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Systematic review of the actual emissions reductions of carbon offset projects across all major sectors

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Abstract

Net-zero targets have significantly increased carbon offset demand. Carbon offsets are issued based on ex-ante estimates of project emissions reductions, though systematic evidence on ex-post evaluations of achieved emissions reductions is missing. We synthesized existing rigorous empirical studies evaluating more than 2,000 offset projects across all major offset sectors. Our analysis shows that offset projects achieved considerably lower emissions reductions than officially claimed. We estimate that only 12% of the total volume of existing credits constitute real emissions reductions, with 0% for renewable energy, 0.4% for cookstoves, 25.0% for forestry and 27.5% for chemical processes. Our results thus indicate that 88% of the total credit volume across these four sectors in the voluntary carbon market does not constitute real emissions reductions. This offset achievement gap corresponds to almost twice the annual German CO_2 emissions. We complement evidence from offset projects with 51 additional studies conducting ex-post evaluations of field interventions with settings comparable to offset projects. For cookstoves and forestry projects, these field interventions were more effective at reducing emissions than the voluntary offset projects, likely due to more careful intervention targeting, stricter monitoring and enforcement of intervention protocols.

Introduction

The United States and the European Union want to reach net-zero emissions by 2050, China by 2060, and India by 2070. By December 2022, 138 countries had already made net-zero pledges covering more than 80% of global emissions[1]. Similarly, many large corporations – including Amazon and Volkswagen – have promised to reach carbon neutrality by mid-century or earlier [1], and various firms claim that they are already 'carbon neutral' today. Yet, many of these claims entail the purchase of carbon offsets. These are "reduction, avoidance or removal of a unit of greenhouse gas (GHG) emissions by one entity, purchased by another entity to counterbalance a unit of GHG emissions by that other entity."[2] Offsets in the voluntary carbon market today almost exclusively rely on reducing or avoiding emissions through, for instance, more fuel-efficient cookstoves or improved forest protection. While offsets based on carbon removal are growing, they only constitute a minor share of current voluntary carbon markets and are not the focus of this study.

What explains the major role that offsets are playing in corporate strategies is the implicit assumption that carbon offsets are economically efficient, as emissions reductions are achieved where they are cheapest [3]. However, for an offset project to contribute to emissions reductions, offsets need to conform to environmental integrity criteria, such as additionality[4,5] (i.e., reduction/removals would not have occurred without the project), durability (i.e., reduction/removals are not subject to near-term reversal or renewed at fixed intervals), and not leading to leakage (i.e., merely displacing emissions elsewhere). In addition, many carbon offset projects aim to create additional positive environmental and socioeconomic co-benefits, such as enhanced biodiversity or poverty alleviation.[2]

Carbon offsets have come under considerable criticism, however, as the underlying projects may not lead to actual emissions reductions[6]. Carbon offsets are commonly issued by comparing the actual carbon reductions of a project to a hypothetical baseline scenario if the project had not been implemented. This counterfactual baseline scenario is typically based on extrapolating historical emission trends. Yet, historical baselines are commonly an imperfect guide to future emissions. It is, therefore, critical to contrast the ex-ante estimated emissions reductions to the ex-post achieved emissions reductions by offset projects. This allows us to gauge what the offset achieved relative to what has been claimed ex-ante. We call this the 'offset achievement ratio' (see Methods for detailed explanation), which is the share of achieved emissions reductions based on credible academic studies relative to the claims made by project developers ex-ante.

While several studies have assessed the actual emissions reductions that were realized in individual offset projects relative to the expected reductions claimed by the verifiers[6,7], systematic and large-scale evidence of the actual reductions covering the full range of offset sectors is missing (for definition and a full list of sectors, see Table 1). In line with conventional systematic review methodology[8] and based on a Context-Intervention-Mechanism(s)-Outcome(s) logic (CIMO) [8], the central question of this analysis is therefore: 'What is known in the scientific literature about the differences between ex-ante estimates and ex-post outcomes of individual carbon offsetting projects adopted to enable the transition towards a net-zero emission economy across multiple sectors?'

We proceed in four steps. First, we define keywords to identify potentially relevant scientific studies across all major carbon offset sectors. As many offsetting sub-sectors only constitute a fraction of a per cent, we focus on the largest sub-sectors which, combined, make up more than 90% of credits issued in the voluntary offset market (Figure 1). Second, we use the artificial-intelligence-supported systematic review tool AS Review[9] to filter for relevant studies (e.g., using experimental or rigorous observational research methodologies) from 64,993 potentially relevant studies identified in the first step (Supplementary Figure 1 and Supplementary Table 1 & 2 for search terms). Third, we download the full text of the studies identified using AS Review and manually check for relevance (see Supplementary Table 3 for criteria). Fourth, two researchers independently extract the ex-post computed emissions reductions from individual projects and other relevant aspects of the study detailed in our Codebook. Lastly, for each project, we compute an offset achievement ratio. For field interventions that did not officially issue offsets, we compute a 'synthetic' offset achievement ratio (i.e., the ratio of achieved emissions reductions if these projects had used assumptions of similar, real-world projects to issue offsets; see Methods for detailed approach). In total, our final sample comprises more than 2,000 offset projects, and 130 effect sizes from 61 studies (see Extended Data 1).

Our analysis extends the existing literature in two major ways: First, we provide the first cross-sectoral, quantitative assessment of the offset achievement ratio of carbon offset projects in the peer-reviewed literature[10] and highlight insights on durability, co-benefits, and other relevant factors from these studies (see Supplementary Table 4 for previous meta-analyses in the non-peer reviewed literature). Second, we complemented the evidence on offset projects with 51 ex-post evaluations from field interventions that tested interventions similar to offset projects and jointly comprise 1.2 million observations. For instance, less than half of projects that attempt to reduce deforestation from deforestation and forest degradation

(REDD+) have issued offsets[11]. Yet, there is a large, high-quality literature that investigates the underlying effectiveness of such interventions[12,13] allowing us to assess whether assumptions made by project developers using these interventions for offset projects are realistic.

Offset projects and field interventions

We conducted a systematic review of the offset achievement ratio of offset projects. In total, our set of studies includes offset sectors that jointly issued around 90% of carbon offsets (Figure 1). These contain 7 main sectors and 14 sub-sectors as defined by the Berkeley Carbon Trading Project[14] (Table 1).

Forestry & Land Use	
REDD+	Reducing deforestation and forest degradation in the global south. Many REDD+ projects bundle several activities (e.g., improved forest management, afforestation/reforestation). The "+" in REDD+ refers to the many project co-benefits (e.g., biodiversity).
Improved Forest Management	Applying practices which increase above and below-ground carbon stocks including reducing timber harvest levels, extending timber harvest rotations, designating reserves, fuel load treatments, enrichment planting, and stand irrigation or fertilization
Afforestation & Reforestation	Planting trees and reducing barriers to natural regeneration in non-urban areas.
Renewable Energy	
Wind	Installing wind turbines for grid-connected electricity generation replacing traditional, fossil-fuel or natural gas combustion for electricity production
Hydropower	Installing large and small-scale hydroelectric power plant (HEPP) turbines to generate electricity through regular dam flow operations or additions to multipurpose reservoirs
Solar	Installing solar modules as electricity production for grid-connected energy use.
Biomass	Generating heat, electricity (grid-connected or direct use), and/or biogas from renewable biomass, commonly utilizing agricultural waste biomass.
Waste management	
Landfill/wastewater methane	Landfill: Reducing and combusting methane from landfills including municipal, industrial, and other solid waste facilities. Wastewater: Treating wastewater to capture and flare methane, process with anaerobic digesters, and/or dewater sludge by drying before disposal
Chemical processes	
Ozone-depleting substances	Collecting and destroying refrigerants that are ozone-depleting substances with high GWP from discarded equipment such as air conditioners, refrigerators, and foam. *We also include the recovery and destruction of SF_6 and HFC-23 in this category.*
N_2O destruction in nitric acid production	Installing abatement measures and catalytic reduction units to destroy N_2O emissions from nitric acid factories and caprolactam production plants. Nitric acid (HNO_3) and caprolactam are crucial components of fertilizer and synthetic fibre production.

Household and community	
Cookstoves	Building improved cookstoves to replace or minimize the use of dung or firewood for cooking. Carbon benefits are realized in the form of reduced emissions from burning biomass as well as reducing deforestation. Less smoke leads to improved health benefits.
Industrial manufacturing	
Mine methane capture	Capturing and destroying or using mine methane that would otherwise be released to the atmosphere from active and abandoned coal, trona, and precious and base metal mines.
Natural gas electricity production	Constructing new natural gas-fired grid-connected electricity generation plants replacing higher greenhouse gas intensity fuels like coal. The fuel sources for the plants are fossil fuel natural gas, not renewable natural gas harvested through decomposition processes.
Carbon capture and storage	
Carbon Capture and Enhanced Oil Recovery	Capturing carbon dioxide from industrial processes followed by compression, transport and injection for permanent storage underground while also enhancing oil recovery.

Table 1: Sectors, sub-sectors and descriptions of offset sectors. *Directly cited and text shortened from Berkeley Voluntary Registry Offsets database scope & types document (Version April 2021).*[12]

Projects from forestry and renewable energy projects dominate the voluntary carbon market and constitute 74% of issued credits (Figure 1a/b). Industrial manufacturing, waste management, chemical processes, and household and community jointly constitute 23% (we use household and cookstoves interchangeably throughout the text as there is only one category). Carbon Capture and Storage (CCS), agriculture, and transportation together account for around 3%. Each sector is composed of sub-sectors. For instance, the forestry sector contains projects related to REDD+, forest management, and afforestation (though for forestry there is substantial overlap between these categories as REDD+ is a broad term). In turn, the renewable energy sector contains projects from wind, solar, biomass, and hydropower.

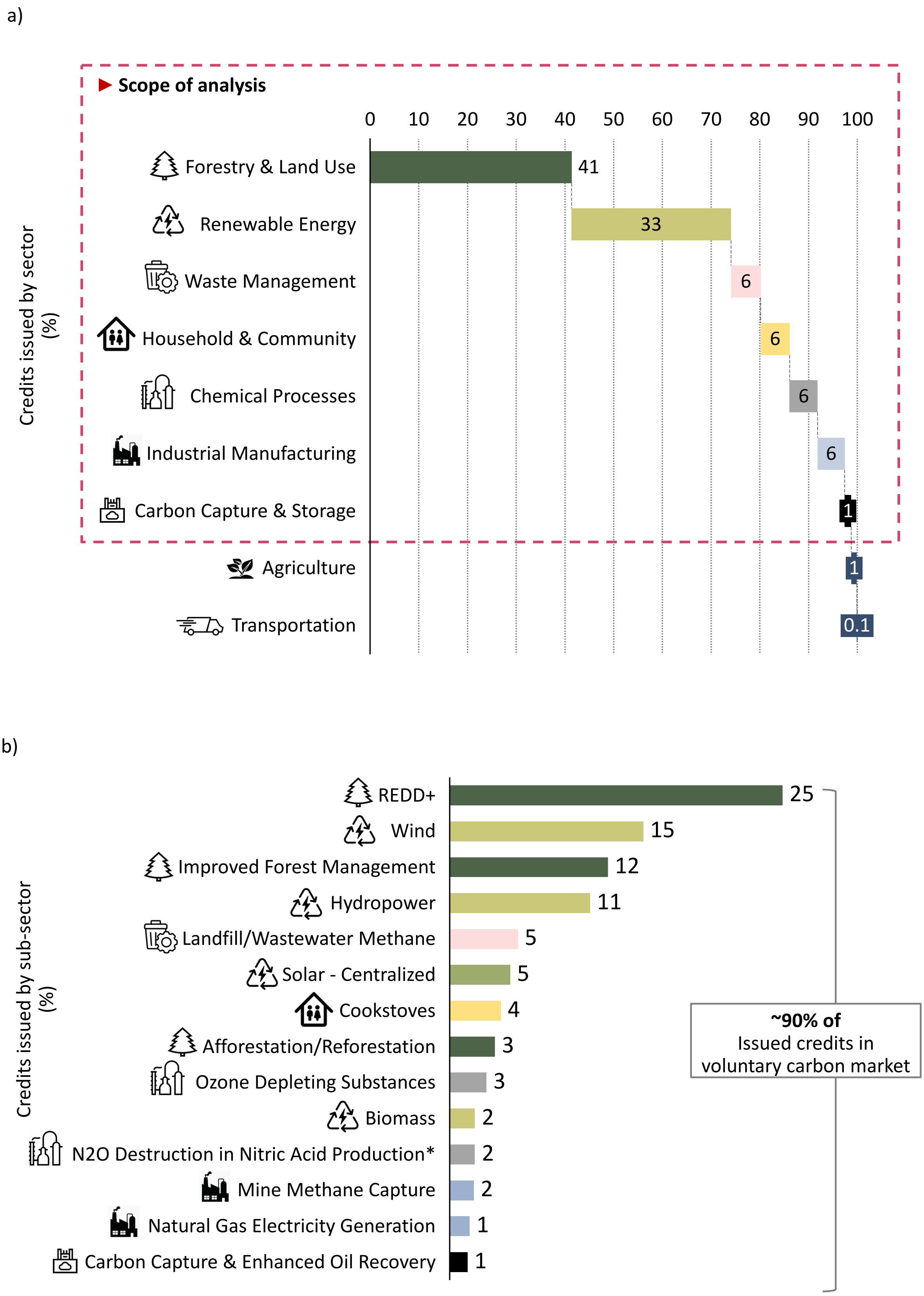

Figure 1: Credit issuance in the voluntary carbon market*. a) Issued credits in voluntary carbon markets by sector and b) by sub-sector from 1996 – November 2022. The numbers next*

to the bars are in %. The scope of our analysis includes all major sectors. Each sector comprises a range of sub-sectors. Collectively, we cover sub-sectors accounting for ~90% of the credits issued. Please note that adding the sectors in Figure 1a accounts for more than 90% as many sectors contain a range of small sub-sectors, which were outside the scope of our analysis. Based on the Berkeley Carbon Trading dataset (v6, November 2022). Clean Development Mechanism (CDM) credits are included only if they were transferred to a voluntary registry. [10] *Numbers mentioned in the text may differ slightly from those in Figure due to rounding. REDD+ refers to projects related to Reducing Emissions from Deforestation and Forest Degradation.*

Following the typology of the Berkeley Carbon Project, we classify each of the 61 studies in our review into one of seven sectors with 14 sub-sectors (Figure 1). We differentiate between studies that investigate projects that officially issued carbon offsets and those projects that used a similar field intervention but did not officially issue offsets. We found 10 studies investigating 2,244 offset projects across four sectors (Figure 1a) and 51 studies investigating field interventions without issued carbon credits with a total of 1.2m observations (Figure 1b). For the other 3 main sectors (waste management, industrial manufacturing, and carbon capture and storage), we could not find any ex-post studies using a credible control group.

We have the strongest concentration of offset evaluations in the forestry sector, followed by renewable energy and chemical processes (Figure 1a/b). Offset evaluations are split between different geographies (apart from Africa with 0 studies). Similarly, for field interventions, most studies focus on forestry and are mainly focused on Latin America as most forestry projects are being implemented in tropical forests. Overall, both offset and field interventions mainly rely on rigorous observational studies (e.g., difference-in-difference and propensity score matching methodologies). In contrast, only 8 of 61 studies use randomised controlled trials (mainly evaluating the impact of fuel-efficient cookstoves, with one exception in forestry[15]).

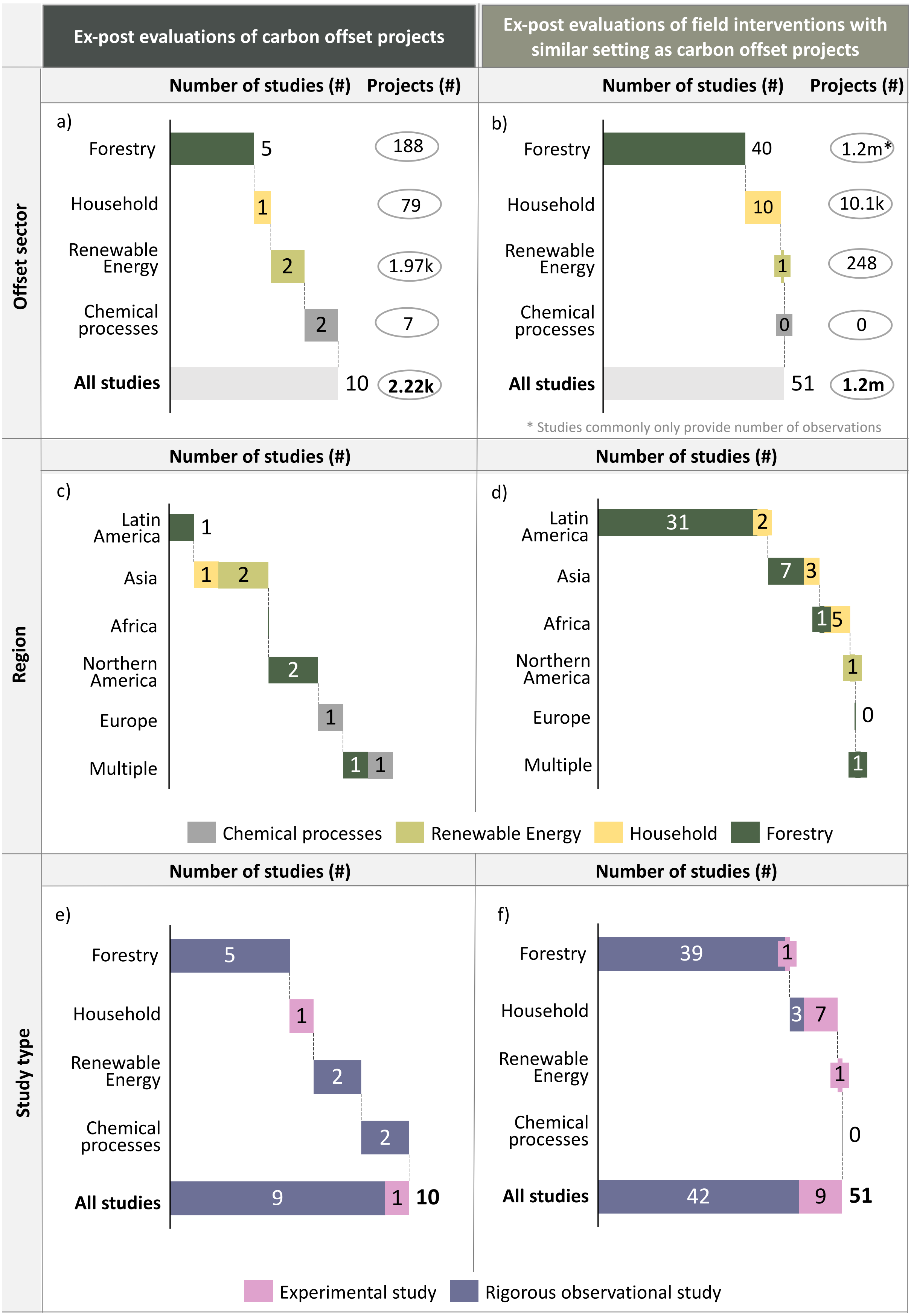

Figure 2: Overview of studies in the systematic review*. a/b) Distribution of studies across offset sectors, c/d) across regions, and e/f) methodology types. Note: k refers to the number in*

thousands, and m refers to the number in millions. See Supplementary Table 5 for a descriptive overview of the sample.

The offset achievement ratio

The central question of this review is: what is known in the scientific literature about the differences between ex-ante estimates and ex-post outcomes of individual carbon offsetting projects? To operationalise this question, we introduce a new, simple metric, which we call the offset achievement ratio (see Methods Section for detailed description). The offset achievement ratio compares ex-post estimates from empirical studies with ex-ante estimates made by offset project developers. Hence, if a project reduced only half of what was originally claimed, the offset achievement ratio would be 50%.

For assessing offset achievement ratios, we only include empirical impact evaluations that contain a credible control group. A credible control group has similar characteristics as the treatment group. For instance, if a project seeks to avoid deforestation, then the deforestation trends within the conservation project would be compared to a forest with similar biophysical (e.g., type of forest, distance to forest edge) and socio-economic (e.g., distance to roads) characteristics that was not protected by the offset project.

This counterfactual approach stands in stark contrast to offset verifiers, which rely on simplistic comparisons of the offset project against a historical baseline to determine whether the project achieved its intended goals. For instance, in projects Reducing Emissions from Deforestation and Forest Degradation (REDD+), historical deforestation trends are commonly used, but these are often unsuitable to gauge the impact of the project for two main reasons [16]. First, changes in underlying political and economic conditions may lead to reductions in deforestation that are wrongfully attributed to the offset project, as likely happened with Brazil's policy effort to thwart deforestation post-2004 [6,16]. Second, project developers have an incentive to inflate deforestation baselines to benefit from the sale of a larger number of offset credits, which results in questions regarding the actual emissions reductions[6].

Overall, we find that offset projects achieved considerably lower emissions reductions than claimed ex-ante. We find the lowest values for the offset achievement ratio in the renewable energy (0%) and household (0.4%) sector, followed by forestry (25.0%) and chemical processes (27.5%) (Figure 3a). In contrast to offset projects, estimates from field interventions show higher results for cookstoves (17.1%) and forestry (39.2%) but not for renewable energy (no data on chemical processes) (Figure 3b). For our estimates in Figure 3, we use the central estimates from the studies. For studies that only report an upper bound, we do not include them in our main estimates (but show them graphically in Figure 3a) as the authors make clear that the results could be as low as zero[17] (see Methods section for discussion). We discuss issues of permanence in Section *leakage, durability, and co-benefits*.

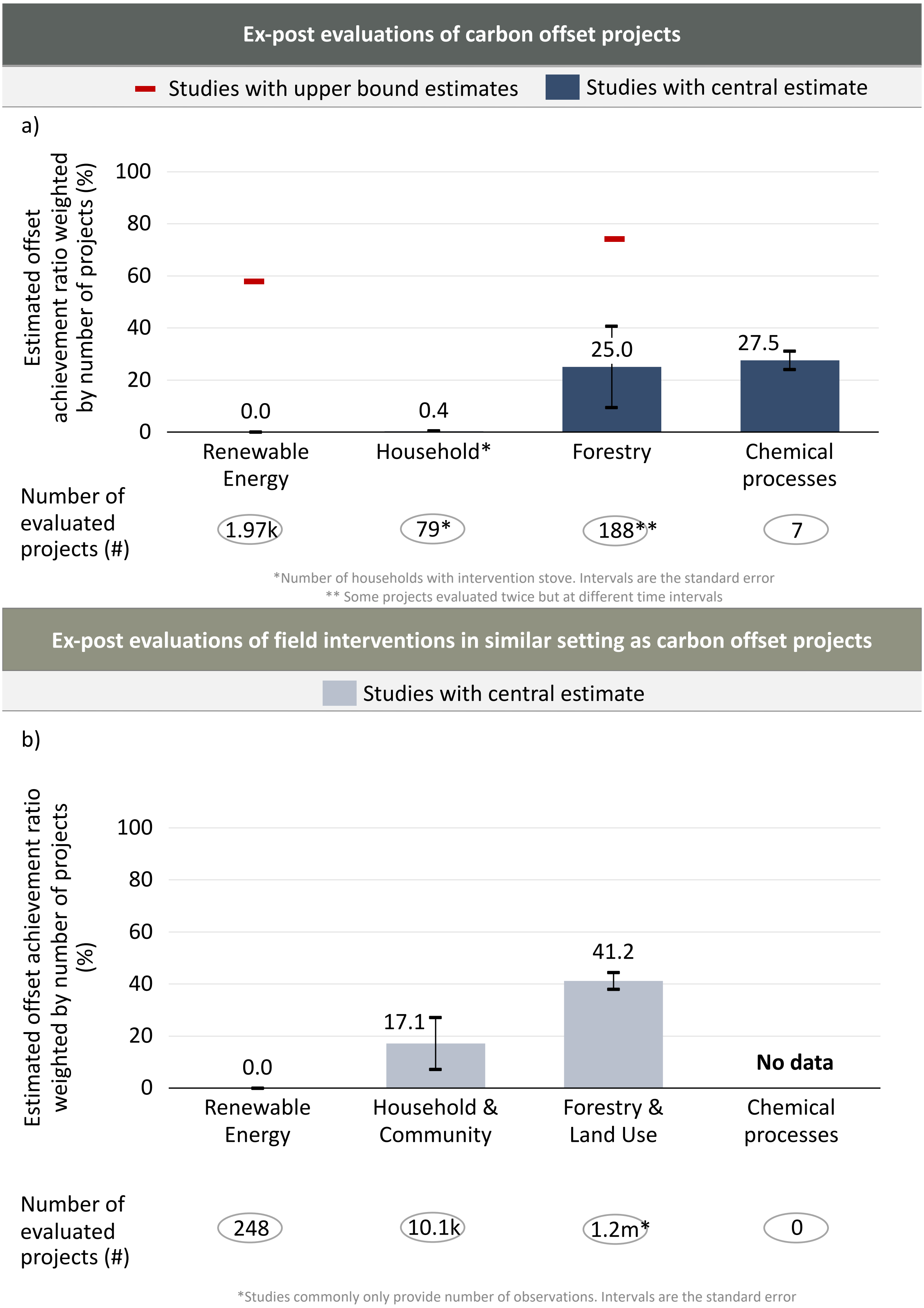

Figure 3: Estimated offset achievement ratios across sectors *with a) estimates from carbon offset projects, and b) from field interventions in a setting comparable to carbon offsets but*

without the official issuance of offsets. The offset achievement ratio is weighted by the number of offset projects analysed in each study. Intervals are standard errors.

The offset achievement gap

When generalizing the estimates from offset project studies in Figure 3a, we estimate that only 12% of the total volume of existing credits constitute real emissions reductions. Hence, 88% of the current voluntary carbon market across the main four sectors may not achieve the claimed offset goals. These non-achieved emissions reductions claimed by offsets are sizeable: the volume corresponds to almost twice the annual CO_2 emissions of the entire German economy.

Forestry and renewable energy credits account for around 90% of the current market (Figure 4a). Most renewable energy credits are likely not achieving the claimed goals, whereas a share of forestry credits likely represents actual emissions reductions. (Figure 4b). While industrial credits have a higher offset achievement ratio, their overall share in the voluntary carbon market is relatively low.

Field interventions show a higher degree of 'synthetic' offset achievement ratio, but even applying these more optimistic estimates from field interventions, almost 80% of the current market would not constitute actual emissions avoidance or reductions. We delve into the external validity of our findings, the potential reasons for the observed low achievement and the divergence between offset projects and field interventions in the discussion section.

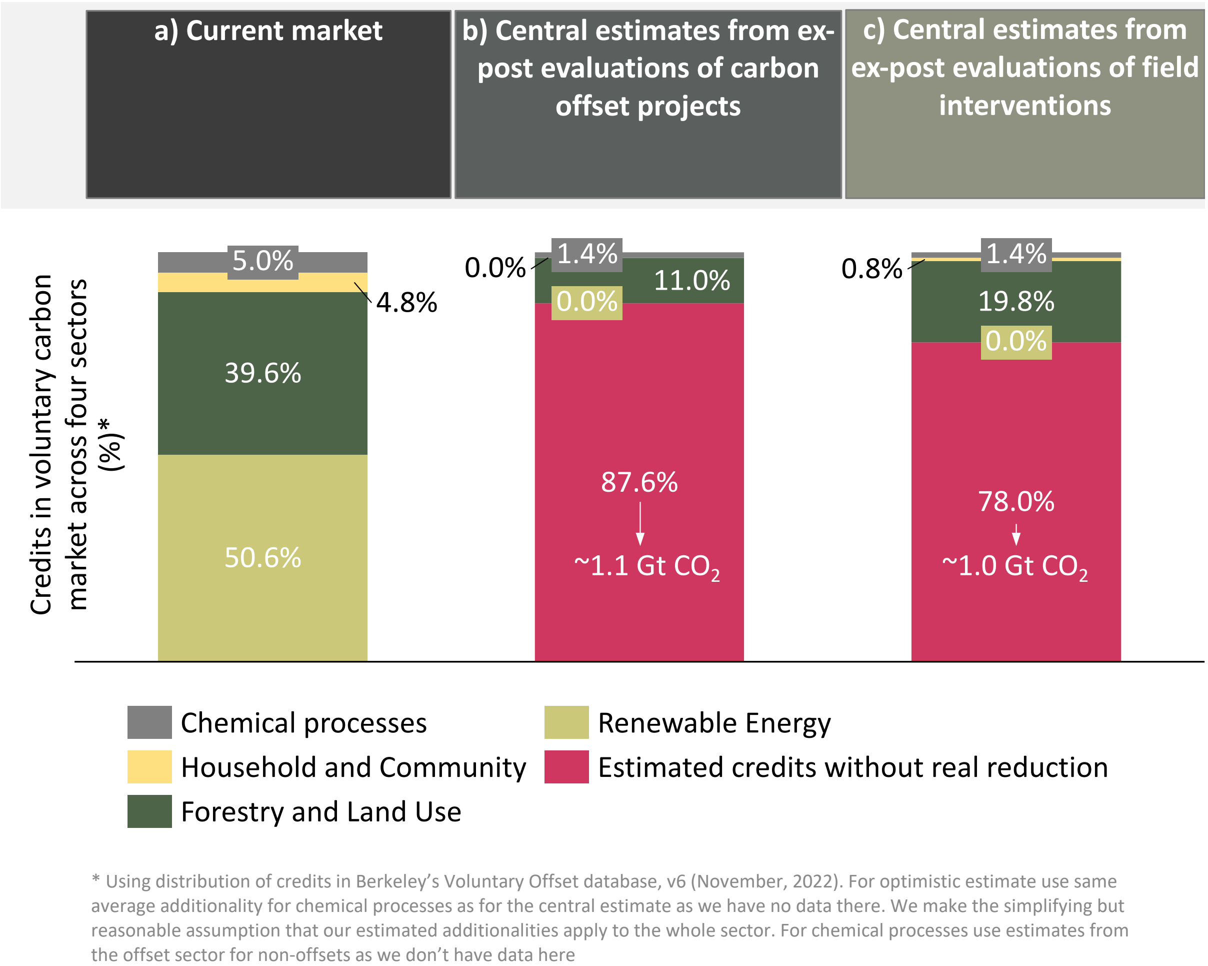

Figure 4: Current and estimated distribution of credits in the voluntary carbon market*. a) Current market distribution according to Berkeley's Voluntary Offset database, b) central estimates from ex-post evaluations of carbon offset projects, and c) central estimates from ex-post evaluations of field interventions in similar settings to carbon offset projects.*

Leakage, durability, and co-benefits

Although the offset achievement ratio across sectors is the central focus of this study, we also evaluated whether offset project and field intervention studies address other important considerations related to carbon offsets. Our results show that studies investigating the emissions reduction potential of carbon offset projects or field interventions only partly consider leakage, durability, and co-benefits.

Some carbon offset projects may only displace carbon emissions instead of avoiding them. Only in the forestry sector, do some studies consider leakage (for which it is arguably the biggest risk) (Figure 5a). Within this sector, around ¼ of studies analyse leakage. For those that analyse leakage, 73% of these studies find no evidence of leakage and the rest a mixed picture. Leakage effects can be positive as one forestry study found additional conservation effects in nearby areas to field interventions.[18]

Another key consideration for carbon offset projects is durability, which denotes the time that the carbon offset projects avoid, reduce, or remove emissions. Avoided emissions are not per se permanent, as the avoidance may only be temporary if, for instance, a protected forest is later cut down. On average, studies in our sample analyse on average 6.5 years of intervention, with the shortest average timeframes found in cookstove studies (2 years), whereas chemical processes, renewables and forestry investigate longer intervention periods (7-11 years) (Figure 5b). Many cookstove studies rely on randomised controlled trials. Since these are costly to implement, they tend to be more short-term in nature. In addition to the relatively short intervention periods studied, almost none of the sectors considers post-intervention effects (e.g., once the payments run out). The only exceptions are a few studies in the forestry sector (13% of all forestry-related studies), which tend to show that once payments run out, conservation effects are likely to be reversed.

Lastly, co-benefits/harms are also important considerations for offset projects to assess whether a project's impacts go beyond carbon reductions. For example, these include positive effects of cookstove projects on health (co-benefit) or an increase in poverty levels (co-harm) due to a forestry conservation project. For chemical and renewable projects, no study investigates these effects (Figure 5c). In contrast, 22% of forestry projects and 64% of cookstove projects investigate co-benefits/harms. Cookstoves projects find neutral to positive effects (especially on time saving in collecting fuelwood[19] and cooking[20], and reductions in indoor air pollution[7]). In forestry studies, co-benefits also tend to be neutral to positive (especially on socio-economic factors such as participants' subjective wellbeing[21] and poverty alleviation[2223] as well as ecological factors, such as improved agricultural productivity[24] and hydrological services[2526,27]). Only one forestry study found negative effects on the subjective well-being of project participants, mainly related to frustrations around project implementation.[28]

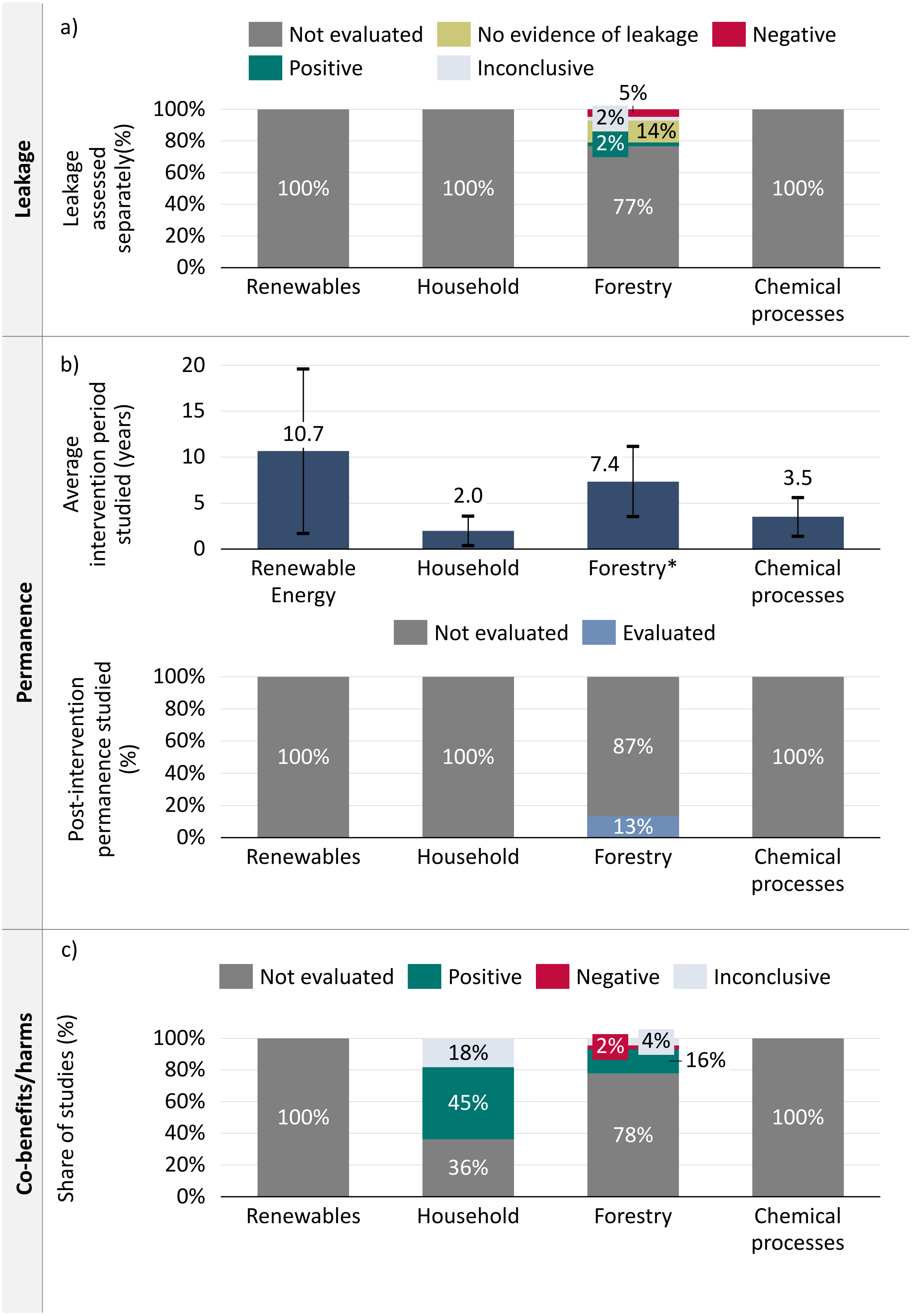

Figure 5: *a) Leakage, b) intervention period (and standard deviation) and share of the post-intervention period studied, and c) co-benefits/harms reported in studies in our study sample.*

Discussion

Overall, our review indicates that actual emissions reductions of offset projects are substantially lower than claimed. Furthermore, there is a dearth of empirical evidence around leakage, durability, and co-benefits arising from these interventions. We next turn to potential reasons that are behind the offset achievement gap across the main four offset sectors investigated. We then turn to external validity and potential bias in our results.

Renewable Energy

Across the four sectors, studies document the lowest offset achievement ratio for renewable energy (0%). Utility-scale renewable energy projects require high up-front investments and a secure cash flow to secure funding from banks and investors. As revenue streams from offsets are often low and may fluctuate substantially, as in the CDM, revenues generated by offsets are unlikely to substantially affect the financial viability of renewable energy projects. For instance, the most prominent policy schemes for renewable energy promotion have been feed-in-tariffs, offering stable power prices for commonly 20 years[29]. These projects have been deliberately shielded from the fluctuations of power markets, which are hard to predict far in advance. While the studies in our sample analyse wind projects, the findings likely extend to other renewable energy projects which feature similar capital structures, such as utility-scale solar, hydro and biomass[30]. Ultimately, the findings of several scholars, such as Haya[31], question whether accurate, verifiable ex-ante projections can even be constructed for renewable energy projects, such as wind[32] or hydropower[33]. It is important to note, however, that existing offset studies exclusively focus on utility-scale renewable projects and may not extend to small-scale projects.

Cookstoves

Cookstove offset projects feature similarly low offset achievement ratios (0.4%), though the literature is very limited. While cookstoves are often claimed to offer win-win solutions for health and the environment, the low additionally may be explained by behavioural and cultural reasons that interfere with the correct usage and full substitution of low emissions cookstoves. These factors render the project developers' emissions reduction assumptions of cookstove offset projects commonly taken from laboratory tests highly unrealistic. These laboratory tests assess the thermal efficiency in a highly artificial environment, which often does not represent how the stove is used outside of the lab. For instance, more fuel-efficient cookstoves are typically used next to the existing stoves, therefore serving as a complement rather than a substitute [34].

While only one study assesses an official cookstove offset project (finding no emissions reductions[7]), 10 studies that have analysed field interventions show substantial variation in the achieved emissions reductions. For instance, Hanna et al.[34] conducted a large-scale RCT in India and found no environmental benefits from stove adoption. In contrast, Berkouwer and Dean[35] conducted a study with a similar set-up in Kenya finding substantial emissions reductions from the BURN stove. Various reasons could explain this divergence in findings, including price, stove design, user behaviour and maintenance.

Hence, these findings indicate that cookstove projects are not ineffectual in general, but that the effectiveness is context-dependent, and more work is needed to understand the specific drivers of effectiveness.

Forestry

Studies on forestry offsets document higher offset achievement ratios than in renewable energy and cookstoves, yet overall remain below expectations (25.0%). The studies underscore common problems in conservation projects since they may be situated in areas with low overall deforestation risk, which reduces the likelihood that these projects avoid deforestation that would have happened otherwise.

We found that studies diverge substantially in their offset achievement ratio assessments, even if the same forestry offset project is analysed. 20 forestry projects certified by Verra have been analysed by at least two studies. Figure 6 shows estimates for these projects. Whereas Guizar-Coutiño et al.[36] find medium to high achievement (44% offset achievement ratio across projects), West et al. [6,16] find comparatively low achievement (5%). It is noteworthy that the study estimates across these forest projects show only a low correlation between these studies ($r = 0.17$).

Several reasons could explain this divergence. First, studies differ on methodological grounds. West et al. [6,16] rely on synthetic control (SC) methods, which compare projects to a weighted combination of potential control units to estimate the additional emissions reductions achieved by the project. In contrast, Guizar-Coutiño et al.[36] rely on a difference-in-difference approach, which matches pixels drawn from projects to similar pixels from forests not covered by the projects. The robustness of each approach hinges on the ability to construct a credible control group to evaluate the impact of the offset project. Difference-in-difference approaches make the simplifying assumptions that project and control sites would have followed the same trend in the absence of the project ("parallel trends assumption"). In contrast, the SC method relies on a weighted combination of control units allowing to reduce bias in cases where the parallel trend assumption is violated. Yet, the SC method typically features smaller sample sizes due to a more limited set of potential control units. Difference-in-difference approaches typically draw on larger samples but cannot control for time-invariant heterogeneity. In addition, Guizar-Coutiño et al.[36] et al rely on more fine-grained satellite data (30m) compared to West et al. [6,16]. Lastly, the somewhat different time coverage could explain some of the results, as Guizar-Coutiño et al.[36] analyse the first 5 years of projects compared to longer time frames analysed in West et al. [6,16].

The observed divergence underscores the challenge of estimating the offset achievement ratio of forestry avoidance projects. Estimates are very sensitive to the creation of the control group, a non-trivial task due to the unobservable nature of these groups and the necessity of their construction via statistical methods. Overall, while the findings diverge, both West et al. [6,16] Guizar-Coutiño et al.[36] indicate that forest protection was much less effective than assumed in the Verra projects ex-ante estimates.

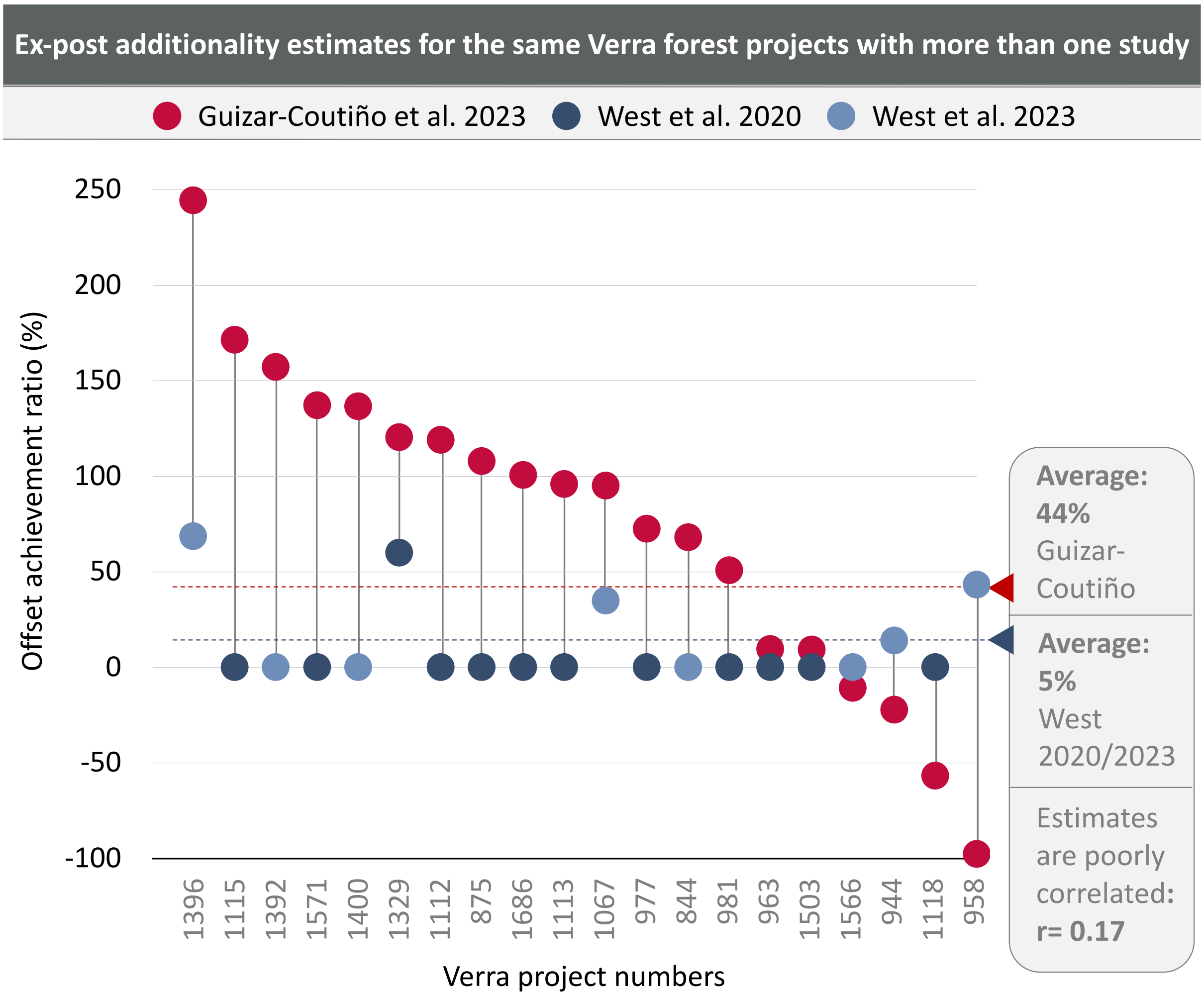

Figure 6: Comparison of offset achievement ratio for the same forestry projects across studies. *Source: Authors, based on studies mentioned in Figure. For Guizar-Coutiño we divide the achieved emissions reductions reported in the paper by the ex-ante predicted emissions reductions in the project design documents by Verra. The average achievement ratio in each study is weighted by expected project emission reduction in the first 10 years. Hence, projects that are expected to avoid more CO_2 are weighted more strongly.*

The overall intervention length covered by the studies was only 7 years. This presents an additional challenge since it is expected that the offset achievement ratio would become even lower than 25.0% after more than 7 years. Offset projects contain buffer pools – a share of credits that are not sold used to cover non-permanence risks – but studies suggest that tend to be insufficient given increased risks to forests through fires. For instance, Badgley et al.[37] document that the forestry projects' buffer pools in California's cap and trade programme are almost empty after their first 10 years despite needing to protect against forest fire risk over the next 100 years. In addition, although afforestation projects have become a popular offsetting mechanism, there are no offset studies investigating the offset achievement ratios of afforestation projects.[36]

Chemical processes

Projects in chemical processes (HFC-23 and SF_6 destruction) yielded the highest offset achievement ratio in our sample. We could only find two empirically rigorous studies that evaluated the impact of HFC-23 and SF_6 in Russia. In theory, the abatement of the above-mentioned substances should offer high offset achievement ratios without financial or regulatory incentives as there is commonly no business case for these interventions. Yet, the high abatement potential of these greenhouse gases can lead to perverse incentives that increase their production in the first place. This has been shown for projects under the Joint Implementation Mechanism in Russia. While the CDM addressed some of the issues of perverse incentives, qualitative research indicates that it still represents an issue.

Divergence in results between offset projects and field interventions

We find that forestry and cookstove projects designed and implemented as field interventions with similar settings as offset projects achieve higher emissions reductions than offset projects. For forestry projects, the offset achievement ratio from study intervention projects compared to offset projects is 39% (~1.6 times higher). For cookstove projects, field interventions – in contrast to offset projects – achieve a significant, though relatively low, average offset achievement ratio of 17.1%. For wind projects, the average offset achievement ratio is also non-significant. For chemical processes, we did not find field interventions that fulfilled the eligibility criteria (see Codebook for details).

We can only speculate about the reasons but hypothesise that one fundamental difference might drive the difference in observed outcomes. Field interventions (in contrast to offset projects) are often designed by researchers or non-governmental organisations – especially for RCTs – that want to test the effectiveness of a particular intervention instead of maximising financial gains as with private firms developing offset projects. For instance, Delacotte et al.[38] show that NGOs tend to locate forest protection projects in higher-risk areas than private firms that only aim to sell carbon credits. These differences in motivation could in turn affect a range of factors that lead to higher observed offset achievement ratios across projects such as improved targeting, implementation, and monitoring. We further explore potential reasons for the divergence between offset studies and field interventions in Supplementary Note 2.

Bias and external validity

Our analysis should be seen as preliminary and subject to several limitations concerning the external validity of the individual studies we analyse (even though it is the largest and only cross-sectoral effort to date) and the calculation of synthetic offset achievement ratio for field intervention studies.

Our estimates about sectoral offset achievement ratios rely on the generalisation of individual project observations to overarching sectors, which neglects potentially important factors such as country, year, or implementing organisation. For some sectors, such as cookstoves and chemical processes, our study sample is relatively small which could cause a biased generalisation to the overall offset achievement ratio. In addition, carbon offset projects may also provide additional climate benefits that are not captured by existing methodologies, such as soil effects in forest carbon protocols[39,40]. Lastly, the funnel plot and Egger's test (see Supplementary Note 1 and Supplementary Figure 5) suggest a small-study bias in our analysis, whereby studies with smaller samples find higher additionalities, suggesting the presence of publication bias.[41]

In addition, to calculate the synthetic offset achievement ratio of field interventions, we matched field interventions with similar offset projects to compare ex-post observations from field interventions to ex-ante projections by offset issuers. The matching was based on intervention type, country, and year assuming that matched projects provide suitable proxies for ex-ante projections. To increase robustness, at least two matching offset projects were selected. Further research on offset projects and field interventions is needed to increase the robustness and external validity of our offset achievement ratio estimates.

While our analysis is preliminary, the offset studies in our sample analysed offset projects with considerable ex-ante estimated credit volumes, such as 216 megatons of CO2 for forestry (equivalent to 33% of the current voluntary carbon market (VCS) forestry volume), 167 megatons for renewables (equivalent to 32% of the current VCS renewables volume), and 0.43 megatons of cookstoves (or around 1% of the current VCS cookstove volume) and 104 megatons for industry (160% of current market volume in the VCM, as these credits primarily stem from the regulated markets (e.g., CDM), which surpass current VCS volumes). Hence, for cookstove offsets, in particular, more work is needed.

Conclusion

We synthesize existing rigorous empirical studies from more than 2,000 offset projects that estimate the extent to which offset projects have achieved avoided or reduced carbon emissions.

Overall, we find low offset achievement ratios across sectors, with 0% for renewable energy, 0.4% for cookstoves, 25.0% for forestry and 27.5% for chemical processes. Based on the offset achievement ratios, we calculate that up to 88% (or ~1.1 GT of 1.3 GT CO_2) of offsets across these four sectors may not constitute real emissions reductions. The estimated share of credits without real emissions reductions corresponds to roughly twice the current annual emissions of the entire German economy. For field interventions without official credit issuance, we document higher effectiveness for cookstoves and forestry. This divergence indicates that offset projects using these interventions can likely be improved, though their overall offset achievement ratio of the field interventions still lies considerably below the emissions reduction potential that project developers commonly claim. We recognise that these results should be seen as a synthesis of the best available evidence to date but still exploratory given the low number of rigorous empirical studies that are available.

Voluntary carbon markets are expected to grow significantly over the next decades[42] and the Article 6 mechanism envisaged by the Paris Agreement will further increase demand for carbon offsets[43]. Yet, our results substantiate doubts about the environmental integrity of carbon offsets projects from the four sectors we study. Our analysis suggests that there is no one-size-fits-all solutions and specific targeting, local context adaptation, and continuous, dynamic monitoring are the cornerstones of increasing offset achievement ratios.

Yet, implementing these changes will not only increase the costs of these carbon offsets, but it will also render the underlying project-based funding model less effective. Carbon offset revenues are inherently difficult to predict as the timing, price, and quantity may change over a project's lifetime. Improvements in offset protocols, such as dynamic baselining[44], may decrease the likelihood of low offset achievement ratios, but also increase uncertainty regarding the revenues that can be generated from offset sales by a project.

Furthermore, our results underscore the recommendations from the Oxford Principles for Net Zero Aligned Carbon Offsetting[45] to move away from avoidance-based offsets towards more durable solutions. We study sectors that generate offsets based on avoided emissions and only provide short-lived storage (e.g., in forests). The inherent difficulties of ensuring effectiveness and scaling these projects while safeguarding environmental integrity, strongly support the move towards other carbon credits based on carbon removal (not avoidance) with long-lived storage. Transitioning to carbon removal with long-lived storage is particularly important if offsets are continued to be used to offset fossil fuel emissions, which remain in the atmosphere for hundreds to thousands of years. Using offsets with questionable impact and short-lived storage is therefore inadequate to properly offset these emissions. Our analysis, therefore, underscores that current voluntary carbon markets need to be substantially improved if they are to become an important enabler of the net-zero transition.

Methods

Analysis framework: We developed a framework which we use to systematically assess whether offsets achieve the intended goal of reducing or avoiding carbon emissions. Based on this framework, we searched the academic literature. The framework has the following four components: sectoral classification of carbon offsets, the development of criteria for the evaluation of offsets, the systematic review process, and the analysis of offset achievement ratios.

i) Sectoral classification of carbon offset

To set the scope of our analysis, we rely on voluntary carbon market data provided by the Berkeley Carbon Trading project[46]. We assess offset achievement ratios of carbon offsets that represent all major offset sectors. To our knowledge, this is the most comprehensive open-access database maintained on voluntary carbon markets (see Figure 1).

We assess seven major sectors and 14 sub-sectors collectively comprising sectors that account for more than 90% of issued carbon offsets on the voluntary markets (Figure 1b). For the classification of offset projects into different categories we rely on the Berkeley Carbon Trading offset typology [14]. As there are many small sub-sectors, we concentrate our literature search on all major sectors and sub-sectors, which collectively cover ~90% of issued credits (Table 1 and Figure 1).

We base our keyword search on this list of carbon offset sectors and the relevant sub-sectors. The full list of keywords can be found in Supplementary Tables 1 & 2.

ii) Criteria and outcomes for the evaluation of the offset

This study relies on a systematic review methodology to assess the carbon reduction and avoidance impacts of various offset projects. We only include studies that are either experiments (where researchers assign treatment) or rigorous observational studies (in which researchers leverage plausible exogeneous sources of variation to estimate project impacts) (see Supplementary Table 3 for inclusion and exclusion criteria). The fundamental difference between typical offset projects and these rigorous studies is that they include a credible control group that can plausibly answer the question: What would have happened if the project had not been implemented? Typically, offset projects use historical baselines as the control group, which is an imperfect approximation of project impact as contemporaneous socio-economic changes may drive the apparent project impact, not the project itself.[6,16]

iii) Systematic review process

In line with a large body of systematic reviews[9], we employ the Context-Intervention-Mechanism(s)-Outcome(s) (CIMO) framework to define keywords and select the studies for the systematic review. The CIMO framework includes the definition of the central research question, inclusion, and exclusion criteria to select studies from the large pool of potentially relevant studies, as well as a description of the final sample. We proceed as follows. After having defined the keywords and inclusion and exclusion criteria (see two sub-sections before), we use the AI-supported systematic review tool AS Review[9] to filter for relevant studies (e.g., using experimental or rigorous observational research methodologies) from 64,993 potentially relevant studies identified in the first step (Supplementary Figure 1 and Supplementary Table 1 & 2 for search terms). We then download the full text of the studies identified using AS Review and manually check for relevance. Then, two researchers independently extract the reported additionalities from individual projects and other relevant aspects of the study detailed in our Codebook. For field interventions that did not officially issue offsets, we compute a 'synthetic' additionality (i.e., the additionality if these projects had used assumptions of similar, real-world offset projects to issue offsets; see next section for details). In total, our final sample comprises more than 2,000 offset projects, and 130 effect sizes from 61 studies (see Extended Data 1). The detailed ROSES flow diagram for systematic reviews can be found in Supplementary Figure 1 and all included studies in Supplementary Table 6.

iv) Analysis of the offset achievement ratio

Carbon offsets are typically issued by comparing the actual carbon reductions of a project to a hypothetical baseline scenario if the project had not been implemented. This counterfactual baseline scenario is typically based on extrapolating historical emission trends. Yet, historical baselines are commonly an imperfect guide to future emissions. It is, therefore, critical to contrast the ex-ante estimated emissions reductions to the ex-post achieved emissions reductions by offset projects. We call this the 'offset achievement ratio', which is the share of achieved emissions reductions based on credible academic studies relative to the claims made by project developers ex-ante.

For field interventions without official offset issuance, we approximate the offset achievement ratio by developing our approach to compute a 'synthetic' offset achievement ratio if these field interventions had issued offsets and had employed standard assumptions from similar, real-world offset projects. We first discuss assessing the offset achievement ratio of official offset projects, followed by our approach to assessing field interventions. Lastly, we discuss how we synthesise the offset achievement ratio is related to the commonly used concept of additionality and how we integrate different project estimates (lower, medium, and upper bound estimates) (see Figure 3, which contains upper bound estimates),

Official offset projects

Offset projects commonly report two distinct metrics in their project documentation. To illustrate our approach, let's assume we analyse a project that seeks to reduce deforestation and forest degradation (REDD+). A REDD+ project commonly reports ex-ante projection of baseline emissions C_{BL} (e.g., emissions through continued deforestation in the area, commonly a continuation of historical trends) and expected emissions reductions C_E due to the project (e.g., increased protection of forest leading to lower deforestation rates) (see Figure 7). For simplicity, we assume that there are two points in time: t = 0 (before the project) and t = 1 (at the point of evaluation, after the project has been implemented). We assume that the offset achievement ratio stays constant over time.

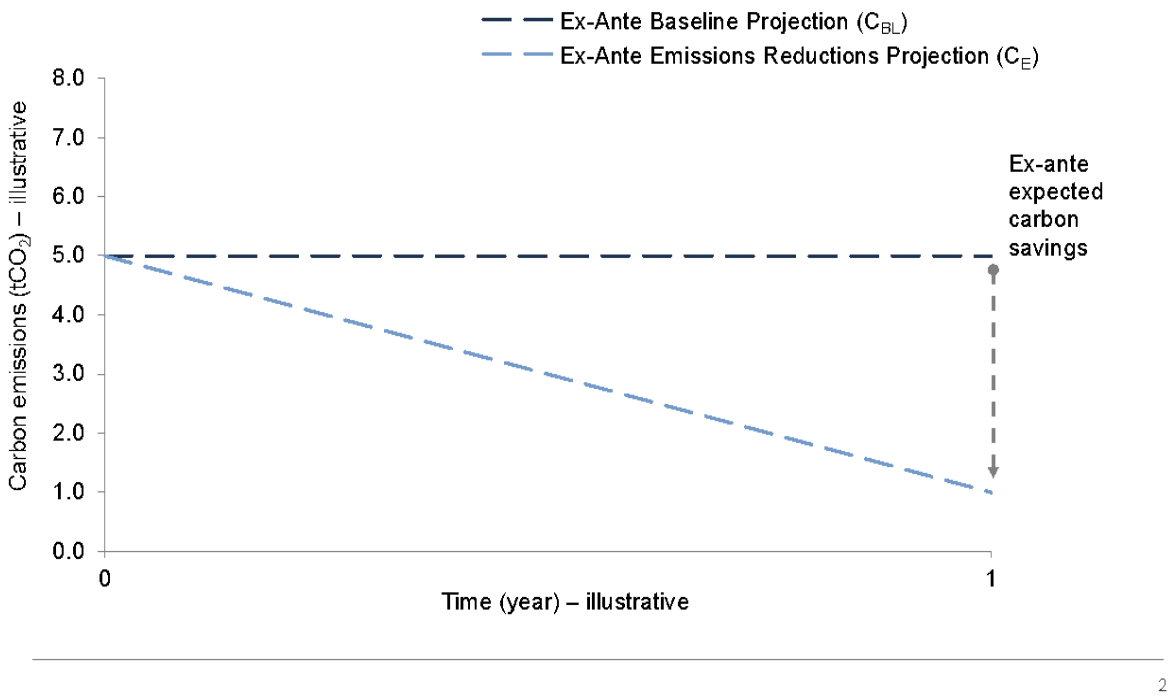

Figure 7: Illustrative ex-ante projections of carbon savings through a carbon offset project. Source: author

Yet, the true carbon emissions reductions from an offset project can only be assessed ex-post (i.e., after project implementation, see Figure 8). Two metrics are important in this regard: Counterfactual emissions C_C – which describes the true baseline emissions that would have occurred without the project. Rigorous empirical studies use a variety of statistical methods – such as propensity score matching and difference-in-difference econometrics – to create a credible control group. For a REDD+ project that could mean that the project area is compared to a similar plot of land, which faces a similar level of deforestation pressure but has not been enrolled in the programme.

In theory, the ex-ante projected baseline emissions could be the same as the ex-post estimated counterfactual emissions ($C_{BL} = C_C$), but as many exogenous factors change during project implementation, the projected and true baseline emissions likely diverge. For instance, an unexpected fall in international beef prices might decrease deforestation pressures suddenly, which in turn would decrease the "true" emissions baseline (Figure 7, see ex-ante baseline projection B_L and ex-post counterfactual C_C).

The second important metric is C_P, which is the true carbon reductions that the project led to. Again, in theory, $C_E = C_P$ could be true, but the project might either be more or less effective in decreasing carbon emissions than projected ex-ante.

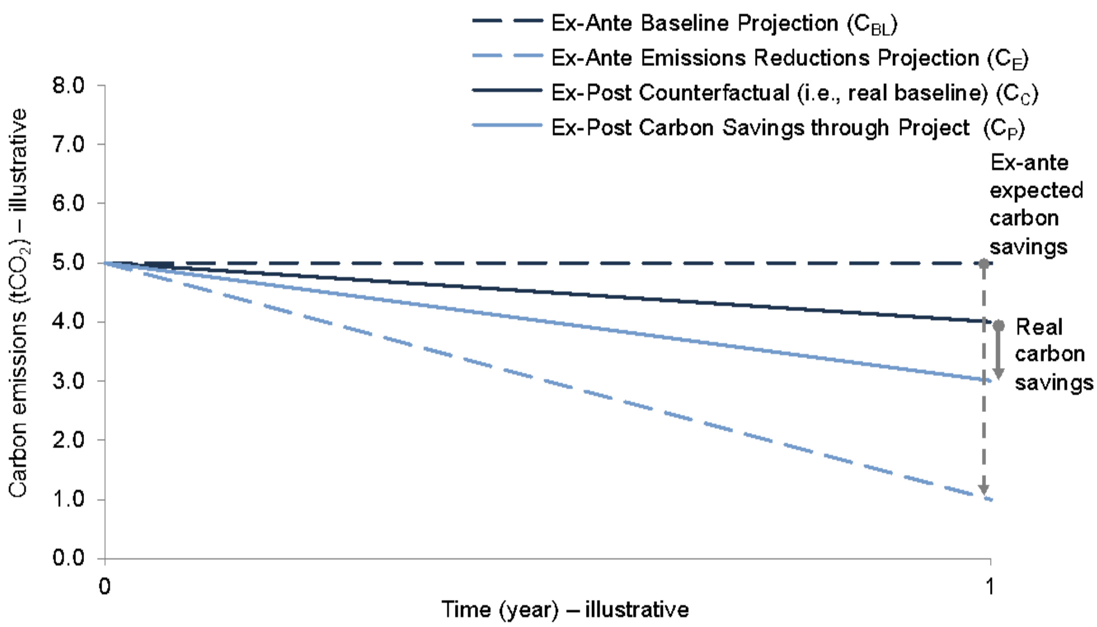

Figure 8: Illustrative ex-post assessment of carbon savings through a carbon offset project. Source: author

We then compute the offset achievement ratio (OAR) of project *i* as:

$$OAR = (C_P - C_C) / C_E \quad (1)$$

where:

$$C_E = C_{BL} * EI \quad (2)$$

EI is an effectiveness index and describes the effectiveness of the project in reducing carbon emissions relative to the baseline. The EI differs from project to project, but it commonly ranges between 0.5 and 1. If the project has an EI of 1, it is assumed that the offset project completely eliminates carbon emissions relative to the baseline. The average assumed EI in project design documents is 100% for renewable energy (relative to the grid factor) and chemical processes (relative to the baseline emissions), 75% reduction relative to the baseline for forestry and 65% for cookstoves projects.

A project that has an offset achievement ratio of 0%, did not lead to any emissions reductions, whereas a project with an OAR of 100% fully yielded the expected emissions reductions. A project with an offset achievement ratio of -100% led to emissions increases proportionally to the size of the initially claimed reductions. In cases where the emissions savings are not reported, we use a corresponding measure from the study that linearly correlates with emissions savings (e.g., reductions in deforestation rates between a project and counterfactual scenario or reduction in fuelwood use by households for cookstoves projects).

For instance, let’s assume $(C_P - C_C)$ was an emissions reduction of -20 t CO_2 (studies commonly report the aggregated effect size between the project and a counterfactual (i.e., true baseline) scenario instead of separate effect sizes for the baseline and counterfactual scenario)). The claimed emissions reduction was -40t CO_2.

Hence:

$$OAR_i = (C_P - C_C) / C_E = -20t / -40t = 50\% \quad (3)$$

If $(C_P - C_C) = 0$, then the OAR is by definition 0. Hence, for studies that show no difference between the baseline and counterfactual scenario, and do not report E, we collect no data on E as E would not change the offset achievement ratio in these cases.

If a project claims to have offset 1 megaton of emissions, but had an OAR of 50%, then only 0.5 megatons were reduced. We call the absolute difference between what was claimed and achieved, the offset achievement gap.

Field interventions

To compute the potential OAR of field interventions that did not officially issue offsets, we approximate the potential OAR. To calculate the OAR by offset sector, we compared actual emissions reductions (from ex-post evaluations of the research studies) with ex-ante estimates of emissions reductions from relevant offset project reports. The matching of research studies with offset projects was conducted in four steps:

1. We developed an algorithm that matched each field intervention with an official offset project from the Berkeley Voluntary Registry Offsets Database[46] in the same sub-sector (e.g., *REDD+*, *cookstoves*), country, and intervention years of the study and randomly shuffled the filtered sample of offset projects using package pandas (Version 1.2.5) in Python (Version 3.8).
2. We manually went through the sample from step 1 in chronological order. For each project, we evaluated if the project resembled the study setting of the research study (e.g., by checking if a similar cookstove was used for the intervention). If the project was not found suitable, we moved to the next project in the sample set. If the project was found suitable, we extracted ex-ante estimates of baseline emissions and project emissions (during crediting period) from the project documents to calculate the estimated percentage of emissions reduction of the project.
3. Next, the project documents were retrieved from the websites of the credit issuers (e.g., Verra, Gold Standard). For each study, we extracted ex-ante estimates of emissions reductions from two different projects. If the estimates deviated from each other by more than 20 per cent, we also included a third project.
4. Finally, we used the mean from the expected projects' emissions reduction estimates as a comparison to the ex-post emissions reductions calculated in the research studies. For instance, if an official cookstove project implemented in the same country at the same time assumed that emissions would be reduced relative to the baseline by 60% but the field interventions only found a 20% reduction, then the offset project would have an offset achievement ratio of 20% / 60 % = 33%.

The flow diagram and the relevant steps can be found in Supplementary Figure 2.

The offset achievement ratio and additionality

Studies employ different approaches to assess whether a project reaches its intended goal of reducing or avoiding carbon emissions. The literature typically employs the concept of 'additionality', which asks what would have happened in the absence of the project. Additionality, therefore, is used to conceptualise the real carbon emissions savings (see Figure 7), which we then divide by ex-ante estimates from project design documents (if the study does not already do so) to calculate the offset achievement ratio.

As the concept of additionality underpins the offset achievement ratio, we therefore briefly discuss these different types, their stringency, and the focus of our study. As the ex-ante estimates are determined by the project developers and are therefore standardised, the additional carbon savings estimated by studies differ substantially (see below).

In Supplementary Figure 3, we differentiate between four types of additionality:

1. **Financial additionality** (Voluntary carbon market leads to financing that the projects would otherwise not have raised via other private or public sources of finance and only this funding makes the project viable. Even with the funding project might still not be implemented
2. **Project additionality** (The sole reason for the existence of the project is the funding/revenue stream that the project acquired via voluntary carbon markets)
3. **Emissions additionality** (Project leads to emissions avoidance, abatement or removal that would not have happened without the project)
4. **Marginal additionality** (Each sale of a carbon offset leads to a decrease in CO_2 emissions in the project)

To illustrate these different types of additionality, assume that we want to evaluate the additionality of a biomass power plant financed by carbon credits. The first, and least stringent criterion, for assessing the additionality of the project, is to ask whether the project could have acquired sufficient financing even without the carbon credits. If the revenue generated through the (prospective) sale of carbon credits was sufficient to make the project financially viable, then the next question becomes whether the project was eventually built (project additionality). If the project was financed and built due to carbon credits, then the question becomes to what extent, the biomass power plant is reducing emissions in the power grid into which it is delivering its electricity. For instance, if the grid is already zero emissions due to large shares of hydropower and conventional renewables such as wind and solar, then the emissions additionality of the project would be zero, as no additional emissions are displaced. Yet, if the biomass plant feeds into a grid dominated by coal-fired electricity, the emissions additionality is clear. Lastly, the most stringent form of additionality, is whether each additional sale of credits leads to an additional decrease of carbon emissions. For instance, if the biomass-fired power plant cannot maintain its operation (e.g., maintenance, buying additional biomass) were it not for the sale of carbon credits, then even the marginal additionality would be fulfilled.

Yet, the studies in our review typically fall into two types of camps. First, studies investigating the additionality of renewable energy typically assess financial[3] and project additionality[17]. While clearing the hurdle of financial and project additionality are necessary conditions for emissions additionality, they are not sufficient. To establish emissions additionality, a detailed power system model would be needed, to assess the exact emissions displaced in the grid, which depends on the exact production volume and time of the wind power plant, its exact location in the supply curve, the grid operator, and many other factors. Hence, the additionality assessments of renewable energy projects should be considered less stringent than studies that assess emissions additionality. In contrast, chemical processes, cookstoves, and forestry projects assess emissions additionality. As there is typically no business case to implement these projects otherwise, financial and project additionality can be assumed to be true (at least, in most cases). Hence, these projects assess emissions additionality, by considering the tailpipe emissions from industrial plants, emissions associated with changes in deforestation levels or fuelwood use. Emissions additionality assessments can therefore be considered more stringent than financial/project additionality. No study in our sample considers marginal additionality, likely due to the complexities of measuring that type of additionality.

Central and upper bound estimates

Studies typically report central estimates. We consider central estimates those empirical estimates that consider two sources of low offset achievement ratios:

1. **Wrong baseline:** The study assesses what the real, counterfactual baseline would have been if the project had not been implemented. Typically, the ex-ante baseline is compared to a credible, ex-post baseline
2. **Wrong project impact:** The study assesses what the real project impact was after the project had been implemented. Typically, the ex-ante, expected emissions reductions associated with the project are compared to a credible, ex-post project impact assessment.

Please note that these two sources of low offset achievement ratio correspond to comparing the real carbon savings to the ex-ante expected carbon savings in Figure 7. For studies that only consider whether the baseline has been inappropriately set, but do not analyse whether the project itself was additional, we consider these estimates to be an upper bound (see, for instance, ref[47]). These are upper-bound estimates, as the project impact could be as low as zero. Similarly, if studies explicitly state that their estimates could be as low as zero, we also record those as upper bound (see ref [17].)

Contributions

All authors developed the research idea. B.P. conducted the empirical analysis with support from M.T., B.P. analysed and visualized the data and wrote the manuscript with support from all authors, while A.K., L.D.A. and V.H. edited the final draft.

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Correspondence to Benedict Probst.

Data availability

The data is available upon reasonable request from the corresponding author.

Code availability

The code is available upon reasonable request from the corresponding author.

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Supplementary Information: Systematic review of the actual emissions reductions of carbon offset projects across all major sectors

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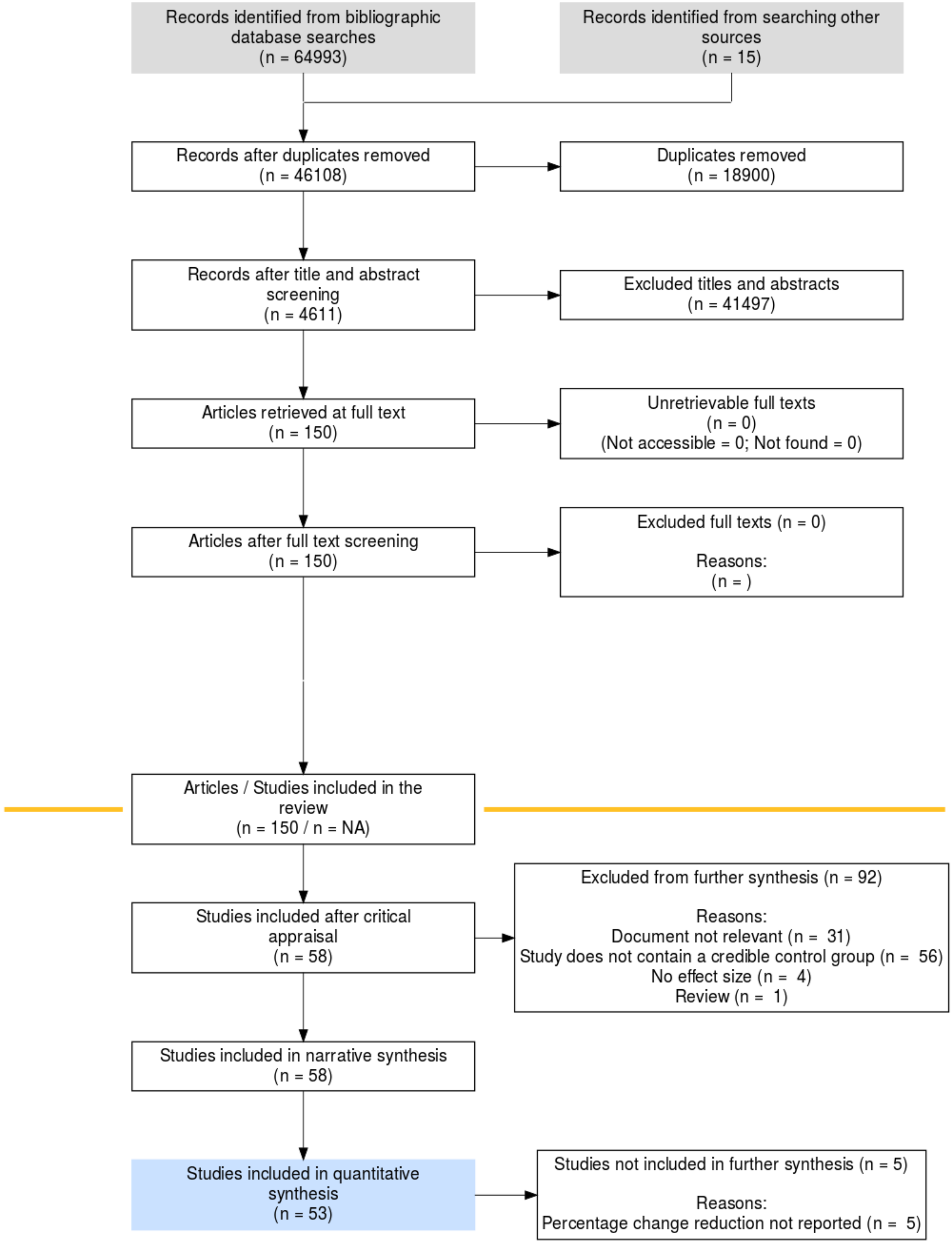
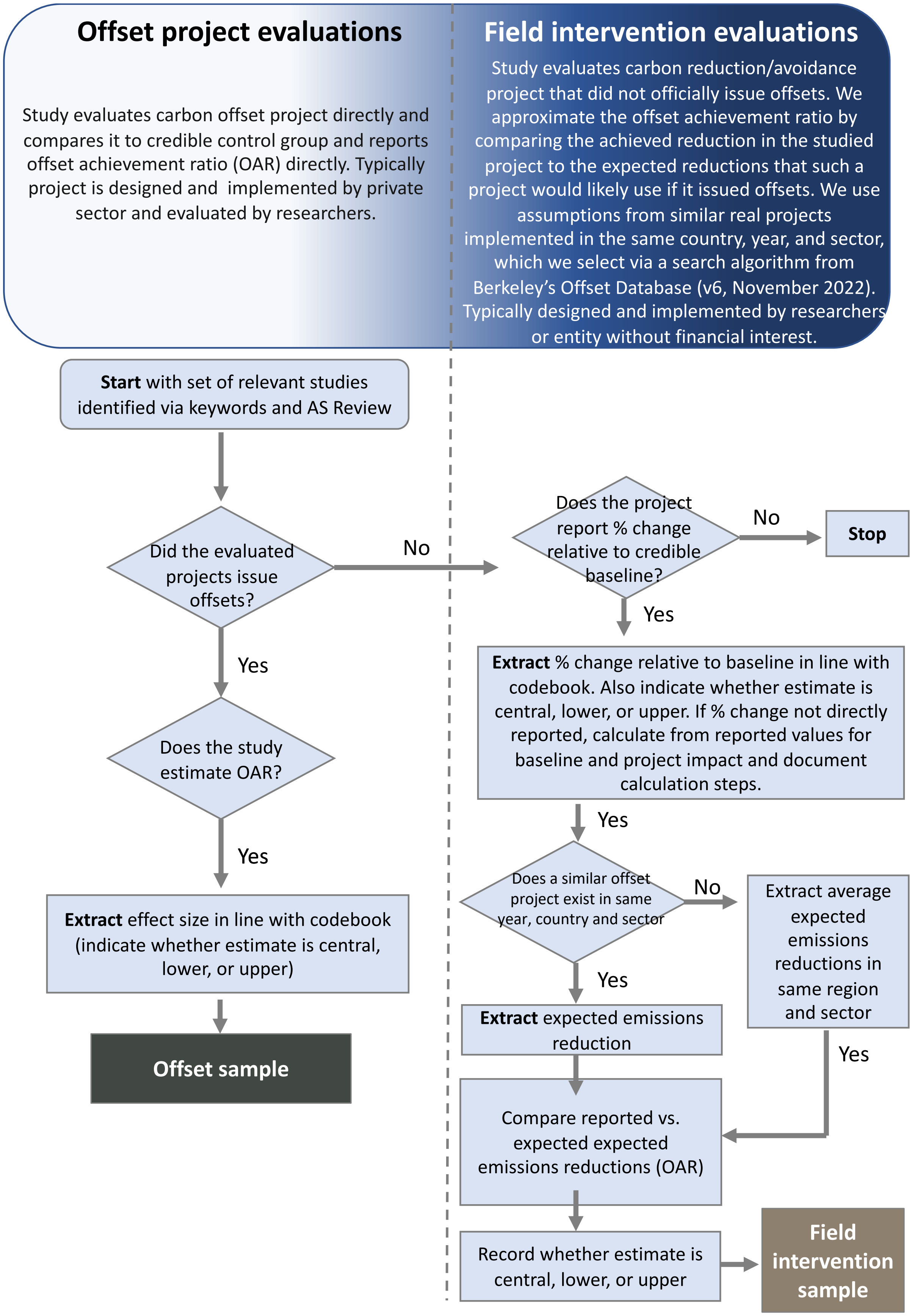
Supplementary Figures

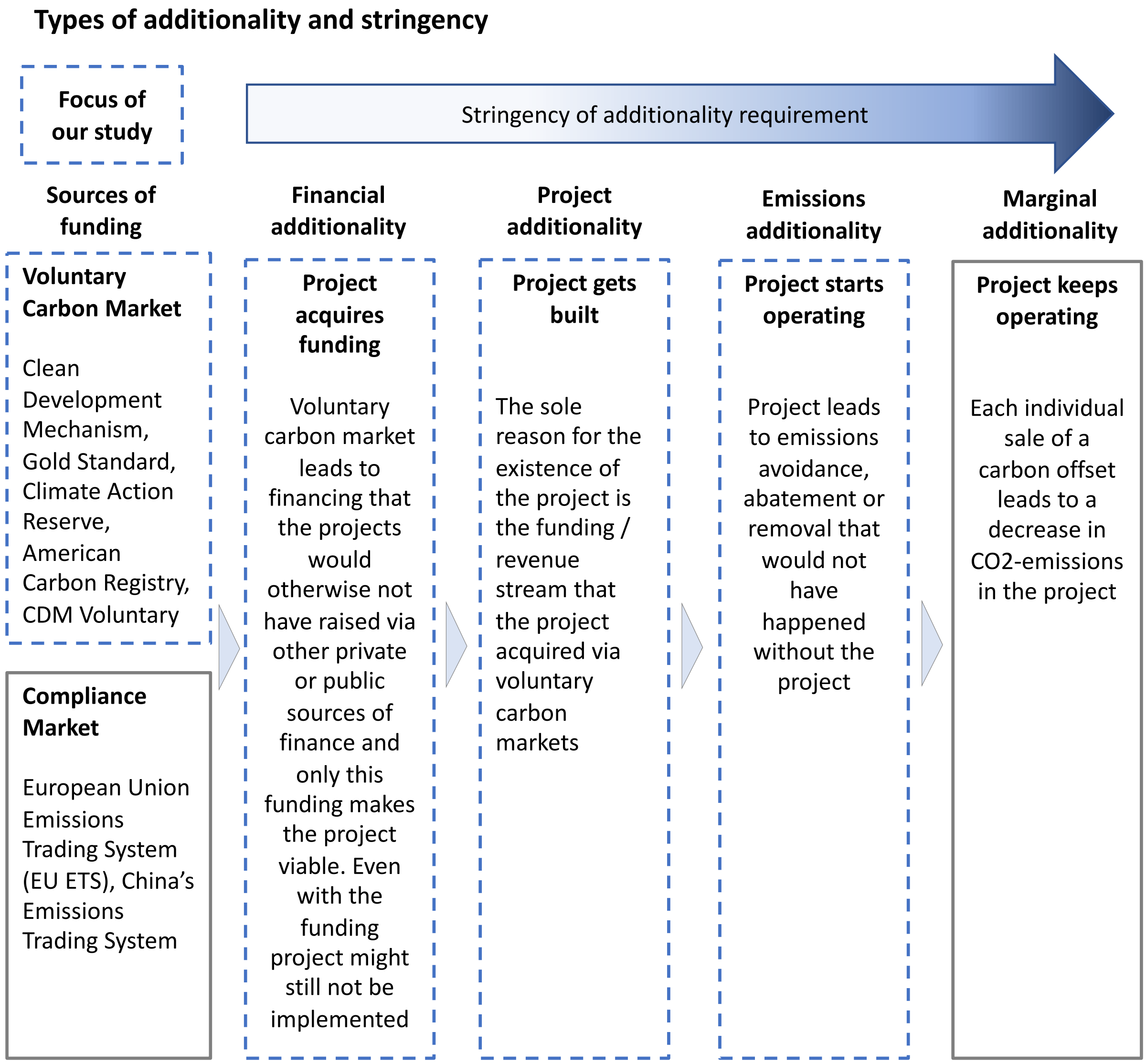
Supplementary Figure 1: ***ROSES flow diagram for systematic reviews.***



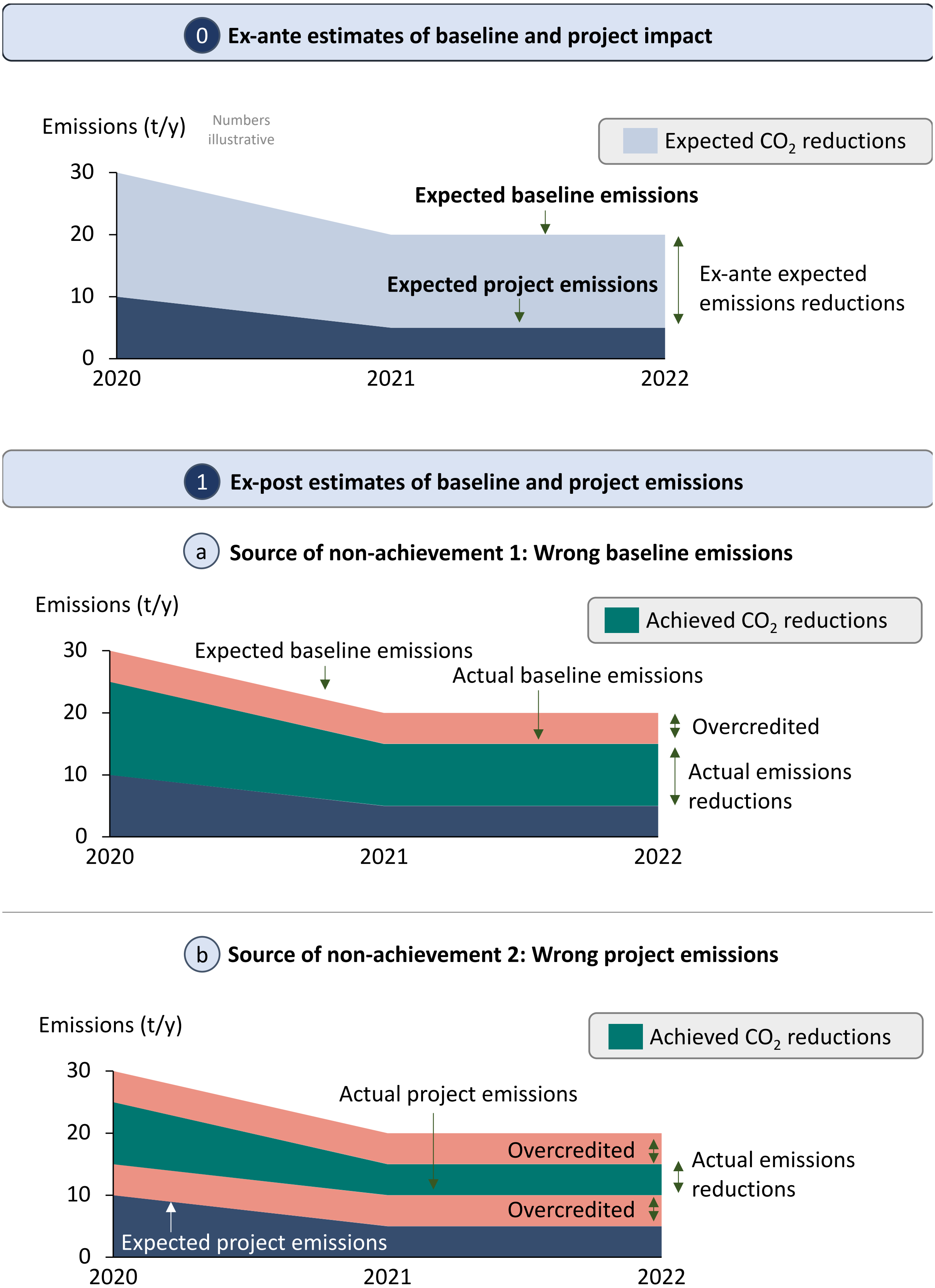
Supplementary Figure 2: Flow of study selection.



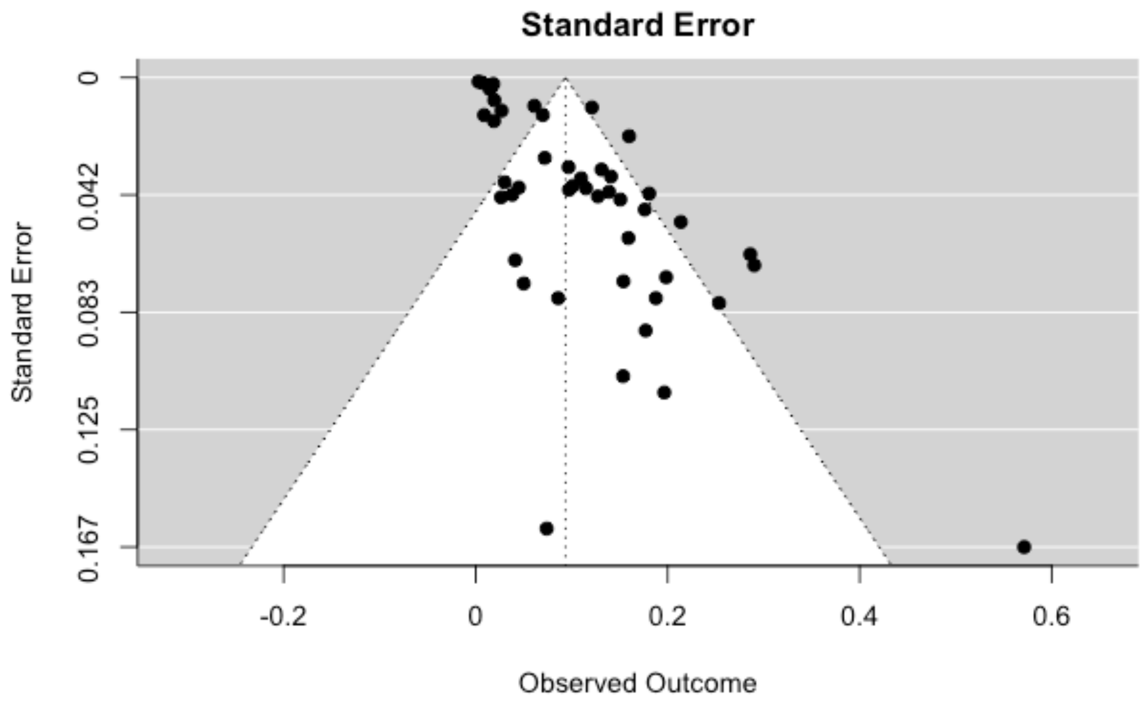
Supplementary Figure 3: Types of additionality and stringency.



Supplementary Figure 4: Ex-ante vs. ex-post project baseline and project emissions.



Supplementary Figure 5: Small sample bias plot.



Supplementary Tables

Supplementary Table 1*: Keywords used for search in SCOPUS. All articles downloaded: 26. Aug. 2022.*

	Search Keywords in SCOPUS
1. Population	-
2. Intervention	
Generic	“project-based mechanism*” OR “tradable emission* reduc* credit*” OR “carbon market*” OR “voluntary project*” OR “carbon W/5 offset*“ OR “condition* payment*” OR “condition* cash transfer*” OR “economic* incentiv*” OR “clean development mechanism” OR “joint implementation mechanism” OR “kyoto protocol*”
Forestry and Land Use	
REDD+	"reduc* emission* from deforestation and forest degradation" OR "reduc* emission* from deforestat* and degradat*" OR "deforestat* reduc*" OR "payment* for ecosystem service*" OR "payment* for environmental services" OR "cash payment" OR “condition* pay*” OR "REDD+" OR "REDD"
Improved Forest Management	"forest*" W/5 ("manag*")

Afforestation / Reforestation	(payment* OR subsid*) W/5 (forest* OR plantat*) OR “afforest*” OR “reforest*”
Renewable Energy	
Wind	(wind) W/5 (farm* OR project* OR power OR energy)
Solar	(solar) W/5 (farm* OR project* OR power OR energy)
Hydro	(hydro*) W/5 (project OR power OR energy)
Biomass	(biomass) W/5 (project OR power OR energy)
Waste management	
Landfill / wastewater methane	“landfill” W/5 (“gas” OR “methane”) OR “wastewater” W/5 (“gas” OR “methane”)
Chemical processes	
Ozone depleting substances	“HFC-23” OR “SF6” OR “ozone” W/5 “deplet*” OR “regfrig*”
N2O destruction in nitric acid production	“N2O” AND “nitric*”
Household and community	
Cookstoves	*stove*
Industrial manufacturing	
Mine methane capture	“mine" AND "methane" AND "captur*
Natural gas electricity production	“natural” AND “gas” W/5 (project OR power OR energy)
Carbon capture and storage	
Carbon capture and enhanced oil recovery	“carbon” W/5 “captur*”
3. Comparator	
Generic	"control group*" OR "randomized trial" OR "evaluat*" OR "before-after-control-intervention" OR assess* OR impact* OR causal* OR "synthetic* control*" OR mechanism OR "quasi-experiment*" OR "Random* Control* Trial" OR "Random* trial*" OR "ex post" OR "ex post" OR baseline OR "difference*-in-difference*" OR "identification strategy" OR compliance OR "synthetic* match*" OR “confound* factors”

4. Outcome	
	“environment* integrity” OR (CO2 OR carbon OR SF6 OR HFC-23 OR “waste gas*” OR deforest* OR “forest*” OR “tree cover” OR “land cover” OR conservation OR “fuel” OR “greenhouse gas*” OR “wood*” OR “*coal”) W/5 (abat* OR “produc*” OR generat* OR lower* OR “conserv*” OR “impact*” OR “increas*” OR loss OR protect* OR “additional” OR “change” OR “decline*” OR “consum*” OR curb OR sav*)

Supplementary Table 2: *Keywords used for search in Web of Science. All articles downloaded: 26. Aug. 2022*

	Search Keywords in WOS
1. Population	-
2. Intervention	
Generic	“project-based mechanism*” OR “tradable emission* reduc* credit*” OR “carbon market*” OR “voluntary project*” OR “carbon NEAR/5 offset*“ OR “condition* payment*” OR “condition* cash transfer*” OR “economic* incentiv*” OR “clean development mechanism” OR “joint implementation mechanism” OR “kyoto protocol*”
Forestry and Land Use	
REDD+	"reduc* emission* from deforestation and forest degradation" OR "reduc* emission* from deforestat* and degradat*" OR "deforestat* reduc*" OR "payment* for ecosystem service*" OR "payment* for environmental services" OR "cash payment" OR “condition* pay*” OR "REDD+" OR "REDD"
Improved Forest Management	"forest*" NEAR/5 ("manag*") W/5 “improv*”
Afforestation / Reforestation	(payment* OR subsid*) NEAR/5 (forest* OR plantat*) OR “afforest*” OR “reforest*”
Renewable Energy	
Wind	(wind) NEAR/5 (farm* OR project* OR power OR energy)
Solar	(solar) NEAR/5 (farm* OR project* OR power OR energy)
Hydro	(hydro*) NEAR/5 (project OR power OR energy)
Biomass	(biomass) NEAR/5 (project OR power OR energy)
Waste management	

Landfill / wastewater methane	“landfill” NEAR/5 (“gas” OR “methane”) OR “wastewater” NEAR/10 (“gas” OR “methane”)
Chemical processes	
Ozone depleting substances	“HFC-23” OR “SF6” OR “ozone” NEAR/5 “deplet*” OR “regfrig*”
N2O destruction in nitric acid production	“N2O” AND “nitric*”
Household and community	
Cookstoves	*stove*
Industrial manufacturing	
Mine methane capture	“mine" AND "methane" AND "captur*”
Natural gas electricity production	“gas” NEAR/5 (project OR power OR energy)
Carbon capture and storage	
Carbon capture and enhanced oil recovery	“carbon” NEAR/5 “captur*”
3. Comparator	
Generic	"control group*" OR "randomized trial" OR "evaluat*" OR "before-after-control-intervention" OR assess* OR impact* OR causal* OR "synthetic* control*" OR mechanism OR "quasi-experiment*" OR "Random* Control* Trial" OR "Random* trial*" OR "ex post" OR "ex post" OR baseline OR "difference*-in-difference*" OR "identification strategy" OR compliance OR "synthetic* match*" OR “confound* factors”
4. Outcome	
	“environment* integrity” OR (CO2 OR carbon OR SF6 OR HFC-23 OR “waste gas*” OR deforest* OR “forest*” OR “tree cover” OR “land cover” OR conservation OR “fuel” OR “greenhouse gas*” OR “wood*” OR “*coal”) W/5 (abat* OR “produc*” OR generat* OR lower* OR “conserv*” OR “impact*” OR “increas*” OR loss OR protect* OR “additional” OR “change” OR “decline*” OR “consum*” OR curb OR sav*)

***Supplementary Table 3**: Inclusion and exclusion criteria for studies.*

	Population	Intervention	Comparator	Outcome	Study type
Inclusion	-	Conditional payments for CO2e-emissions reduction	Projects, plots of land, or people that were not subject to the intervention	CO2e-emissions reduction (or comparable metric, such as deforestation)	Empirical quantitative studies that include a control group
Exclusion	-	Interventions that do not adhere to principle of conditionality	Without comparator	Without quantified impact of intervention	Simulation or modelling-based studies

***Supplementary Table 4:** Previous-meta-analyses.*

Name of study	Literature search strategy	Years covered	Databases used	Studies covered
Cames et al (2016)	No specific literature search strategy, but qualitative analysis of project design documents of 300 of projects in the Clean Development Mechanism	2006-2015	CDM project database, but no standardised literature search	NA

***Supplementary Table 5:** Descriptive overview of sample. Please also see Figure 5 in the main manuscript for other co-variates not reported here and the Extended Data 1 for the raw data.*

No	Variable	Stats / Values	Frequency
1	Publication year	Mean (sd): 2017.7 (3.5) Min < median < max: 2007 < 2018 < 2022	13 distinct values
2	**Sector**	• Forestry • Household • Renewable Energy • Chemical processes	• 45 • 11 • 3 • 2 4 distinct sectors
3	**Sub-Sector**	• REDD+ • IFM • Afforestation/Reforestation • Cookstoves • Wind • Ozone depleting substances	• 42 • 2 • 1 • 11 • 3 • 2 6 distinct sub-sectors
4	**Region**	• Latin America	• 34

		• Asia • Africa • Multiple • Northern America • Europe	• 13 • 6 • 4 • 3 • 1 5 distinct regions (+ multiple)
5	**Country**	• Mexico • Brazil • Ecuador • India • Peru • Multiple • Costa Rica • Senegal • United States of America • Cambodia • China • Indonesia • Chile • Colombia • Ethiopia • Guatemala • Guyana • Inner Mongolia • Nepal • Russia • Uganda	• 10 • 8 • 5 • 5 • 4 • 4 • 3 • 3 • 3 • 2 • 2 • 2 • 1 • 1 • 1 • 1 • 1 • 1 • 1 • 1 • 1 21 distinct countries (+ multiple)
6	**Intervention Start Year**	Mean (sd): 2006.2 (5.5) Min < median < max: 1992 < 2007 < 2019	20 distinct values
7	**Intervention Duration in Years**	Mean (sd): 6.5 (4.3) Min < median < max: 0.33 < 6 < 21	19 distinct values
8	**Total sample**	Mean (sd): 20906.7 (77774.09) Min < median < max: 1 < 522 < 473,282	53 distinct values
9	**Generic study design**	• Difference-in-difference + matching • Linear regressions + matching • RCT • Synthetic Control Method • Fixed effects • Before-after comparison • Difference in-means + matching • Difference-in-difference • Fixed effects + matched • Financial modelling • Multiple • Blatantly inframarginal projects methodology developed in the paper • Comparison coarse baseline vs. ecologically-grounded baseline • Heckman two stage model	• 11 • 10 • 8 • 5 • 4 • 3 • 3 • 3 • 3 • 2 • 2 • 1 • 1 • 1 • 1 • 1 • 1 • 1

		• IV • Logistic regression + matching • Randomised Controlled Trial • t-test + matching	
10	**Percentage change**[1]	Mean (sd): -49.9% (146.1%) Min < median < max: -995.6% < -20% < 25.2%	41 distinct values
11	**Estimate type (across all studies)**	• Point estimate • Lower bound • Upper bound • No point estimate	• 52 • 3 • 3 • 3
12	**Uncertainty quantification**	• Point estimate with uncertainty • Only point estimate without uncertainty • No point estimate / no uncertainty	• 49 • 9 • 3
13	**Offsets issued (only offset studies)**	• Yes • No	• 10 • 51
14	**Reported additionality (only offset studies)** [2]	Mean (sd): 25.0% (28.6%) Min < median < max: -1% < -16.6% < 70.1%	

__Supplementary Table 6:__ Studies included in the review

Number	Authors	Title	DOI	Publ_year	Region	Country	Sector	Sub_sector
1	Chan and Huenteler	Financing Wind Energy Deployment in China through the Clean Development Mechanism	NA	2015	Asia	China	Renewable Energy	Wind
2	Calel et al	Do Carbon Offsets Offset Carbon?	NA	2021	Asia	India	Renewable Energy	Wind
3	Gillenwater et al	Additionality of wind energy investments in the U.S. voluntary green power market	10.1016/j.renene.2013.10.003	2013	North America	United States of America	Renewable Energy	Wind
4	Ludwinski D., Moriarty K., Wydick B.	Environmental and health impacts from the introduction of improved wood stoves: evidence from a field experiment in guatemala	10.1007/s10668-011-9282-z	2011	Latin America	Guatemala	Household	Cookstoves
5	Jeuland M.A., Pattanayak S.K., Samaddar S., Shah	Adoption and impacts of improved biomass cookstoves in rural rajasthan	10.1016/j.esd.2020.06.006	2020	Asia	India	Household	Cookstoves

[1] For forestry projects, a value below -100% indicates that deforestation was fully offset and – in addition – new forest cover gained (e.g., -130% means that deforestation 100% reduced and 30% additional forest cover gained (relative to area that was deforested in counterfactual). A value above 0% indicates that the project led to increases in emissions relative to the baseline (i.e., did not offset any emissions, but actually increased them).

[2] Please not that these numbers deviate from the results reported in the main text as estimates in the main text only include central estimates (and here we also include upper bound estimates)

	R., Vora M.							
6	Brooks N., Bhojvaid V., Jeuland M.A., Lewis J.J., Patange O., Pattanayak S.K.	How much do alternative cookstoves reduce biomass fuel use? evidence from north india	10.1016/j.reseneeco.2015.12.001	2016	Asia	India	House hold	Cookstoves
7	Adrianzen, A.	Improved cooking stoves and firewood consumption: quasi-experimental evidence from the northern peruvian andes	10.1016/j.ecolecon.2013.02.010	2013	Latin America	Peru	House hold	Cookstoves
8	Mekonen, A., Beyene, A., Bluffstone, R., Gebreegziabher, Z., Martinsson, P., Toman, M., Vieder, F.	Do improved biomass cookstoves reduce fuelwood consumption and carbon emissions? Evidence from a field experiment in rural Ethiopia	10.1016/j.ecolecon.2022.107467	2022	Africa	Ethiopia	House hold	Cookstoves
9	Hanna R., Duflo E., Greenstone M.	Up in smoke: the influence of household behavior on the long-run impact of improved cooking stoves	10.1257/pol.20140008	2016	Asia	India	House hold	Cookstoves
10	Beltramo T., Levine D.I.	The effect of solar ovens on fuel use, emissions and health: results from a randomised controlled trial	10.1080/19439342.2013.775175	2013	Africa	Senegal	House hold	Cookstoves
11	Bensch G., Peters J.	The intensive margin of technology adoption – Experimental evidence on improved cooking stoves in rural Senegal	10.1016/j.jhealeco.2015.03.006	2015	Africa	Senegal	House hold	Cookstoves
12	Aung T.W., Jain G., Sethuraman K., Baumgartner J., Reynolds C., Grieshop A.P., Marshall J.D., Brauer M.	Health and climate-relevant pollutant concentrations from a carbon-finance approved cookstove intervention in rural india	10.1021/acs.est.5b06208	2016	Asia	India	House hold	Cookstoves
13	Bensch and Peters	Alleviating Deforestation Pressures? Impacts of Improved Stove Dissemination on Charcoal Consumption in Urban Senegal	10.3368/le.89.4.676	2013	Africa	Senegal	House hold	Cookstoves

14	Berkouwer, S., Dean, J.	Credit and attention in the adoption of profitable energy efficient technologies in Kenya	10.1257/aer.20210766	2022	Africa	Kenya	Household	Cookstoves
15	Carrilho C.D., Demarchi G., Duchelle A.E., Wunder S., Morsello C.	Permanence of avoided deforestation in a transamazon redd+ project (pará, brazil)	10.1016/j.ecolecon.2022.107568	2022	Latin America	Brazil	Forestry	REDD+
16	Simonet G., Subervie J., Ezzine-De-Blas D., Cromberg M., Duchelle A.E.	Effectiveness of a redd project in reducing deforestation in the brazilian amazon	10.1093/ajae/aay028	2018	Latin America	Brazil	Forestry	REDD+
17	Von Thaden J., Manson R.H., Congalton R.G., L√≥pez-Barrera F., Salcone J.	A regional evaluation of the effectiveness of mexico's payments for hydrological services	10.1007/s10113-019-01518-3	2019	Latin America	Mexico	Forestry	REDD+
18	Jayachandran S., De Laat J., Lambin E.F., Stanton C.Y., Audy R., Thomas N.E.	Cash for carbon: a randomized trial of payments for ecosystem services to reduce deforestation	10.1126/science.aan0568	2017	Africa	Uganda	Forestry	REDD+
19	Montoya-Zumaeta J., Rojas E., Wunder S.	Adding rewards to regulation: the impacts of watershed conservation on land cover and household wellbeing in moyobamba, peru	10.1371/journal.pone.0225367	2019	Latin America	Peru	Forestry	REDD+
20	Le Velly, G; Sauquet, A; Cortina-Villar, S	PES impact and leakages over several cohorts: the case of the psa-h in yucatan, mexico	10.3368/le.93.2.230	2017	Latin America	Mexico	Forestry	REDD+
21	Mohebalian P.M., Aguilar F.X.	Design of tropical forest conservation contracts considering risk of deforestation	10.1016/j.landusepol.2017.11.008	2018	Latin America	Ecuador	Forestry	REDD+
22	Jones K.W., Holland M.B., Naughton-Treves L., Morales M., Suarez L., Keenan K.	Forest conservation incentives and deforestation in the ecuadorian amazon	10.1017/s0376892916000308	2017	Latin America	Ecuador	Forestry	REDD+
23	Costedoat S., Corbera	How effective are biodiversity	10.1371/journal.pone.0119881	2015	Latin America	Mexico	Forestry	REDD+

	E., Ezzine-de-Blas D., Honey-Ros√©s J., Baylis K., Castillo-Santiago M.A.	Conservation payments in mexico?						
24	Clements T., Milner-Gulland E.J.	Impact of payments for environmental services and protected areas on local livelihoods and forest conservation in northern cambodia	10.1111/cobi.12423	2014	Asia	Cambodia	Forestry	REDD+
25	Ramirez-Reyes C., Sims K.R.E., Potapov P., Radeloff V.C.	Payments for ecosystem services in mexico reduce forest fragmentation	10.1002/eap.1753	2018	Latin America	Mexico	Forestry	REDD+
26	Honey-Roses J., Baylis K., Ramirez M.I.	A spatially explicit estimate of avoided forest loss	10.1111/j.1523-1739.2011.01729.x	2018	Latin America	Mexico	Forestry	REDD+
27	Arriagada R.A., Ferraro P.J., Sills E.O., Pattanayak S.K., Cordero-Sancho S.	Do payments for environmental services affect forest cover? a farm-level evaluation from costa rica	10.3368/le.88.2.382	2012	Latin America	Costa Rica	Forestry	REDD+
28	Ruggiero P.G.C., Metzger J.P., Reverberi Tambosi L., Nichols E.	Payment for ecosystem services programs in the brazilian atlantic forest: effective but not enough	10.1016/j.landusepol.2018.11.054	2019	Latin America	Brazil	Forestry	REDD+
29	Robalino, J; Pfaff, A; Sandoval, C; Sanchez-Azofeifa, GA	Can we increase the impacts from payments for ecosystem services? impact rose over time in costa rica, yet spatial variation indicates more potential	10.1016/j.forpol.2021.102577	2021	Latin America	Costa Rica	Forestry	REDD+
30	Robalino et al	Evaluating Interactions of Forest Conservation Policies on Avoided Deforestation	doi.org/10.1371/journal.pone.0124910	2015	Latin America	Costa Rica	Forestry	REDD+
31	Bos A.B., Duchelle A.E., Angelsen A., Avitabile V., De Sy V., Herold M., Joseph S., De Sassi C., Sills E.O., Sunderlin W.D., Wunder S.	Comparing methods for assessing the effectiveness of subnational redd+ initiatives	10.1088/1748-9326/aa7032	2017	Multiple	Multiple	Forestry	REDD+

32	Correa J., Cisneros E., B√∂rner J., Pfaff A., Costa M., Raj√£o R.	Evaluating redd+ at subnational level: amazon fund impacts in alta floresta, brazil	10.1016/j.forpol.2020.102178	2020	Latin America	Brazil	Forestry	REDD+
33	Ellis E.A., Sierra-Huelsz J.A., Ceballos G.C.O., Binnq√ºist C.L., Cerd√°n C.R.	Mixed effectiveness of redd+ subnational initiatives after 10 years of interventions on the yucatan peninsula, mexico	10.3390/f11091005	2020	Latin America	Mexico	Forestry	REDD+
34	Roopsind A., Sohngen B., Brandt J.	Evidence that a national redd program reduces tree cover loss and carbon emissions in a high forest cover, low deforestation country	10.1073/pnas.1904027116	2019	Latin America	Guyana	Forestry	REDD+
35	Sims K.R.E., Alix-Garcia J.M.	Parks versus pes: evaluating direct and incentive-based land conservation in mexico	10.1016/j.jeem.2016.11.010	2016	Latin America	Mexico	Forestry	REDD+
36	Alix-Garcia J.M., Sims K.R.E., Yañez-Pagans P.	Only one tree from each seed? environmental effectiveness and poverty alleviation in mexico's payments for ecosystem services program	10.1257/pol.20130139	2015	Latin America	Mexico	Forestry	REDD+
37	Alix-Garcia J.M., Shapiro E.N., Sims K.R.E.	Forest conservation and slippage: evidence from mexico's national payments for ecosystem services program	10.3368/le.88.4.613	2012	Latin America	Mexico	Forestry	REDD+
38	Chervier C., Costedoat S.	Heterogeneous impact of a collective payment for environmental services scheme on reducing deforestation in cambodia	10.1016/j.worlddev.2017.04.014	2017	Asia	Cambodia	Forestry	REDD+
39	Jones K.W., Mayer A., Von Thaden J., Berry Z.C., López-Ramírez S., Salcone J., Manson R.H., Asbjornsen H.	Measuring the net benefits of payments for hydrological services programs in mexico	10.1016/j.ecolecon.2020.106666	2020	Latin America	Mexico	Forestry	REDD+
40	Giudice R., Börner J., Wunder S., Cisneros E.	Selection biases and spillovers from collective conservation incentives in the peruvian amazon	10.1088/1748-9326/aafc83	2019	Latin America	Peru	Forestry	REDD+

41	Jones K.W., Lewis D.J.	Estimating the counterfactual impact of conservation programs on land cover outcomes: the role of matching and panel regression techniques	10.1371/journal.pone.0141380	2015	Latin America	Ecuador	Forestry	REDD+
42	Cisneros E., Börner J., Pagiola S., Wunder S.	Impacts of conservation incentives in protected areas: the case of bolsa floresta, brazil	10.1016/j.jeem.2021.102572	2022	Latin America	Brazil	Forestry	REDD+
43	Etchart N., Freire J.L., Holland M.B., Jones K.W., Naughton-Treves L.	What happens when the money runs out? forest outcomes and equity concerns following ecuador's suspension of conservation payments	10.1016/j.worlddev.2020.105124	2020	Latin America	Brazil	Forestry	REDD+
44	Pagiola S., Honey-Rosés J., Freire-González J.	Evaluation of the permanence of land use change induced by payments for environmental services in quindío, colombia	10.1371/journal.pone.0147829	2016	Latin America	Colombia	Forestry	REDD+
45	Fiorini A.C., Mullally C., Swisher M., Putz F.E.	Forest cover effects of payments for ecosystem services: evidence from an impact evaluation in brazil	10.1016/j.ecolecon.2019.106522	2020	Latin America	Brazil	Forestry	REDD+
46	Montoya-Zumaeta J.G., Wunder S., Rojas E., Duchelle A.E.	Does redd+ complement law enforcement? evaluating impacts of an incipient initiative in madre de dios, peru	10.3389/ffgc.2022.870450	2022	Latin America	Peru	Forestry	REDD+
47	Sharma B.P., Karky B.S., Nepal M., Pattanayak S.K., Sills E.O., Shyamsundar P.	Making incremental progress: impacts of a redd+ pilot initiative in nepal	10.1088/1748-9326/aba924	2020	Asia	Nepal	Forestry	REDD+
48	Zhou T., Shen W., Qiu X., Chang H., Yang H., Yang W.	Impact evaluation of a payments for ecosystem services program on vegetation quantity and quality restoration in inner mongolia	10.1016/j.jenvman.2021.114113	2022	Asia	Inner Mongolia	Forestry	REDD+
49	España F., Arriagada R., Melo O., Foster W.	Forest plantation subsidies: impact evaluation of the chilean case	10.1016/j.forpol.2022.102696	2022	Latin America	Chile	Forestry	Afforestation/Reforestation
50	Fu G., Uchida E., Shah M., Deng X.	Impact of the grain for green program on forest cover in china	10.1080/21606544.2018.1552626	2019	Asia	China	Forestry	REDD+
51	Hayes T., Murtinho F., Wolff	Effectiveness of payment for ecosystem services	10.1038/s41893-021-00804-5	2022	Latin America	Ecuador	Forestry	REDD+

	H., López-Sandoval M.F., Salazar J.	After loss and uncertainty of compensation						
52	Linkie M., Smith, R., Zhu Y., Martyr, D., et al	Evaluating Biodiversity Conservation around a Large Sumatran Protected Area	10.1111/j.1523-1739.2008.00906.x	2007	Asia	Indonesia	Forestry	REDD+
53	Erbaugh J.T.	Impermanence and failure: the legacy of conservation-based payments in sumatra, indonesia	10.1088/1748-9326/ac6437	2022	Asia	Indonesia	Forestry	REDD+
54	Cuenca P., Robalino J., Arriagada R., Echeverría C.	Are government incentives effective for avoided deforestation in the tropical andean forest?	10.1371/journal.pone.0203545	2018	Latin America	Ecuador	Forestry	REDD+
55	Badgley G., Freeman J., Hamman J.J., Haya B., Trugman A.T., Anderegg W.R.L., Cullenward D.	Systematic over-crediting in california's forest carbon offsets program	10.1111/gcb.15943	2021	Northern America	United States of America	Forestry	IFM
56	West et al.	Action needed to make carbon offsets from forest conservation work for climate change mitigation	NA	2023	Multiple	Multiple	Forestry	REDD+
57	Guizar-Coutiño A. et al	A global evaluation of the effectiveness of voluntary REDD+ projects at reducing deforestation and degradation in the moist tropics	10.1111/cobi.13970	2022	Multiple	Multiple	Forestry	REDD+
58	Coffield et al	Using remote sensing to quantify the additional climate benefits of California forest carbon offset projects	10.1111/gcb.16380	2022	Northern America	United States of America	Forestry	IFM
59	West T.A.P., B√∂rner J., Sills E.O., Kontoleon A.	Overstated carbon emission reductions from voluntary redd+ projects in the brazilian amazon	10.1073/pnas.2004334117	2020	Latin America	Brazil	Forestry	REDD+
60	Schneider, L; Kollmuss, A	Perverse effects of carbon markets on hfc-23 and sf6 abatement projects in russia	10.1038/nclimate2772	2015	Europe	Russia	Chemical processes	Ozone depleting substances
61	Schneider, LR	Perverse incentives under the cdm: an evaluation of hfc-23 destruction projects	10.3763/cpol.2010.0096	2011	Multiple	Multiple	Chemical processes	Ozone depleting substances

Supplementary Note 1: Small sample bias.

We standardised the effect sizes (Cohen's d) to test for the presence of publication bias. The funnel plot in Supplementary Figure 5 shows the individual effect size estimates and their respective standard error. If there was no bias, then the individual effect sizes (or dots in the plot), would be spread symmetrically around the mean estimate (dotted line). Studies that contain precise estimates should be found near the average, whereas studies with lower precision should be spread symmetrically around the average in a funnel. In our case, smaller studies tend to report stronger effects, which suggests a small sample bias. We also conducted the Standard Egger's test, which supports the presence of a small-sample bias ($t = 8.11$, $p<0.001$).

Supplementary Note 2: Divergence in results between offset projects and field interventions

The divergence in findings between offset projects and field interventions could be explained by a few different factors. We can only speculate about the reasons but hypothesise that one fundamental difference might drive the difference in observed outcomes. Field interventions (in contrast to offset projects) are often designed by researchers or non-governmental organisations – especially for RCTs – that want to test the effectiveness of a particular intervention instead of maximising financial gains as for private firms developing offset projects. For instance, Delacotte et al.[38] show that NGOs tend to locate forest protection projects in higher risk areas than private firms that only aim to sell carbon credits. These differences in motivation could in turn affect a range of factors that lead to higher observed offset achievement ratios across projects.

First, careful targeting of ecosystems, regions, or households as subjects for offset interventions is crucial to ensure potential for additional emissions reductions. Some forests may be more at risk to deforestation than others and, therefore, more in need of protection via offset projects. For instance, Wunder et al[13] report that only 9% of REDD+ projects used spatial targeting based on threats to the forest. Likewise, the provision of efficient cookstoves to households with particularly high financial needs, fuelwood consumption, and emissions increases the emissions reduction potential.[7]

Second, adapting to local contexts in project design and implementation is important to ensure that an offset intervention, which has proven effectiveness in other ecosystems, regions, or during laboratory experiments, also works in the project-specific setting. This includes, for example, selecting cookstoves appropriate to local cooking habits and meals; planting trees that fit into the natural ecosystem; or incorporating the economic value of natural ecosystems for local communities. Adapting to local contexts may also entail laying the educational groundwork for later interventions. For instance, Mobarak et al[48] document low interest in the health impacts of improved cookstoves among women, and especially men. If participants do not perceive the benefits of the stoves and do not easily accustom themselves, they may not fully switch to the new stove or proceed in using it.[34]

Third, through continuous monitoring, interaction, and sanctioning for non-compliance divergences from projected project outcomes can be identified and addressed. This includes malfunction of technologies (e.g., broken stoves)[49], external shocks (e.g., wildfires, extreme weather)[37], or lack of compliance with offset protocols (e.g., continued business as usual)[7]. For example, in field interventions for cookstove studies NGOs visited the intervention villages on daily bases to fix broken stoves or adjust cookstove heights to the needs of the cooks. In forestry studies, 63% of field interventions monitored compliance regularly, though only one quarter of projects sectioned participants for non-compliance.[13]

These insights from the literature suggests that there are no one-size-fits-all solutions. While the cornerstones of increasing the offset achievement ratio may be specific targeting, local context adaptation, and continuous, dynamic monitoring, considering these factors in project design and implementation will also make it more difficult to scale these interventions. Hence, there is likely a trade-off between environmental integrity and transaction cost.[3] These trade-offs are likely particularly high for cookstove projects as the targeting of households and monitoring of compliance is more costly and less scalable as in the case of forestry where larger areas can be approximated, and monitoring can be informed via new tools based on satellite images and other technology.

Codebook

Systematic review of the actual emissions reductions and costs of carbon offset projects across all major sectors

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Review Process[3]

We proceeded in the classical three steps of (1) searching, (2) filtering, and (3) coding studies. The first two steps are described in detail in the main article. Here we describe the process for step 3, where we code the studies that have been selected via steps 1 & 2.

Coding studies

From the studies selected via steps 1 & 2, we manually extract effect sizes and additional context information. From 150 studies selected in step 2, 92 were excluded from the coding. We highlight these excluded studies, including the corresponding justification, in the Supplementary Data 1.

The following three reasons justify the exclusion of a study from the coding:

- Document not relevant (study does not focus on quantifying the emissions reductions of offset project or project in related setting)
- No effect size (or cannot be retrieved)
- Study does not contain a credible control group

Information extraction from each study

For each relevant study, we extract various paper features, which can be found in the table below. We extract data of the study on the following levels:

- Document
- Scope
- Intervention timing
- Sample size
- Study design
- Dependent variable
- Effect size
- Other (e.g., permanence, co-benefits)

[3] Our codebook follows the approach outlined in other systematic reviews, such as Khanna et al (2022).

Category	Sub-category	Explanation	Example outcomes
Document	Authors	Authors of the study	Ludwinski D., Moriarty K., Wydick B.
	Title	Main title of the study	"Environmental and health impacts from the introduction of improved wood stoves: evidence from a field experiment in guatemala"
	Abstract	Full abstract of the study manuscript.	"Improved wood-burning stoves offer a possible solution (...)"
	DOI	Digital Object Identifier of the study publication.	10.1007/s10668-011-9282-z
	Publ_year	Year of publication	2011
Scope	Region	Region where the project was implemented. We classify the regions in line with the UN Stat's (2022) definition. We split the 'Americas' into Northern America and Latin America and the Caribbean, mainly for visualization.	Africa Northern America Latin America and the Caribbean Asia Europe (including Russia) Oceania (incl. Australia and New Zealand)
	Country	Country where the project was implemented. In case of multiple countries, use 'multiple'.	Guatemala
	Sector	Sector of the project. We rely on the Berkeley Carbon Trading Project categorization for sector classification (see Figure 1 main article).	Household
	Sub_sector	Sub-sector of the project.	Cookstoves
Intervention timing	Start_year	Start year of the intervention.	2009
	Baseline year	Baseline year of data collection (e.g., baseline measurements) before intervention. If there was no baseline data collection, record 'NA'	2008
	Intervention_month	Intervention period of the project (in months). Multiply the rounded	12
	Post_intervention_month	Time in months between end of intervention and an additional data collection (in months) to study long-term effects or permanence. 'NA' if not applicable.	'NA'
	Total_study_month	Entire study period (including the baseline, intervention, and post-intervention periods).	26
Sample size	Total_sample	Full sample size including control and all treatments. Record number of observations including for pre- and post- treatment set-ups if that	83

		is part of the main specification of the study).	
	Treatment_sample	Sample size used in the empirical model to estimate specific efect. For studies that observe treated units multiple times, capture the total number of observations in each group.	38
	Control_sample	Capture the sample size of control group (this should be the group that does not receive treatment). For studies that observe control units multiple times, capture the total number of observations in each group.	48
Study design	Generic_study_design	Specific the study design. **Experimental study:** Treatment assignment done by researcher (e.g., randomized controlled trials) **Rigorous observational study:** Treatment either through credibly exogenous process or researchers ascertain that treatment and control group have similar observable characteristics, e.g., through matching).	Experimental
	Detailed_study_design	Specify sub-type of experimental or rigorous observational study design. **Experimental studies:** ● Randomised controlled trial **Rigorous observational studies:** ● Instrumental variable ● Difference-in-difference ● Difference-in-difference + matching ● Synthetic Control Method In case the study uses multiple approaches (e.g., diff-and-diff and synthetic control methods), record 'multiple' and document the exact approaches in Notes_study_design).	RCT IV
Effect size	Dependent_variable	Studies utilize various metrics to study changes in CO_2 emissions	Changes in CO_2 emissions

		(or a related environmental metric) related to a certain offset metric	Changes in deforestation rates Changes in forest cover (primary) Change in forest cover (primary and seconday) Changes weekly wood consumption Changes daily wood consumption Changes in wood consumption during last meal
	Statistical_method	Specify the statistical technique of the study design. If multiple are used, report the method used for the corresponding effect.	Logit Probit Difference of means ANOVA OLS regression Time/ Project or both Project Fixed effects Time Fixed effects Project and time fixed effects Random effects
	Page_effect	Page where specific effect is presented in the study.	7
	Coefficient_r	Value of the relevant regression coefficient based on study-specific measurement units. In case multiple statistical estimates are reported, report the statistical estimates of the main models (can be multiple). Some studies report the effect of the intervention group, time (before/after intervention) and an interaction between intervention and time. In that case, capture the interaction term.	0.402
	Coefficient_sd	Record the variance by the standard error of the coefficient. Also extract the specific uncertainty measure employed in the study (standard error, robust standard errors etc), otherwise record 'NA'.	0.0787
	Standardized_effect	Record whether the effect can be standardized. For studies that do not provide a point estimate and standard errors record 'No', otherwise 'Yes'.	Yes
	Cohen's d	Record the transformed effect size.	0.2

	Mean_treament	Record the group means for the treatment group. Record the absolute values.	0.3
	Mean_control	Record the group means for the control group. Record the absolute values	0.4
	Mean_diff	Record (or compute) the difference between the treatment and control group.	0.1
	P-value	In case of mean difference estimates, record the associated p-value of the difference (or any related metric)	5%
	Baseline_emissions	Record the baseline carbon emissions (or related metric) estimated in the baseline for the treatment group. If relevant, record any differences between the treatment and control group baseline emissions in the Notes: Effect size.	3
	Post_intervention_emissions	Record the post-intervention carbon emissions (or related metric). This should be the estimated impact of the offset project on emission compared to the a credible control group (i.e., net impact of the project). For instance, if the project abated 2 tons of CO2, but 1 ton would have happened anyway, then the net project impact is 1 ton.	1
	Percentage_change	Percentage change of carbon emissions (or related metric) after treatment relative to a credible control group. A negative sign signifies a reduction relative to the control group, a positive sign an increase. Please not, that this is the **relative change in percent, not the absolute change in percentage points.** For forestry projects, a value below -100% indicates that deforestation was fully offset and – in addition – new forest cover gained (e.g., -130% means that deforestation 100% reduced and 30% additional forest cover gained (relative to area that was deforested in counterfactual).	-66%

	Percentage_change_w_correction	Calculate the changes in carbon emissions post-intervention relative to the control group. This calculation includes any adjustments or correction factors that need to be undertaken (see below). Please describe the rationale for the correction factor in detail in the Notes: Effect size with references to the exact location in the study.	-33%
	Correction_factor	Some studies adjust their central estimates up- or downward based on discussions in the main text or supplementary information. Record the relevant correction factor and describe all relevant information to be able to understand the rationale in Notes: Effect size.	0.5
	Coefficient_sd_type	Record the type of standard error (e.g., clustered)	Clustered
	Effect_direction	Direction of the effect of the intervention (decrease/increase).	-1
Other	Central_estimate_type	Record whether the study estimate represents a central estimate or lower/upper bounds.	Central estimate Lower bound Upper bound
	Uncertainty_quantification	Record whether the study quantifies uncertainty of its estimations (e.g., via p-value, confidence intervals, or standard errors) or merely provides a point estimate.	'Only point estimate'; 'Point estimate with uncertainty', 'No point estimate'
	Post_intervention_permanence	Binary variable whether study investigates post-intervention permanence in the main outcome variable (e.g., carbon savings) and any other metrics (e.g., co-benefits, leakage) (record key-takeaways in Notes: Permanence The central estimates of studies typically refer to the intervention period. Yet, some studies analyse treatment effects after the intervention period (e.g., after payments have ceased).	'Yes','No'

	Co-benefits	Binary variable whether study investigates benefits from the programme that go beyond the goal of reducing CO2 emissions (or related environmental metric) that are an effect of the project (record key-takeaways in Notes: Co-benefits). These co-benefits should accrue during the implementation of the project and should be explicitly studied (e.g., via a regression investigating effects on poverty) and not just speculative.	'Yes', 'No'
	Co-benefits_asessment	Please record whether the assessment of the study authors of co-benefits is 'positive', 'neutral'[4] (if neither positive nor negative outcomes) 'mixed'[5] (if both positive and negative outcomes were observed) or 'negative'. If no co-benefits assessment, then record 'NA'	'Mixed'
	Leakage_investigated	Binary variable whether study investigates leakage (record key-takeaways in Notes: Leakage)	"Yes"
	Leakage_assessment	Please record whether the assessment of the study authors of leakage is 'negative' (increased emissions from displacement), 'positive' (decreased emissions elsewhere), 'no evidence of leakage' or 'inconclusive'[6]. Record NA if not investigated or if not investigated separately to the main effect.[7]	No evidence of leakage
	Number_control_variables	Record the number of control variables used in the main specification. If not necessary for	4

[4] Example: Jayachandran S., De Laat J., Lambin E.F., Stanton C.Y., Audy R., Thomas N.E. (2017): "We examined expenditures as a proxy for income and did not find strong evidence that it either increased or decreased."

[5] Example: Montoya-Zumaeta J., Rojas E., Wunder S. (2019): "We also find positive effects on incentive-treated households' incomes and assets; however, their self-perceived wellbeing counterintuitively declined. We hypothesise that locally frustrated beneficiary expectations vis-a-vis the ambitiously designed PES-cumICDPintervention help explain this surprising finding."

[6] For instance, Roopsind et al (2019; p.3) report some increases in the border region, however unclear whether due to mineral prices or the REDD+ programme ("We found that tree cover loss along the border region with Guyana and the interior region of Suriname did increase during the Norway–Guyana REDD+ program, but coincided with a 250% increase in the price for an ounce of gold")

[7] For instance, see Jones et al (2016) who state that their main effect captures leakage since estimate based on surrounding areas as controls. In that case, effect of leakage 'hidden' in the main effect.

		calculating standardised effect sizes or not available, use 'NA'.	
	Offsets_issued	Please record whether the projects officially issued offsets. 'Yes', 'No'	Yes
	Additionality_estimate	Record the estimated additionality in %. NA if study did not directly estimate additionality (or could not be computed from the paper).	30%
	Additionality_estimate_type	Record whether the estimated additionality represents a 'lower', 'central' or 'upper estimate. Note that this can diverge from the information in the Central estimate type. [8]	Central
	Number_offset projects_evaluated	Report how many distinct projects were analysed that have issued offsets (only for studies that investigate projects that officially issued offsets)	12
	Offset_registry	For those papers that study projects that issued credits, record the registry where the project has been listed	'Verified Carbon Standard'
	Volume_credits_issued_MT	For those papers that study projects that issued credits, record the total volume of ex-ante estimated credits in megatons (MT)	
Notes	Notes_document	Detail any relevant facts relevant to the sub-section.	
	Notes_scope	Detail any relevant facts relevant to the sub-section.	
	Notes_time	Detail any relevant facts relevant to the sub-section. Detail any relevant facts relevant to the sub-section.	
	Notes_sample_size	Detail any relevant facts relevant to the sub-section.	
	Notes_study_design	Detail any relevant facts relevant to the sub-section.	
	Notes_effect_size	Detail any relevant facts relevant to the sub-section.	
	Notes_other	Detail any relevant facts relevant to the sub-section (apart from notes relating to permanence and co-benefits, which should be recorded in a separate section (see below)).	

[8] For instance, Badgley et al (2022) report the lower, central, and upper bound for their estimate of overcrediting. However, since the project does not look at other sources of non-additionality (such as the impact of the conservation areas vs. similar non-treated areas), the estimates likely are the 'upper bound' as these other sources of non-additionality are not addressed in the paper.

	Notes_permanence	Detail any relevant facts relevant to the sub-section.	
	Notes_co_benefits	Detail any relevant facts relevant to the sub-section.	
	Notes_leakage	Detail any relevant facts relevant to the sub-section	

Project matching and additionalities

Category	Sub-category	Explanation	Example outcomes
Study	ID	Detail any relevant facts relevant to the sub-section.	0
	Author	Authors of the study	Carrilho C.D., Demarchi G., Duchelle A.E., Wunder S., Morsello C.
Project basics	Index	Internal ID of Berkeley Voluntary Offset Registry, v6.	3979
	Project_id	ID used by verifiers	VCS1382
	Project_name	Project name as reported in Berkeley Voluntary Offset Registry, v6.	The Envira Amazonia Project - A Tropical Forest Conservation Project in Acre, Brazil
	Voluntary_registry	Name of voluntary registry	VCS
	Voluntary Status	Status of project. We only use projects for comparison that have been registered	Registered
	Sector	Sector of the project as reported in Berkeley Voluntary Offset Registry, v6.	Forestry & Land Use
	Sub-sector	Sub-sector of the project as reported in Berkeley Voluntary Offset Registry, v6.	REDD+
	Reduction / Removal	Indicates whether project aimed at reducing or removing CO2.	Mixed
	Methodology / Protocol	Methodology/protocol verifier used to register project	VM0007
	Region	Region of the project	South America
	Country	Country of the project	Brazil
	Start_year	Official start year of the project (first year of credit issuance)	2008
	Project_link	URL to the project design document (or other relevant document that reports the ex-ante emissions reductions/removal) by project	https://registry.verra.org/mymodule/ProjectDoc/Project_ViewFile.asp?FileID=45077&IDKEY=uiquwesdfmnk0iei23nnm435oiojnc909dsflk9809adlkmlkfm62161183
Project estimates	Project_emissions	Reported estimated emissions in the project activity (usually in tons CO2e; see Unit for more information). If not reported, record 'NA'	NA
	Expected_reductions	Some project directly report the expected reductions (usually in tons CO2e; see Unit for more information)	15491971
	Baseline_emissions	Reported baseline emissions without the project	17771310

	Percentage_change	Reported expected percentage change in emissions due to the project (relative to baseline)	-87%
	Buffer_pool	Percentage of credits (of total expected emissions reductions) that went into the buffer pool. Please note that some projets report the buffer pool as a % of total expected emissions reductions, while some project report the % change directly. In case the project reports the total number of emissions credits in the buffer pool, divide these by the total estimated emissions reductions.	12%
	Unit	Unit of ported emissions baseline and reductions	tCO2e
	Page	Page in project document where these estimates can be found	
Notes	Study	Notes pertaining to the study section	
	Project_basics	Notes pertaining to the project_basics section	
	Project_estimates	Notes pertaining to the project_estimates	