231–251.

Kotchen, M. and Vogt, A. (2024). Thoughts on whether (forest) carbon offsetscan contribute to solving the climate problem? Yale University (slide deck).

Krueger, P., Sautner, Z., and Starks, L. T. (2020). The importance of climate risks for institutional investors. *The Review of Financial Studies*, 33(3):1067–1111.

Longuet-Marx, N. (2024). Party lines or voter preferences? explaining political realignment. Columbia University, Sustainable Development Program.

McKinsey & Company (2021). A blueprint for scaling voluntary carbon markets to meet the climate challenge. *McKinsey Quarterly*.

NFGS (2022). Central banking and supervision in the biosphere: An agenda for action on biodiversity loss, financial risk and system stability. Occasional paper, Network for Greening the Financial System.

Osuri, A. M., Gopal, A., Raman, T. R. S., DeFries, R., Cook-Patton, S. C., and Naeem, S. (2020). Greater stability of carbon capture in species-rich natural forests compared to species-poor plantations. *Environmental Research Letters*, 15(3):034011.

Pattanayak, S. K., Wunder, S., and Ferraro, P. J. (2010). Show me the money: Do payments supply environmental services in developing countries? *Review of Environmental Economics and Policy*, 4(2):254–274.

Reynaert, M., Souza-Rodrigues, E., and Benthem, A. V. (2024). The environmental impacts of protected area policy. *Regional Science and Urban Economics*, 107:103968.

Salzman, J., Bennett, G., Carroll, N., Goldstein, A., and Jenkins, M. (2018). The global status and trends of payments for ecosystem services. *Nature Sustainability*, 1(3):136–144.

Sanderson, E., Fisher, K., Robinson, N., Sampson, D., Duncan, A., and Royte, L. (2022). The march of the human footprint.

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., and Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B*, 375(1794):20190120.

Song, Y., Aldy, J. E., Holbrook, N. M., Gao, X., and Thompson, J. (2025). Selection and over-crediting in forest-based carbon offset projects: A comparison of regulated and voluntary carbon markets. HKUST – Guangzhou Campus working paper.

Taskforce on Scaling Voluntary Carbon Markets (2021). Final report. Technical report, Institute of International Finance.

The Guardian (2025). Countries failing on biodiversity pledges despite global commitments. https://www.theguardian.com/environment/2025/feb/24/countries-biodiversity-pledges-rome-cop16-aoe. Citing the 2020 United Nations Global Biodiversity Outlook report.

UNEP-WCMC and IUCN (2023). Protected planet: The world database on protected areas (WDPA). Available at: www.protectedplanet.net.

Venter, O., Sanderson, E. W., Magrach, A., Allan, J. R., Beher, J., Jones, K. R., Possingham, H. P., et al. (2016). Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nature communications*, 7(1):1–11.

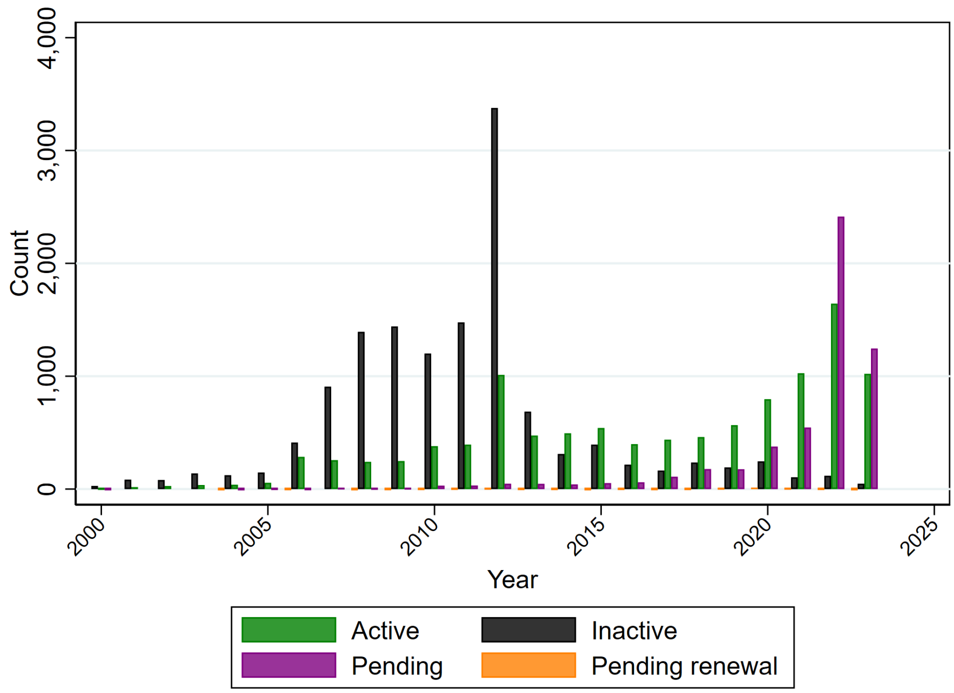
West, T. A., Börner, J., and Fearnside, P. M. (2020). Nature-based solutions and carbon offsets: A reality check. *Global Sustainability*, 3:e24.

West, T. A. P., Wunder, S., Sills, E. O., BÃ¶rner, J., Rifai, S. W., Neidermeier, A. N., Frey, G. P., and Kontoleon, A. (2023). Action needed to make carbon offsets from forest conservation work for climate change mitigation. *Science*, 381(6660):873–877.

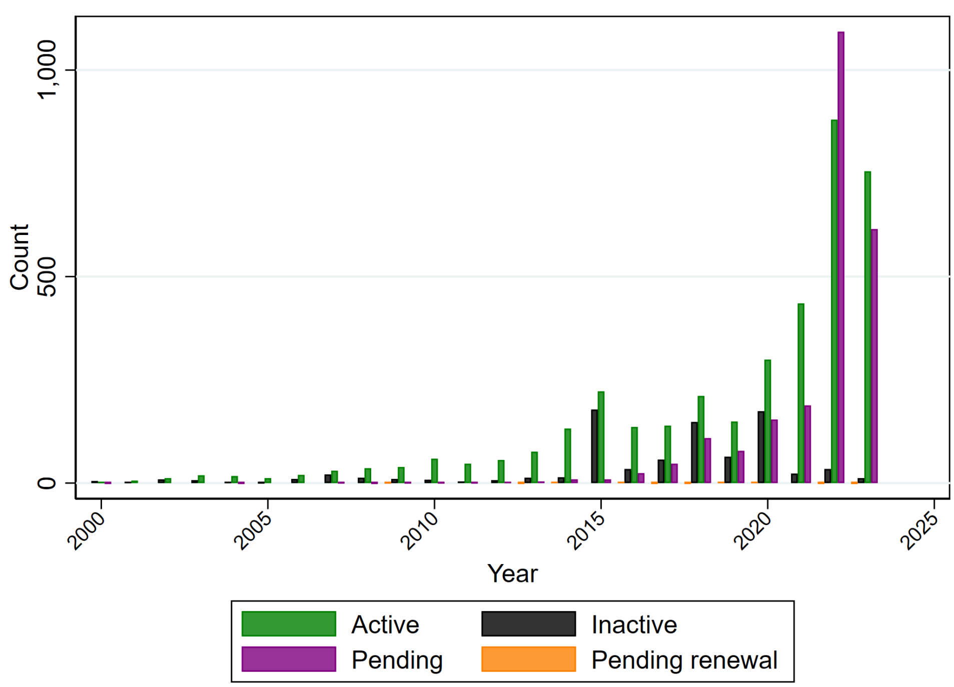
Figure 1: Trends in Carbon Offset Projects

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

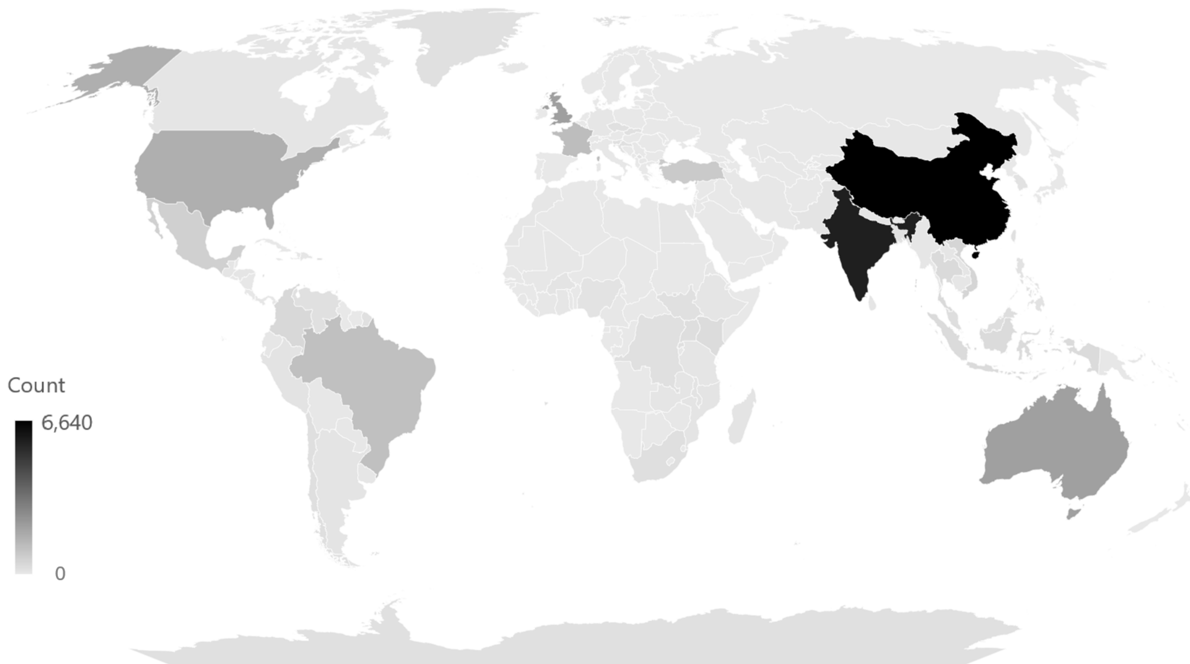
Panel A Carbon Offset Projects



Panel B Carbon Offset Projects Related to Biodiversity



Panel C Carbon Offset Projects



Panel D Carbon Offset Projects Related to Biodiversity

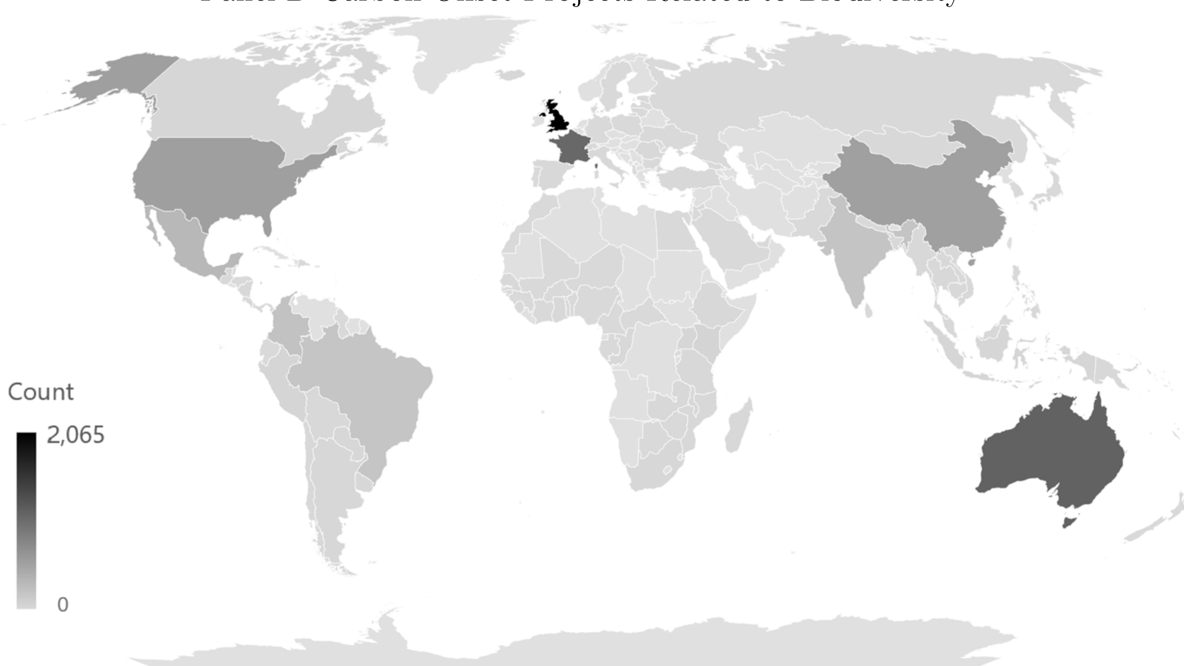
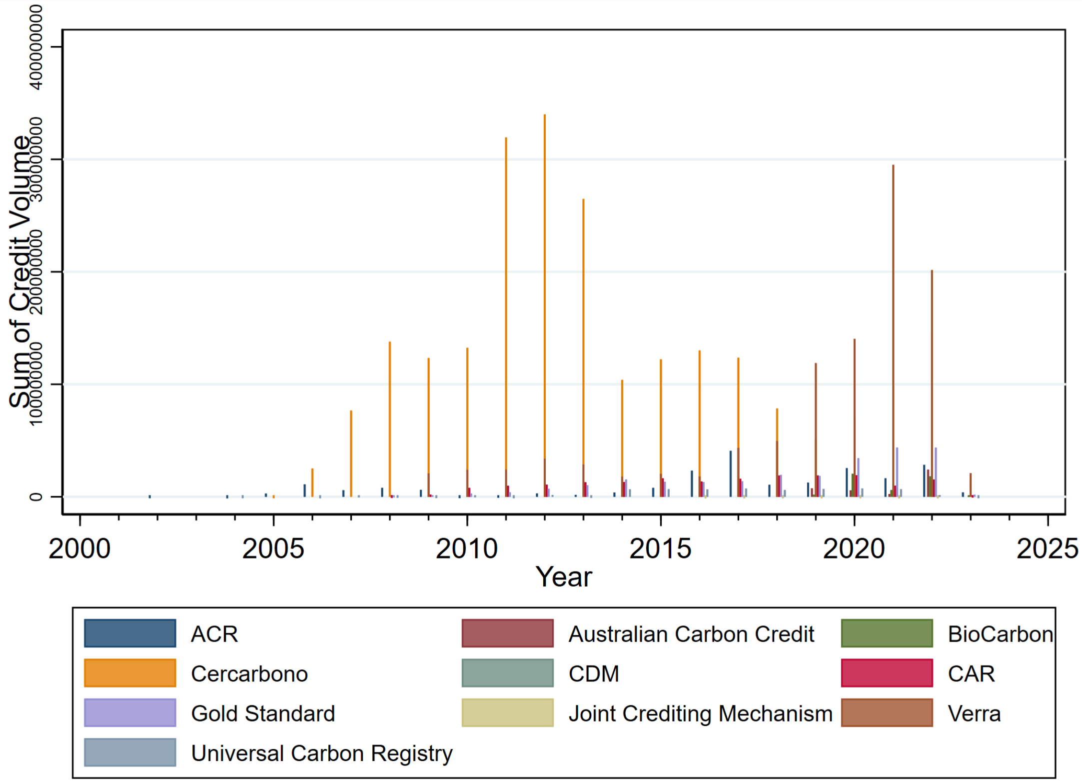


Figure 2: Trends in Carbon Offset Credits

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

Panel A Carbon Offset Credits



Panel B Carbon Offset Credits Related to Biodiversity

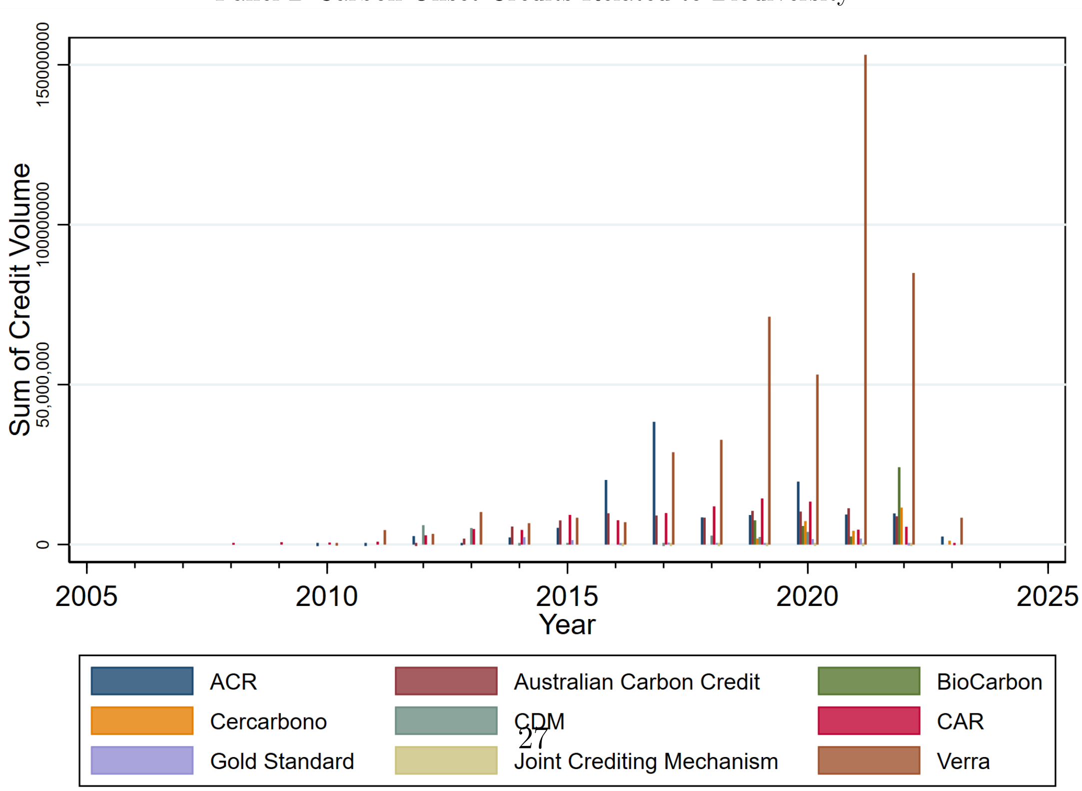
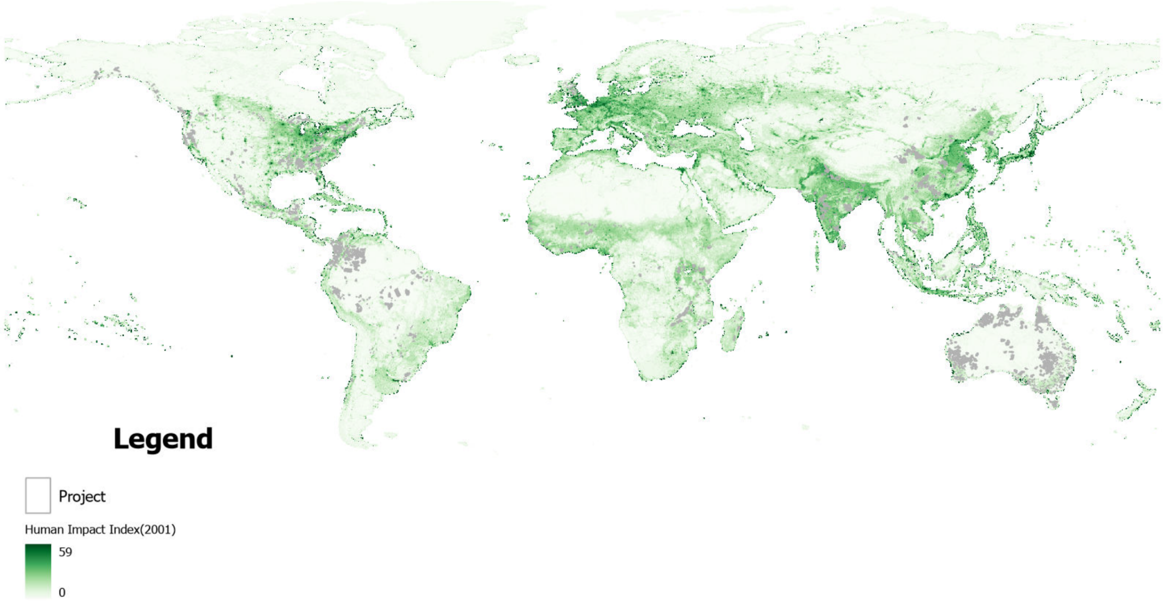


Figure 3: Carbon Offset Projects and Human Influence Index (HII)

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

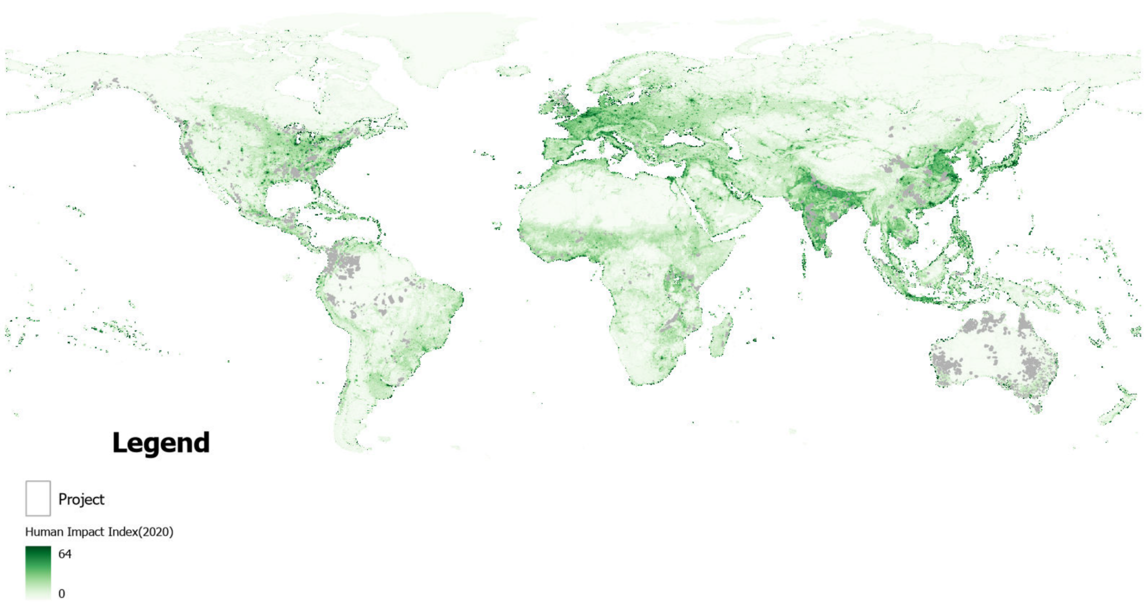
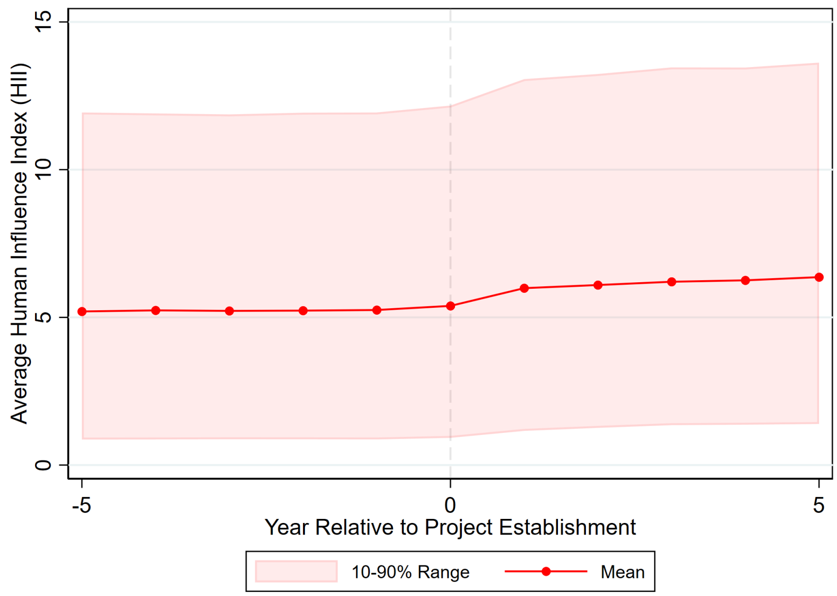


Figure 4: Biodiversity Impact of Carbon Offsetting Projects

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.

Panel A: Full Sample



Panel B: Based on Pre-Establishment HII Levels

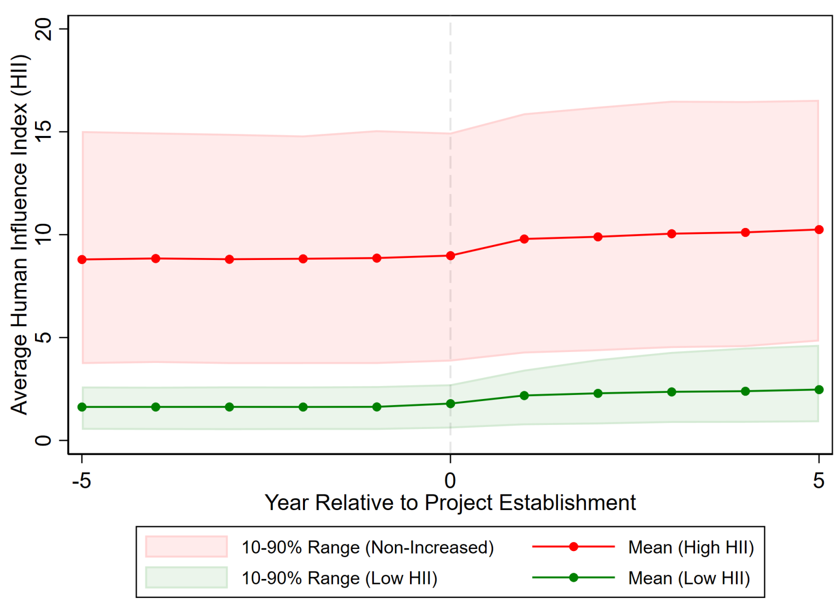
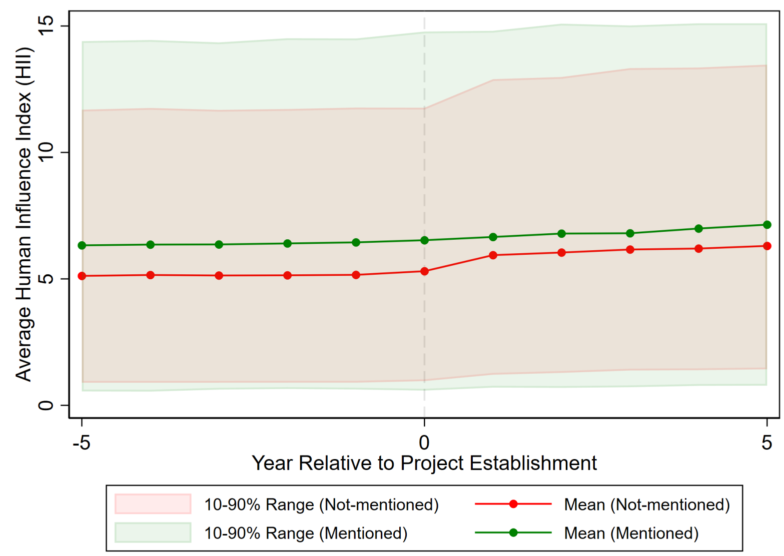


Figure 5: Biodiversity Impact of Carbon Offsetting Projects Based on Project Self-disclosure and Registry Requirements

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

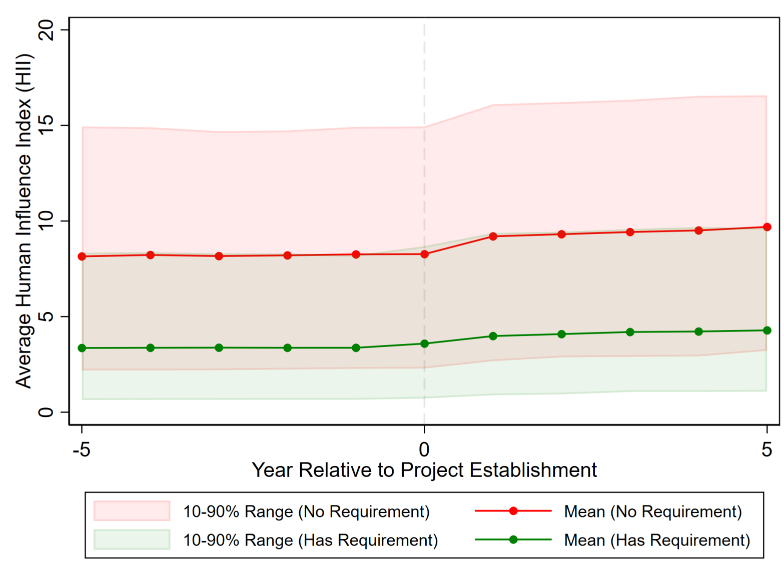


Figure 6: Biodiversity Impact of Carbon Offsetting Projects Based on Protected Area Location

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.

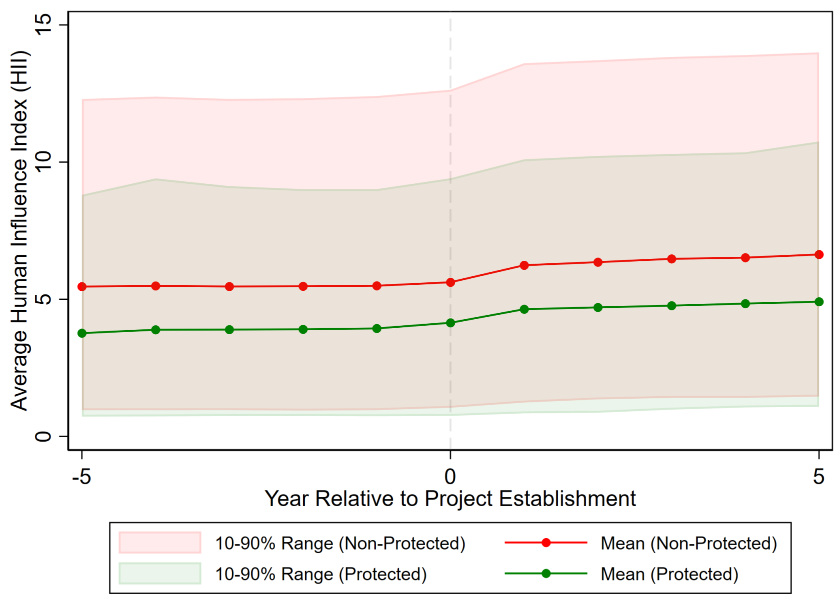


Table 1: Summary Statistics

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: 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 3: 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 4: 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 5: 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 6: 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 7: 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 8: Land Cover Change Following Carbon Offset Project Implementation

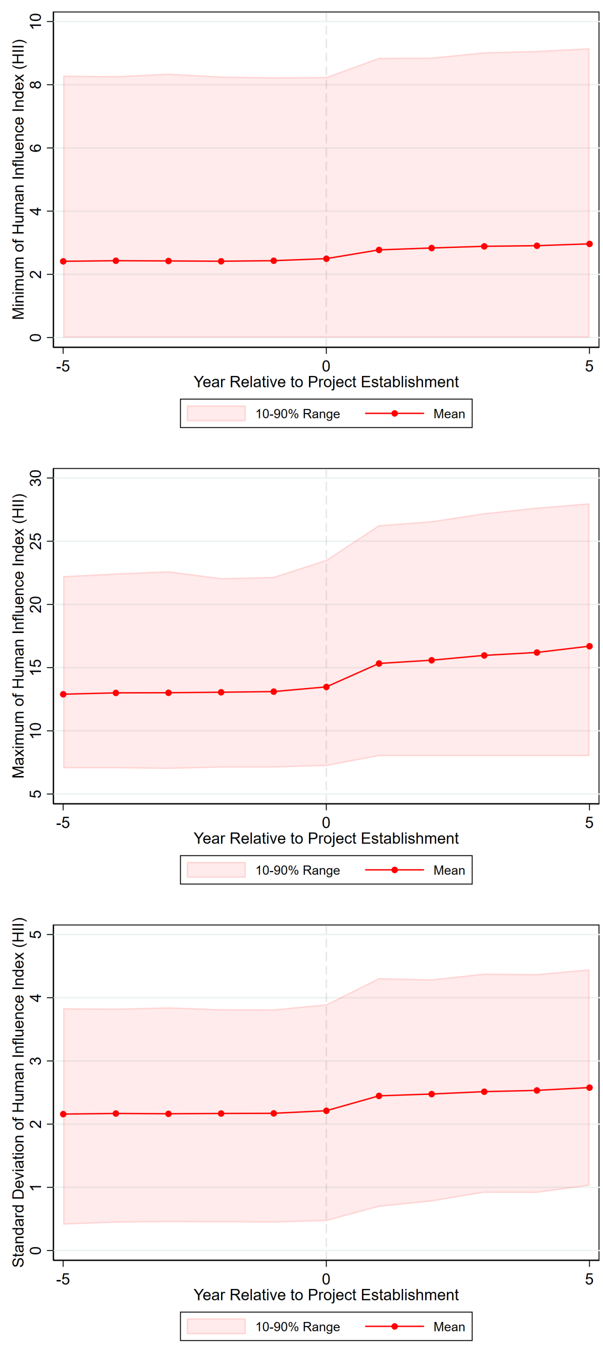
This table reports the estimated effects of carbon offset project implementation on land cover composition, using annual panel data derived from satellite-based Land Use and Land Cover (LULC) maps. The dependent variable in each column is the year-on-year change in area (square meters) of a specific 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

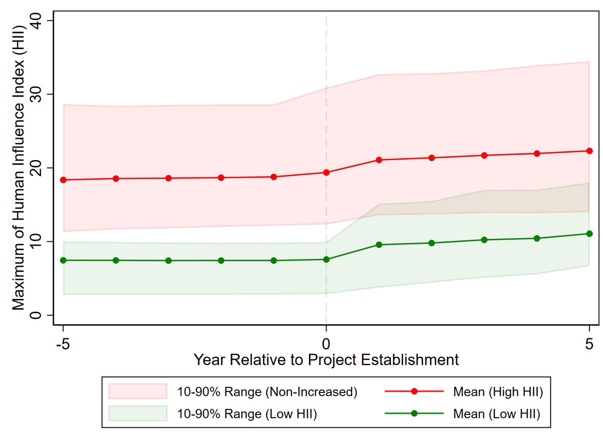
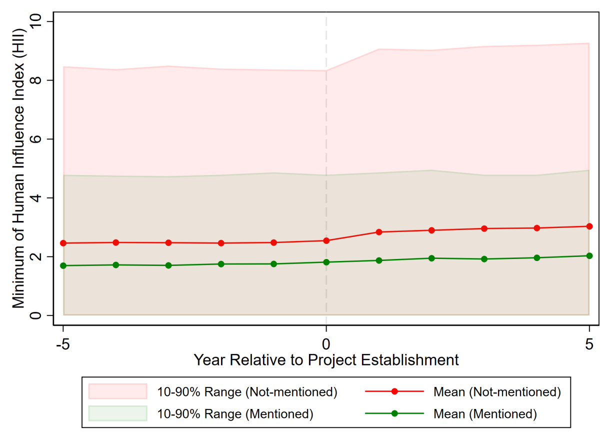
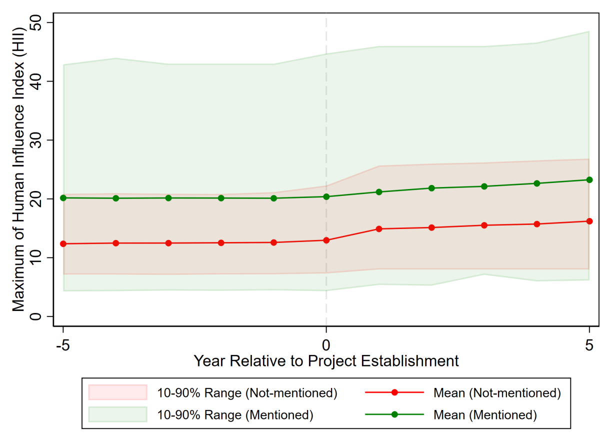


Figure A2: Robustness of Figure 5: Biodiversity Impact of Carbon Offsetting Projects Based on Project Self-disclosure and Registry Requirements

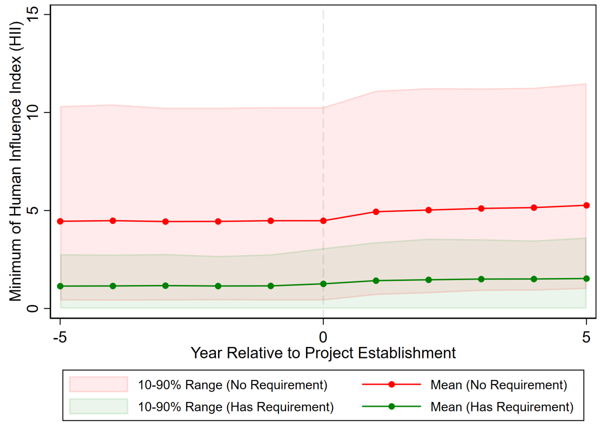
This figure illustrates the biodiversity impact of carbon offsetting projects, categorized by project characteristics. Panel A presents the minimum, maximum, and standard deviation of HII for projects that self-disclose biodiversity benefits in their documentation. Panel B presents the minimum, maximum, 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.

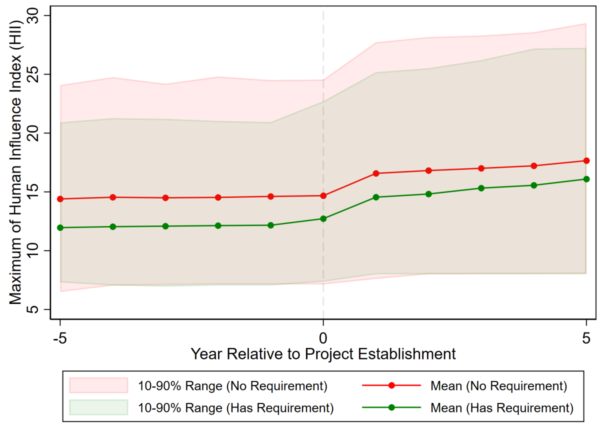
Panel A: Projects Disclosing Biodiversity Benefits





Panel B: Projects with Biodiversity and Conservation Requirements





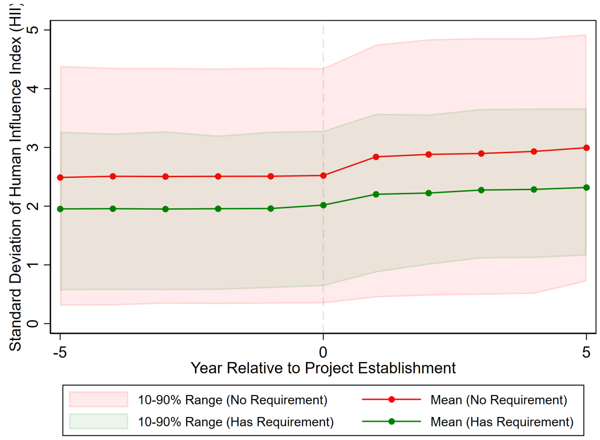
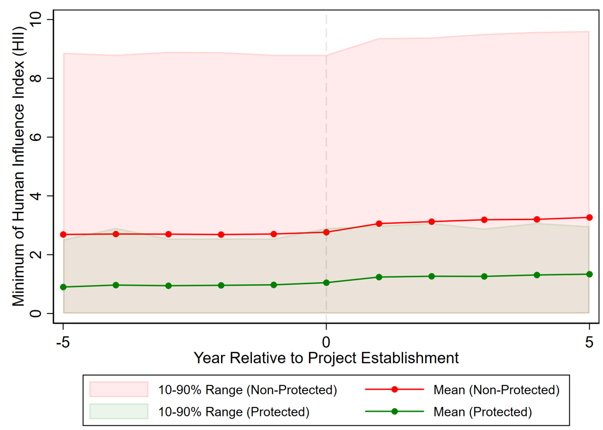
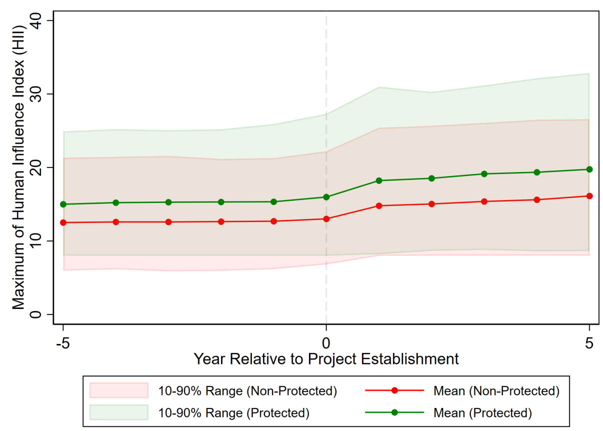


Figure A3: Robustness of Figure 6: Biodiversity Impact of Carbon Offsetting Projects Based on Protected Area Location

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.





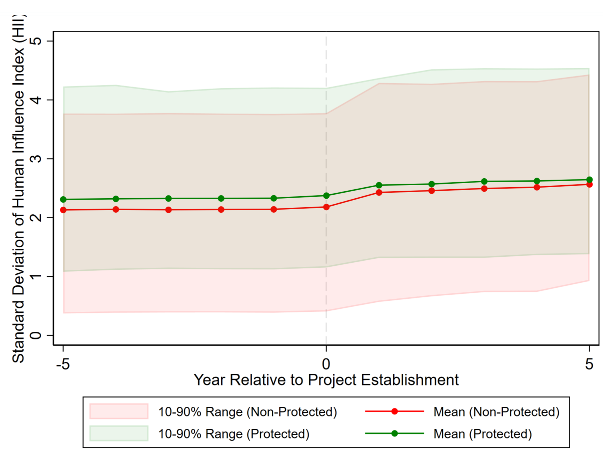


Table A1: Robustness of Table 2: Biodiversity Impact of Carbon Offsetting Projects

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

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	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

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	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 A2: Robustness of Table A3: 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 A3: 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

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
VARIABLES							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

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	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

Table A4: 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 A5: Carbon Offset Project Types and Categories

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

Carbon Offset Project Types and Categories (continued)

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