Review on environmental impacts of forest carbon offset projects and potential assessment methodology on non-carbon ecosystem attributes

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Layman's summary

Climate regulation is one of the ecosystem services that forests could provide. By sequestering carbon, forests become large sinks of greenhouse gases (GHGs) and thus play an important role in combatting global warming. However, deforestation and forest degradation by anthropogenic activities are threatening these natural carbon sinks. Forest carbon offset projects are one way to protect forests by selling carbon credits generated through forest conservation or forest regeneration on the carbon market to GHGs emitters for them to reduce their net emission. This way, the companies can achieve their goals of emission reduction, and the forests are protected and restored. This has been considered as a win-win solution until some evidence suggested otherwise. While in some areas, these projects indeed brought significant positive effects in climate mitigation, in other places the impacts are not as evident. Moreover, doubts have been raised for forest regeneration projects about the use of monoculture, as this measure would harm biodiversity and cause negative effects on water and soil conservation. Since these projects are largely carbon-centric, there is currently no systematically designed assessment methodology in the protocol to evaluation impacts on non-carbon ecosystem attributes. Given the ambiguity of environmental outcomes of these projects and the incomplete and non-holistic impact assessment methodology, the review first summarized studies which provide solid evidence of the *ex-post* environmental impacts of forest carbon offset projects, and then gave another summary of existing indicators and methods used to evaluate forest restoration success as potential choices to be integrated into project assessment protocols. The results showed general overestimation of the projects ability to mitigate climate change and the overlook of non-carbon ecosystem attributes in the *ex-post* assessment of these projects. Although there are many indicators and methods available for impact assessment of forest restoration, sampling process requires a lot of time, labor, and money. Another reason that this process is lagged is the lack of incentive for stakeholders to do so. Thus, more studies should be done in improving the effectiveness in carbon sequestration of forest carbon offset projects and non-carbon environmental impact methodology, as well as in motivating non-carbon ecosystem attributes evaluation.

Abstract

Facing the current climate crisis, forest carbon offset projects have gained attention due to the strong carbon sequestration capacity of forests and have been widely applied globally. The carbon credits generated by these projects can be traded on the carbon market, which allows emitters to reduce their net emission by buying these credits. These projects are also claimed to have co-benefits on other ecosystem services such as biodiversity, water and soil conservation, which are closely related to composition, structure and function of the ecosystem. However, more doubts about the effectiveness of these projects have been raised recently, which requires closer examination of the *ex-post* environmental impacts of these projects. Moreover, there is a lack of impact methodology used to assess non-carbon environmental impacts in the project protocols, making the impact assessment of non-carbon attributes difficult and thus usually overlooked. This article aims to answer two questions through literature review: What are the *ex-post* environmental impacts of forest carbon offset projects? What are the potential impact methodologies that could be integrated into FRR projects under carbon market mechanism to assess non-carbon environmental effects? The results showed an overestimation of carbon sequestration and climate mitigation effect of forest carbon offset projects and the lack of systematically designed assessment studies in non-carbon environmental impacts. Thus, we know very little about the environmental impacts of these projects apart from the carbon aspect. This further proves the current need of developing protocols to assess non-carbon ecosystem attributes. The review of the second question gave an overview of the currently available indicators and methods used to assess forest restoration success as potential options of choice. Although the development of the indicators is relatively mature, traditional sampling methods are time-consuming and expensive, making it difficult to apply to large scale projects and remote sensing technology cannot guarantee the measurement of some important indicators. To conclude, there is an overestimation of climate mitigation effects of forest carbon offset projects and we know little about the non-carbon environmental impacts of these projects. Measures are needed to improve the performance of these projects in climate mitigation and studies are needed in finding more cost-effective sampling methodology for different non-carbon indicators. More attention should also be paid to incentivize the evaluation of non-carbon ecosystem attributes, which is crucial in accelerating the development of relevant protocols.

1 Introduction

Climate change has long been recognized as a global issue that needs to be addressed due to its severe environmental and socioeconomic consequences (Freedman et al., 2009). The newest IPCC report pointed out the already observed impacts of climate change, including changes in climate extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, irreversible damages and losses in ecosystems, reduction of food and water security, adverse effects on human physical and mental health as well as the subsequent adverse impacts on economy (Calvin et al., 2023). There is little doubt that global climate change is a result of anthropogenic greenhouse gas (GHGs) emissions in different domains, including energy use, land-use and land use change, lifestyle and patterns of consumption, and production (Calvin et al., 2023; Freedman et al., 2009; Reyer et al., 2009).

Under such climate crisis, the contribution of forests to climate mitigation has come to the center of public discussion due to their carbon sequestration ability (Buřivalová et al., 2023; Pan et al., 2022). The Kyoto Protocol initiated by the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and ratified by 181 countries and the European Union in 1997 first recognized the contribution of ecological carbon sink in climate mitigation, and permits countries to reduce emissions through the LULUCF activities (land use, land-use change and forestry) (Freedman et al., 2009; Gupta, 2011). There are two roles that forests could play in this context, namely forest carbon stocks conservation by preserving the already existing forests and enhancement of forest carbon sequestration through increase in forests and trees (Bustamante et al., 2014; FAO, 2010). These types of projects could generate carbon credits, which then can be traded to GHGs emitters that are unable to reduce their emissions to the required standards to offset their excessive emissions (Freedman et al., 2009). The first standardized forest carbon offset project was created under Kyoto Protocol's Clean Development Mechanism (CDM) in 2006 (Pan et al., 2022). The offset contracts are offered to investors through compliance and voluntary markets, and 95% of the total carbon market activity happens in the compliance markets, mostly regulated by Kyoto Protocol (Galatowitsch, 2009). Although renewable energy activities are still the main supply of carbon credit on the carbon market, the biosequestration carbon credit sources are becoming increasingly important (World Bank Group, 2023). There are dramatic falls in the costs of renewable energy, making the renewables more economically attractive without extra revenue offered through carbon crediting. On the other hand, credits generated by nature-based activities often provide co-benefits valued by buyers, which provide great incentives for investors (World Bank Group, 2023). In 2022, 54% of newly registered carbon credit projects were forestry and land use activities, suggesting potential expansion of supply in the future (World Bank Group, 2023).

There are three main pathways in forest carbon offset projects, namely avoided deforestation and forest degradation, afforestation/reforestation/forest restoration, and improved forest management (Bustamante et al., 2014; FAO, 2010). The most famous scheme that is contributing to forest-based climate change mitigation actions is REDD+, which was developed from REDD (reducing emissions from deforestation and forest degradation in developing countries), with expanded scope later to also include afforestation, reforestation, sustainable management of forests and enhancement of forest carbon stocks (FAO, 2010; Venter & Koh, 2012). Thus, the carbon market also could generate environmental co-benefits alongside abatement of GHGs emissions by facilitating forest protection and regeneration programs, including the ecosystem services that forests could provide (Bustamante et al., 2014). Deforestation is widely acknowledged to harm biodiversity and contribute to soil erosion, avoiding deforestation can prevent these negative impacts (Bustamante et al., 2014; Visseren-Hamakers et al., 2012). Forest restoration and reforestation can result in the restoration of biodiversity, soil functions, water quality and support regulation of hydrological cycle (Galatowitsch, 2009; Stickler et al., 2009; Townsend et al., 2012; Trabucco et al., 2008). Thus, the forest carbon offset projects could also be transformed into forest restoration and reforestation projects that have more contribution to the environment and people. However, many doubts have also been raised about the actual climate mitigation effects of forest carbon offset projects and whether those anticipated co-benefits would indeed be realized. It is suggested that there is overestimation of carbon sequestration capability (Delacote et al., 2024). Using monoculture or exotic species during reforestation is another concern as it is thought to be the most cost-effective way to maximize carbon sequestration but could lead to a range of negative ecological impacts such as biodiversity loss and even soil moisture depletion (Lindenmayer et al., 2012; Pan et al., 2022).

Furthermore, while the carbon related impact methods have been maturely developed, there is currently no standard impact methodology of non-carbon environmental impacts of these projects, making impact assessment difficult and inconsistent (Bustamante et al., 2014; Galaz et al., 2015; Tedersoo et al., 2024). For example, for the biggest forest carbon offset schemes such as REDD+, Gold standard and CORSIA, biodiversity assessment was not developed, while for Vera and plan vivo it is under the process of development (Tedersoo et al., 2024). Among the forest carbon offset projects, it is especially important for forest restoration and reforestation (FRR) projects to avoid carbon-centered mindset and to build a more comprehensive environmental impact assessment system, since these are not merely protecting the existing forests, but to rebuild complex and functional forest ecosystems. Thus, development of non-carbon environmental impact methodology is of great importance especially for FRR projects under the carbon market mechanism.

Given the ambiguity and controversy of the environmental impacts of forest carbon offset projects and the lack of standard assessment methods for non-carbon effects, this article investigated the following questions by conducting a literature review:

(1) What are the *ex-post* environmental impacts of forest carbon offset projects?
(2) What are the potential impact methodologies that could be integrated into FRR projects under carbon market mechanism to assess non-carbon environmental effects?

The aim of this review is to summarize the *ex-post* environmental impacts of forest carbon offset projects considering both carbon and non-carbon aspects and explore the potential methodologies at hand that could be utilized for the assessment of non-carbon effects for FRR projects under the carbon market mechanism. The environmental impacts specifically include carbon sequestration, biodiversity, and other ecosystem attributes such as water and soil quality. The focused type of forest carbon offset projects in this review are those focusing on forest protection and forest regeneration, including reducing deforestation and forest degradation, afforestation, reforestation and forest restoration, and improved forest management. Although agroforestry also increases forest cover, it was excluded from the review because its purpose is sustainable agriculture instead of forest conservation.

2 Materials and Methods

This literature review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009). Fig. 2.1 shows the flow of the process.

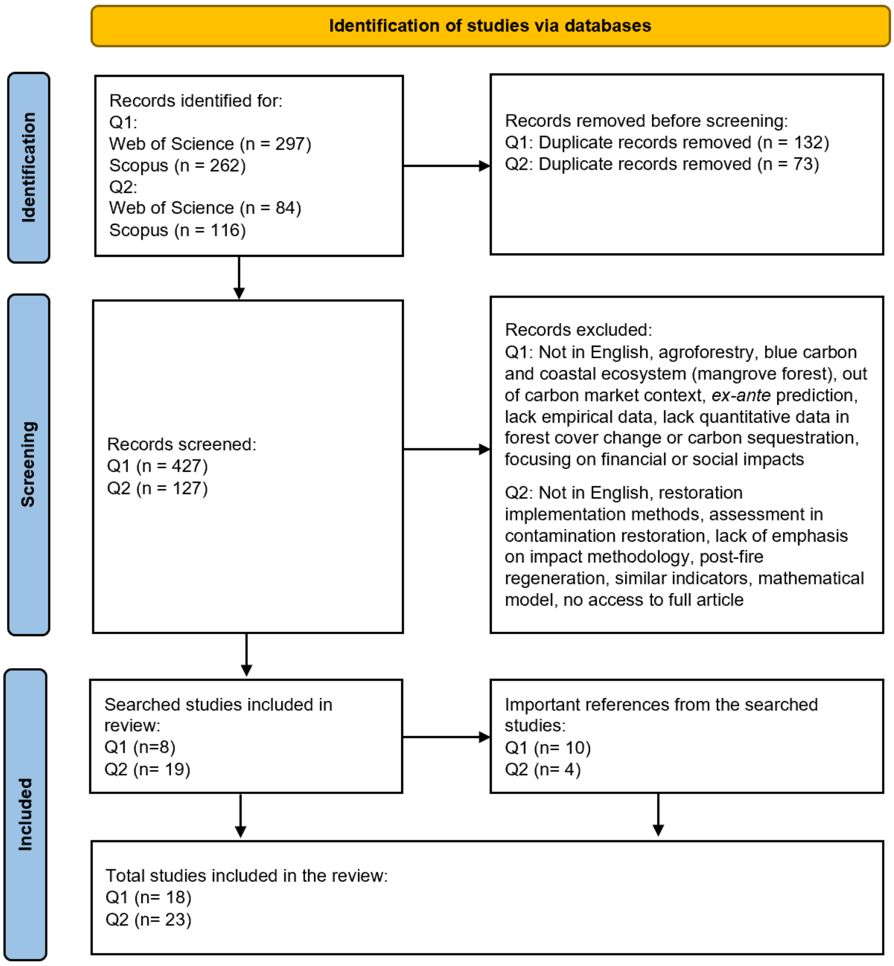

Figure 2.1 PRISMA flow diagram of systematic review and meta-analysis.

Advanced search was done in Web of Science and Scopus using different search strings for different questions. For question (1), the search string in Web of Science is: TS=("carbon credit*" OR "carbon offset*" OR "REDD*" OR "carbon payment*") AND TS=("ecological impact*" OR "environmental impact*" OR "environmental effect*" OR "ecological effect*" OR "biodiversity" OR "water" OR "soil" OR "ecosystem services" OR "climate change mitigation" OR "co-benefit*") AND TS=("forest restoration" OR "reforestation" OR "afforestation" OR "forest conservation" OR "reduced deforestation" OR "forest regeneration"). For Scopus, the search string is: "TITLE-ABS-KEY ("carbon credit*" OR "carbon offset*" OR "REDD*" OR "carbon payment*") AND TITLE-ABS-KEY ("ecological impact*" OR "environmental impact*" OR "environmental effect*" OR "ecological effect*" OR "biodiversity" OR "water" OR "soil" OR "ecosystem services" OR "climate change mitigation" OR "co-benefit*") AND TITLE-ABS-KEY ("forest restoration" OR "reforestation" OR "afforestation" OR "forest conservation" OR "reduced deforestation" OR "forest regeneration"). And for question (2), the search string used in Web of Science is: TI=("forest restoration" OR "reforestation" OR "afforestation") AND TS=("prox*" OR "indicator*" OR "method*") AND TI=("assess*" OR "evaluat*" OR "monitor*"). The search string used in Scopus is: TITLE ("forest restoration" OR "reforestation" OR "afforestation") AND TITLE-ABS-KEY ("prox*" OR "indicator*" OR "method*") AND TITLE ("assess*" OR "evaluat*" OR "monitor*").

I used specific, quoted search terms in the strings, because it helps to narrow down the search scope and generate more related results considering the time constraints for completing this review. And for questions (2), some search terms were confined to the title, this is also to guarantee the high relevance of search result to the question proposed considering the huge amount of literature related to ecological restoration. The time frame for all the search results was set from 2014 to 2024 in consideration of timeliness. Search results for different strings were then dealt with separately, excluding duplications and non-English articles. Then closer examination of the abstract and full article helped to remove articles that are not in the scope of the study questions (Fig. 2.1). For search string of questions (1) for example, articles focusing on agroforestry was excluded because the review does not intend to include these forest carbon offset projects. A snowballing method was also used by extracting relevant references from the searched articles and combine these into the review.

3 Results

3.1 Environmental impacts of forest carbon offset projects

Of the 18 studies included in the review, 13 studies are under the scheme of REDD+, 4 are under the scheme of national offset program, 1 is under the scheme of independent carbon offset program. Considering the amount of studies that focus on REDD+, it is necessary to provide a more detailed overview of global REDD+ implementation. Atmadja et al. (2022) gave a global snapshot of REDD+ projects. There are 377 ongoing REDD+ projects across 56 countries between 2018 and 2020, covering 53 million ha with the total forest cover of these countries being 2.08 billion ha (Fig. 3.1). Countries with highest number of REDD+ projects are Colombia (n=44), Brazil (n=43), China (n=39), India (n=25), Kenya (n=22), Indonesia (n=21) and Peru (n=21). Most of the areas (95%) are under avoided deforestation and degradation and forest conservation (AD) projects, while afforestation/reforestation/ revegetation (AR) projects prevail in number (AR: n=198, AD: n=144). Improved forest management (IFM) only occupies a small part of REDD+ projects. Moreover, most areas that are certified under voluntary carbon market standards are in AD projects (92%).

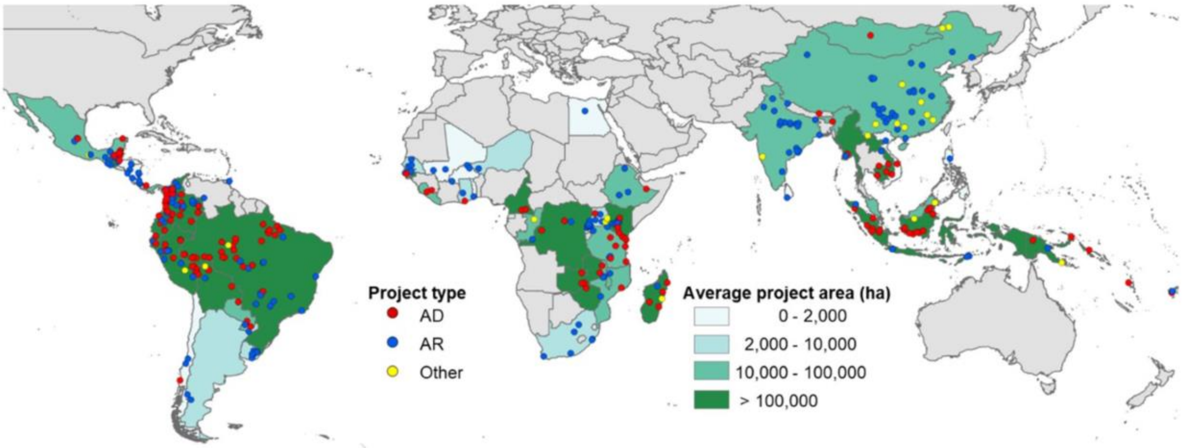

Figure 3.1 Geographic distribution of REDD+ project types: avoided deforestation and degradation and forest conservation (AD), afforestation/reforestation/revegetation (AR) and other goals (other). Dots are approximate location of 377 projects (Atmadja et al., 2022).

For the environmental impacts, 15 studies focus on forest cover change or carbon sequestration, which can be categorized as climate mitigation. The rest of the studies focus on biodiversity (n=2) or other ecosystem services (n=1). The study scale can be categorized as global (n=4, all REDD+), regional (n=11) and local (n=2), while one study is a review of local study cases (Simonet et al., 2018).

3.1.1 Climate mitigation effects

Of the 13 REDD+ studies, 11 focus on the climate mitigation effects of the projects. The findings of different studies differ. The two global studies both found mixed effect of REDD+ projects in reducing deforestation rate. The global study of REDD+ projects in the moist tropics discovered a mean relative reduction of 47% in deforestation rate and a mean relative reduction of 58% in forest degradation rate in the first 5 years of the implementation (Fig. 3.2 (b, d), Guizar-Coutiño et al., 2022). And there is no significant change of the effect through time as seen in the 8 years and 10 years projects developments. However, the absolute reduction in deforestation and forest degradation rate is small and in majority of the studied sites the effect size is close to zero (Fig. 3.2 (a, c), Guizar-Coutiño et al., 2022). In a small amount of study sites, the deforestation and forest degradation even increased. The global study which included 49 REDD+ projects in Colombia, Indonesia and Peru between 2004 to 2018 came to the conclusion that most of the AD and AR projects resulted in lower or equal deforestation trends (Fig. 3.3, Atmadja et al., 2022). A small part has a greater increase (or smaller decrease) in deforestation rates compared to the subnational or national levels. AR projects generally have better effect in reducing deforestation compared to AD projects. The relatively large proportion of projects with neutral impact on deforestation rate is a reflection of poor assessment of projects' additionality (Atmadja et al., 2022). A project is additional only if it can be demonstrated that carbon emission reductions are higher than they would have been in the absence of the project (Richards & Huebner, 2012). The authors also pointed out the limitation of REDD+ in the sense that the current scale is too small to fulfill the potential contribution of tropical and subtropical forests to prevent global warming which was also mentioned by Guizar-Coutiño et al. (2022). It will require an upscale of >40× to limit global temperature rising to <2°C (Atmadja et al., 2022).

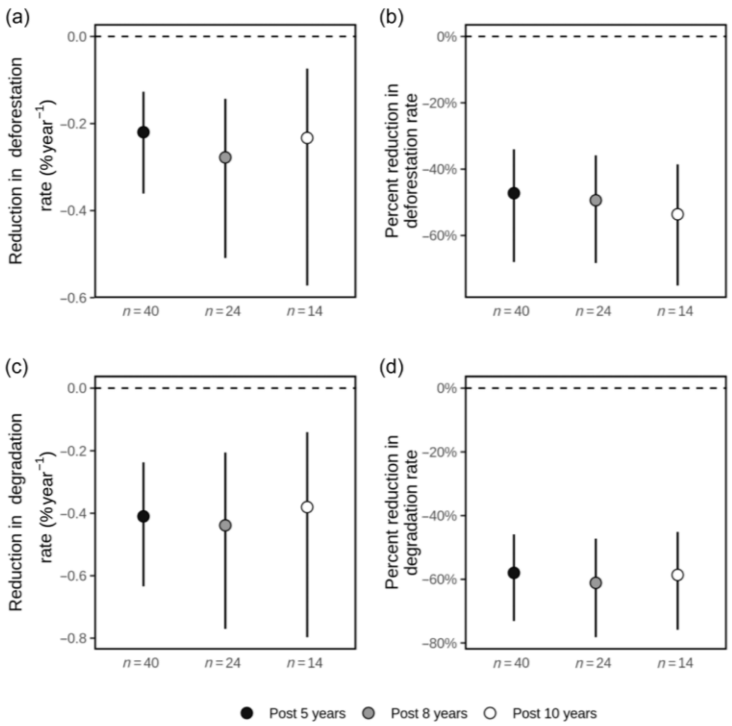

Figure 3.2 In 40 REDD+ projects for 3 postimplementation periods (a, c) reductions in annual deforestation and degradation rates and (b, d) percent reductions in deforestation and degradation rates (means and 95% confidence intervals) (Guizar-Coutiño et al., 2022).

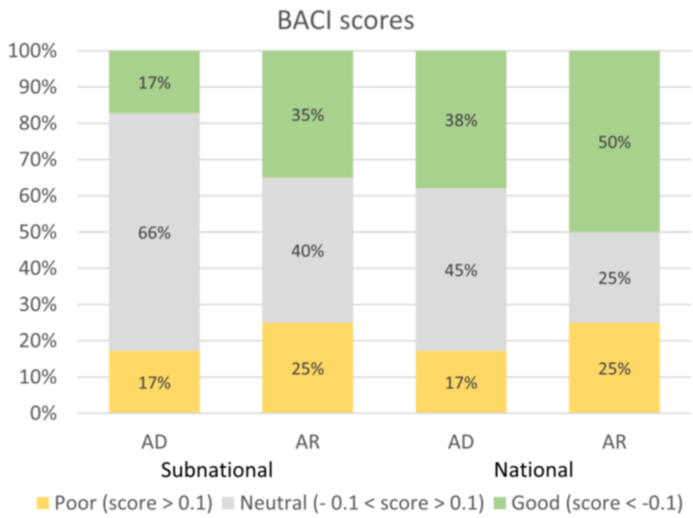

Figure 3.3 Percentage of AD and AR projects with negative, neutral or positive BACI score relative to subnational and national level comparison sites. BACI is before-after-control-intervention approach, the score was calculated using the forest cover loss in the intervention area before and after the project start year (I_{A-B}) to subtract the equivalent forest loss trend in a subnational or national 'comparison area' (C_{A-B}) (Atmadja et al., 2022).

Just as reflected in the global studies, a review which included multiple local studies of the impacts of REDD+ also found their mild positive or no significant impact in climate mitigation

(Simonet et al., 2018). The single case studies found in this systematic search also confirms the variation in the outcome of REDD+ projects worldwide, with 2 studies showing some positive effect in reducing deforestation rate or GHG emission (Roopsind et al., 2019; Simonet et al., 2019), and 3 studies showing no significant effect (Correa et al., 2020; Ellis et al., 2020; West et al., 2023). Carrilho et al. (2022) found positive effect of the REDD+ project on reducing deforestation in Pará, Brazil, while in a long term the effect is insignificant. Two other studies found that while there is indeed mitigation in deforestation rate or GHGs emissions with the REDD+ projects, the actual impact was smaller than that is projected in the plan, resulting in overestimation of carbon reduction (Kiswanto et al., 2018; West et al., 2020). Non-REDD+ forest carbon offset projects also show similar results. One NGO initiated carbon forest project in Uganda failed to achieve its carbon reduction goal due to compromise in carbon offsets verification and the conflict between the local community and other stakeholders made the project to stop in the end (Cavanagh & Benjaminsen, 2014). Two studies about the California's forest carbon offsets program showed the lack of additionality in carbon offsets (Coffield et al., 2022) and the overestimation of carbon sequestration capacity (Badgley et al., 2022). One study in the human-induced regeneration projects under the Australia's carbon offset scheme revealed insignificant change in woody vegetation regeneration in credited areas (Macintosh et al., 2024).

3.1.2 Biodiversity and other environmental impacts

There are only 3 studies focusing on non-carbon impact of forest carbon offset projects and 2 of them are under the scheme of REDD+. The only study regarding biodiversity examined 80 existing REDD+ projects on how they address biodiversity issues, what are the biodiversity benefits they aim to provide, their plans to monitor biodiversity and the final impacts of biodiversity they deliver (Panfil & Harvey, 2016). For afforestation/reforestation projects, the most common goal is to restore natural forest, thereby enhancing biodiversity conservation. And for reduced emissions (i.e. reduced deforestation and forest degradation) projects, all of them had preventing habitat loss as a means of biodiversity conservation (Fig. 3.4). However, there is a lack in quantitative targets for biodiversity objectives in all projects, and the monitoring description all lack details in sampling design and methodology (Panfil & Harvey, 2016). Among the 80 projects, only 15 had reported the *ex-post* impact of their activities on biodiversity by mentioning the number of native trees planted or the area covered. However, none of them have solid data to support their claim of enhancement of biodiversity, no matter in plant composition or faunal community (Panfil & Harvey, 2016). Moreover, only 48% of the afforestation/reforestation projects used native species exclusively (Panfil & Harvey, 2016). The other study which is about REDD+ provides comparison between REDD targeted countries and non-REDD targeted countries in the economic values of non-carbon ecosystem services (Ojea et al., 2016). The results showed that REDD targeted countries carry higher values for ecosystem services including air quality and water regulation, food and fiber, wild species diversity, recreation and various services (such as watershed protection, existence value etc.) (Ojea et al., 2016).

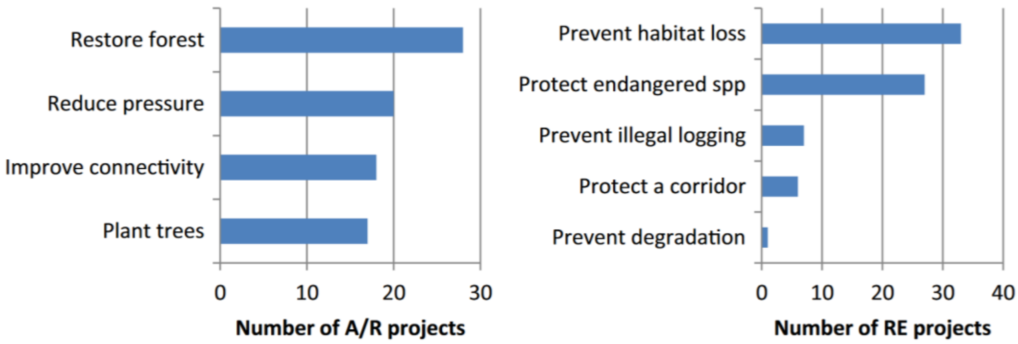

Figure 3.4 Biodiversity goals of afforestation/reforestation (A/R) projects and reduced emissions (RE) projects (Panfil & Harvey, 2016).

The only study regarding ecosystem services outside the REDD+ context is under the scheme of California's forest offset program (Anderson et al., 2017). Although the paper also investigated the carbon additionality of the program, it lacks quantitative analysis in forest cover change and thus this part was excluded from chapter 3.1.1. The results of non-carbon benefits in this study were also only confined to voluntary reporting, with 79% reporting benefits on water quality, 67% on recreation and 87% on wildlife (Anderson et al., 2017).

3.2 Potential impact methodologies for non-carbon impacts assessment

A noticeable fact in chapter 3.1 is that the environmental impacts of interest in forest carbon offset projects are forest cover and carbon sequestration ability (above ground biomass). There is an obvious focus on carbon storage assessment while other ecosystem attributes are neglected. This is consistent as expected since climate mitigation is the main goal of these projects. In this part of the review I will address the second research question, trying to extract more methods to evaluate other ecosystem attributes from FRR and afforestation projects which are not based on carbon market mechanisms as potential options to integrate into assessment protocols in FRR carbon offset projects.

Of the 23 included articles, 5 are review papers and 18 papers describe case studies. Two reviews and 10 case studies provide a summary and examples of common indicators used to assess forest restoration success. One review and 6 case studies discussed the design of traditional sampling strategy, and 2 reviews and 2 case studies focus on the application of remote sensing in monitoring and assessing forest restoration success. This chapter first summarizes the common indicators involved, then elaborate on the sampling methods and the application of remote sensing in impact assessment.

3.2.1 Common indicators to assess forest restoration success

Gatica-Saavedra et al. (2017) made a comprehensive review of ecological indicators used for assessing forest restoration success. According to the multi-facet needs of forest restoration, the composition, structure, and function are aspects of the restored ecosystem that need to be assessed. Composition refers to the elements inside one system and it includes species diversity and abundance (Noss, 1990). Diversity indicators include richness, similarity, evenness, and dominance (Gatica-Saavedra et al., 2017). Structure is the pattern or physical organization of a system and is related to the suitability of the habitat (Franklin et al., 1981). Function represents the ecological and evolutionary processes and is related to the resilience of the restored ecosystem (Franklin et al., 1981).

For vegetation composition, richness, abundance and density of plant species are the most frequently measured indicators, while for structure, coverage by vegetation life forms, height and diameter of trees and canopy cover are the most frequently measured indicators (Gatica-Saavedra et al., 2017). If the aim is to evaluate vegetation development of the restoration project, some of both composition and structure indicators are commonly used to make a more holistic assessment. For example, Manrique-Hernández et al. (2016) recorded presence/absence of non-tree species and number of individuals of each tree species in sampling plots. The diameter at 1.3m from ground (DBH) was also measured for trees with DBH > 2.5cm. Calculated vegetation structural variables include importance values, basal area, tree density and species abundance at each plot (Manrique-Hernández et al., 2016). Similarly, Freitas et al. (2019) assessed species richness, density of individuals per size class, basal area, canopy height, aboveground biomass, and canopy cover in evaluation of tropical forest restoration using direct seeding (the sowing of seeds directly into soil). In a novel protocol developed for evaluating large-scale forest restoration projects in the tropics, common indicators such as density of trees, species richness, evenness, height and canopy cover are all included (Ribeiro de Moura et al., 2022). They used plots with the area of 100 m^2 (25×4m) with a maximum of 50 plots per project considering the area of intervention (Ribeiro de Moura et al., 2022).

There is also evidence that these simple indicators are related to more complex parameters. A study dedicated to the Atlantic Forest restoration discovered the canopy cover with native vegetation, density and richness of native plants spontaneously regenerating are associated with richness of zoochorous regenerant species, density of non-pioneer regenerants and dominance, which are considered as more qualified ecological parameters corresponding to function of seed dispersal, composition and structure (Massi et al., 2022).

As for animal composition indicators, the most used ones are richness, and absolute or relative abundance of animal species (Gatica-Saavedra et al., 2017). They are usually bioindicators which are sensitive to environmental change (Gatica-Saavedra et al., 2017). The common examples are birds and arthropods (e.g. ants, dung beetles) (Gatica-Saavedra et al., 2017; Nickele et al., 2023; Ramírez-Soto et al., 2018). Presence/absence of endangered species and traces of fauna recovery are also used as an indicator in animal composition (Ribeiro et al., 2019).

Soil parameters are the most frequently measured functional indicators. The most commonly used are pH, bulk density, soil moisture, nutrient content, and biomass of litter (Gatica-Saavedra et al., 2017). Lozano-Baez et al. (2021) found similar results in a review in soil indicators used in forest restoration evaluation in Colombia. They found that the most used chemical soil indicators are sodium and phosphorus concentrations, closely followed by nitrogen and pH. Soil bulk density and soil texture are the most used physical soil indicators. Soil organic carbon is another indicator that receives attention due to its role in climate mitigation (Rasiah & Florentine, 2018; Tran et al., 2015). Moreover, bioindicators not only can act as composition indicators but also as function indicators since they are linked to ecological processes such as seed dispersal, decomposition and nutrient cycling (Gatica-Saavedra et al., 2017). Soil microbes is also gradually becoming an important bioindicator with recent studies unravelling their interactions with ecosystem multifunctionality (Cao et al., 2021).

3.2.2 Sampling design of indicator measurement

Extensive efforts have been made to investigate available indicators to measure the success of forest restoration, and people can choose corresponding indicators according to restoration goals and forest type. However, another matter that also requires attention is the sampling design and measurement methodology. It is still a question in discussion as to what size of grain or plot should be chosen to measure the vegetation indicators. It is difficult to determine the most appropriate plot size as there is no unanimous optimal scale for all studies and plant communities (Chiarucci et al., 2001; Maccherini et al., 2019). Nevertheless, current studies with different forest types have drawn some conclusions. For restored coniferous forest, it has been proved that the scale of observation (grain size) can influence the assessment of the species richness or community heterogeneity (Dodson & Peterson, 2010; Metlen & Fiedler, 2006). Significant increase in native species richness was not found in $1m^2$ plots, but was found in $1000m^2$ plots (Metlen & Fiedler, 2006). It is necessary to sample in multiple spatial scales to fully describe the vegetation of the restoration site (Metlen & Fiedler, 2006).

Studies in typically species-rich tropical forests also found similar phenomena, that small plots often provides incomplete and biased information about species with low relative abundance in the local community (Chazdon et al., 1998, 2022). Chazdon et al. (2022) assessed tree species diversity during the natural regeneration over 12-20 years using eight 1 ha plots and subplots in Costa Rica in both second growth forests and old-growth reference forests. They found that annual surveys in the 1-ha plots miss substantial amount of rare or infrequent species. But subsamples of 0.5 ha or greater were sufficient to give inference of the diversity of more abundant species. It is suggested therefore that for restoration projects in tropical forests that aim to restore native biodiversity, the sample plots should be at least 0.5 ha. But this suggested area is also only suitable for plant diversity regarding abundant and common species because the rare species are more sensitive to area change, and thus more rare species are still expected to be found in larger sampling area (Chazdon et al., 2022). Londe et al. (2022) studied the optimal sampling area using the large-scale vegetation monitoring information in Brazilian Amazon and concluded with the optimal sampling area for 11 indicators in different types of tropical forests with the sample number dependent to area of intervention (Table 3.1). For example for projects larger than 1 ha, five plots (for 1 ha) plus one for each additional hectare were chosen (Londe et al., 2022). Viani et al. (2018) investigated the effect of sampling intensity on the reliability of indicator measurements by using resampling techniques and the calculation of sampling error (<20%). They assessed canopy cover, tree density, vegetation height, and species richness in 18.2 ha plots ranging from 60 to $300m^2$ in size. The results show that a lower sampling intensity could be used for monitoring canopy cover and vegetation height, while tree density requires more plots. As for species richness, it does not stabilize even when 90% of the total number of plots were resampled, and that a reduction in sampling area or units would lead to decrease in the species number. In this case, using plots might not be an optimal method, as it would require high cost of money and time. An alternative approach is to use random walks through the site to count different species and record the new species identified in a given period (transect sampling). When no new species can be identified in this given period, sampling effort is achieved (Viani et al., 2018).

Table 3.1 The optimal sampling area as the percentage of the area of the restoration site (% ± SE) estimated for 11 ecological indicators and three forest types in the Brazilian Atlantic Forest (Londe et al., 2022).

Ecological indicator	Forest type		
	Semidecidual seasonal forest	Dense rainforest	Mixed rainforest
Grass cover	0.07 ± 0.02	0.05 ± 0.02	0.23 ± 0.04
Canopy cover	2.24 ± 0.55	2.32 ± 0.34	3.58 ± 0.42
Canopy height	4.00 ± 1.66	3.59 ± 0.71	1.57 ± 0.15
Basal area	6.08 ± 1.59	NA	1.5 ± 0.14
Tree density	2.86 ± 0.63	1.49 ± 0.14	1.44 ± 0.14
Tree species richness	2.71 ± 0.38	1.54 ± 0.14	1.41 ± 0.10
Regional tree species	4.28 ± 1.85	2.64 ± 0.68	4.00 ± 0.48
Zoochoric tree species	4.00 ± 0.68	4.00 ± 0.58	1.36 ± 0.20
Non-pioneer tree species	4.00 ± 0.53	4.00 ± 0.46	1.46 ± 0.18
Density of regenerating species	2.23 ± 1.02	2.40 ± 0.56	2.40 ± 0.64
Regenerating species richness	4.00 ± 0.72	2.47 ± 0.33	2.44 ± 0.45

NA = No breakpoint was estimated.

However, as mentioned above, different forest types could generate different results concerning the influence of plot size on data reliability, as a study in European beech forest restoration discovered that the plot size is of minor influence on the species abundance data (Maccherini et al., 2019). This is possibly related to the lower species diversity in these ecosystems compared to tropical forests. They also concluded that presence/absence data failed to identify the changes in plant species composition, and that abundance is a better indicator to do so. Moreover, although wildlife monitoring is less concerned in forest restoration, the same problem of sampling design also applies (Block et al., 2001). For example, long and narrow plot allows more precise estimates, but square plot could avoid edge effect. The size of the plots is also dependent on the home range of different species.

3.2.3 Application of remote sensing

Traditional sampling methods can be laborious and time consuming, especially with large-scale restoration sites. Due to these limitations, monitoring and evaluation of many forest restoration projects are still limited to the area restored and the number of trees planted (Almeida et al., 2019). Thus, a cost-efficient method that could monitor restoration outcomes in large spatial scales and provide more detailed information about forest composition and structure is needed (Brancalion & Chazdon, 2017; Holl & Aide, 2011). Remote sensing approaches can meet these requirements and their application in forest restoration monitoring is also getting more and more attention. Depending on the platform and sensor type, remote sensing technology can provide data within different spatial and temporal scales (Camarretta et al., 2020). The principle of this application is the statistical and physical relationships between electromagnetic scattering of vegetation elements and attributes of interest, such as species richness, biomass, basal area, and tree height. But the detection of tree species requires training and validation of machine learning algorithms, which is laborious, and there are only a few species that can be detected (Camarretta et al., 2020). There are passive and active sensors, and different sensors can be mounted on spaceborne, airborne, and ground-based platforms and thus fulfill different requirements for data scale.

Spaceborne platforms are suitable for large scale monitoring such as regional or continental, while airborne platforms are suitable for local level (Camarretta et al., 2020). Airborne platforms include airplanes, helicopters, and Unmanned Aerial Vehicles (UAVs, a.k.a. drones). The costs are high for helicopter and airplanes and the surveying depends on companies that own airplanes, while UAVs are relatively low-cost, agile and autonomous (Almeida et al., 2019). Thus, UAVs and a wide range of sensors capable of generating high-resolution images have promoted the development of new approaches in remote sensing and aerial photogrammetry (Sinegalia et al., 2024). For example, Almeida et al. (2019) used a UAV-lidar system to assess the canopy height, gap fraction, leaf area index, and leaf area density in a mixed-species restoration plantation. Williams et al. (2022) developed a novel pipeline for processing UAVs imagery to map early successional species in tropical forests. A review showed that there are applications of UAVs system in measuring indicators in all three ecological attributes (composition, structure and function), with structure indicators (canopy cover, spatial distribution) being the most frequently measured and thus most developed (Table 3.2, Sinegalia et al., 2024). But it is noticeable that species richness and diversity as two of the most important composition indicators are understudied, which probably shows the unsuitability of using remote sensing to measure diversity indicators.

Table 3.2 Absolute frequencies of the considered indicators in studies in application of UAVs in monitoring forest restoration (Sinegalia et al., 2024).

Indicator	*FA*
Phenology	6
Vital status	3
Tree individual height	1
Canopy height	27
Canopy crown	9
Tree canopy volume	1
Canopy cover	10
Leaf area index	5
Understory	1
Diameter at breast height	7
Spatial distribution	17
Species classification	5
Species richness	1
Species diversity	4
Biodiversity	10
Biomass	8

4 Discussion

4.1 Lack in environmental impact assessment of forest carbon offset projects

During the literature selection process, it was noticed that there is lack of literature focusing on environmental impact of forest carbon offset projects. In the general search conducted in the early stage using very broad keywords (e.g. impact, effect) without specifically pointing towards environmental impacts, there are obviously more articles focusing on socio-economic impacts, such as well-being, income, participation, land tenure, etc. Another review also found that there are more socio-economic than environmental studies in REDD+ outcomes (Duchelle et al., 2018). They found 26 studies regarding social impacts but only 12 studies in carbon/land impacts (Duchelle et al., 2018). This phenomenon reflects ample studies in social safeguards of forest carbon offset projects, but a lack of attention in environmental outcomes (Duchelle et al., 2018). This focus on social impacts might come from the early concerns that forest offset projects would pose a risk to local rights and welfare (Duchelle et al., 2018).

In the more specified search later using keywords related to environmental impacts, it was found that there are plenty of studies focusing on estimating the *ex-ante* impacts or potential benefits of forest carbon projects, which forms a contrast with the small amount of literature that aim to assess the *ex-post* environmental impacts which include counterfactuals. This might indicate the lack of attention in the verification of anticipated environmental impacts. Another possible reason is the difficulties in conducting *ex-post* environmental impact assessments due to the absence of standard monitoring methodology (Asen et al., 2012). Only in the past few years the environmental integrity and credibility of carbon credits start to come under the spotlight (Delacote et al., 2024). However, the main focusing aspect is still on the carbon sequestration and climate mitigation attributes in these projects, with little attention on non-carbon ecosystem attributes such as biodiversity, forest structure and function, which are key attributes in forest restoration projects targeting in rebuilding healthy forest ecosystems. Even with the few articles found including other ecosystem attributes, the assessments lack quantitative methods and systematic design of sampling (Anderson et al., 2017; Panfil & Harvey, 2016). The only article assessing the economic value of non-carbon ecosystem services also took a national scale, with little contribution in understanding the local impacts on ecosystem services (Ojea et al., 2016). The spatial scale being too big is also a problem for environmental impact assessment for these projects in general, with only 2 studies found conducted locally.

Nevertheless, it is still possible that grey literature or existing datasets that are not published would include assessment of environmental impact of these individual projects. An article which investigated the biodiversity data availability in REDD+ projects in Peru found that most of the sub-national actors who are frequently involved in REDD+ pilot projects confirmed the availability of biodiversity data (Entenmann et al., 2014). This includes data for mammals and birds, mostly for flagship species, as well as forest cover (Entenmann et al., 2014). But it was also found that there is a general lack of concern in biodiversity in national level actors as they do not view it as a pressing topic in the REDD+ projects (Entenmann et al., 2014). This lack of attention from higher management group possibly hinders the standardization of monitoring methodology of non-carbon attributes and thus the publication of these studies as it requires high quality and comparable data.

4.2 Overestimation of climate mitigation effects

According to the evidence found in current studies, there are both positive and negative outcomes of the *ex-post* climate mitigation effects of forest carbon offset projects, but more literature (12 out of 15) suggest that these projects did not meet the expected effect in climate mitigation. The lack of additionality in carbon credits is a serious matter as they allow permission to carbon emissions. The failure of generating high integrity credits can even worsen climate outcomes because this would eventually increase net total emission (Macintosh et al., 2024).

One of the reasons that anticipation is not consistent as the actual result is the error in defining baseline (or counterfactual) situations. It was found that the crediting baselines could overstate deforestation compared to the counterfactual estimate based on synthetic controls (West et al., 2020, 2023). Such overestimation of deforestation without the presence of the project is due to changes in background deforestation rate with time, which might be caused by national control of deforestation or other policy changes in protecting forests. When the background deforestation rate changes, the historical baselines would not be applicable anymore to reflect changes in emissions caused only by the offset projects (West et al., 2020). One suggestion is to achieve a standardization of baselines in national or subnational level, by using jurisdictional baselines that are predefined and regularly updated by the government, as well as default carbon stock values or a common carbon density map (West et al., 2020). It is important that the baseline is updated periodically because historical data cannot capture contemporaneous deforestation drivers and their dynamism (Coffield et al., 2022; West et al., 2020). Apart from baseline error, other errors in carbon accounting could also cause deviated estimation of carbon offset capacity, such as sampling error, model error and inaccurate land-use classification based on remote sensing (Yanai et al., 2020). For example, Badgley et al. (2022) identified systematic calculation error in California's forest carbon offsets protocol and showed how averaging disparate tree species across arbitrarily defined regions allowed the generation of non-additional carbon credit. Thus, accounting for uncertainties and errors in the assessment approaches are of utmost importance.

The need to establish a standardized impact assessment methodology was also emphasized, as different assessment methods make results not comparable and might come with opposite conclusions (Guizar-Coutiño et al., 2022). Thus, further research of the pros and cons of different methods are required to realize this need. However, it can be expected that the standardization of methods is extremely difficult to implement as this is not only a technical issue but also related to market needs. The fact that there is no absolute scientifically correct accounting method provides various choices for professional verification and certification organizations (Gifford, 2020). Project developers often choose an accounting protocol that addresses the most desired outcome, rather than changing a project to meet the protocol guidelines (Gifford, 2020).

Apart from methodological flaws and problems, implementation factors also affect the *ex-post* impact greatly. The location choice of the project is important, as unstable social and political environment, low capacity in improving carbon storage due to natural conditions, historically low deforestation rate in the area are all reasons that the project can not meet expectations in climate mitigation (Cavanagh & Benjaminsen, 2014; Correa et al., 2020; Macintosh et al., 2024). Thus, selecting politically and socially stable area with high potential in carbon sequestration enhancement can improve the effectiveness of the project in climate mitigation.

Given the fact that the performance of forest carbon offset projects is not as well as expected, more research should be done regarding the reliability of different carbon accounting protocols. Although the standardization of the methodology is unlikely to be achieved in a global scale, it is still possible to make it in a sub national or national scale. Caution needs to be taken in early assessment before the project is launched regarding the suitability of the location, and possible risks should be identified. During the implementation stage, close monitoring is needed to keep track of the progress. When the project needs to end, efforts should be made to prevent future forest loss in the same area, and government jurisdictional intervention might be necessary (Ellis et al., 2020).

4.3 Developing protocols for non-carbon environmental impacts

The results confirmed lack in non-carbon attributes assessment in these carbon-centered projects. Although concerns have been raised about the possible harm for biodiversity, water, and soil conservation when monoculture is established, there are few systematically designed studies to investigate such speculation. These concerns are mainly about FRR projects as these projects are also expected to rebuild the original ecosystem with healthy structure and function, and the focus on carbon has a great risk to make the outcome fall short in front of these expectations. Thus, there is great need in developing protocols for non-carbon environmental impacts in these projects. It is desired that indicators of composition, structure and function should all be included. From a purely technical perspective, the monitoring and evaluation methodology of forest composition, structure and function have been relatively maturely developed and discussed as shown in the literature review, no matter with traditional sampling methods or advanced technologies such as remote sensing. For composition indicators, traditional sampling is still the most advantageous as it is still very difficult to use remote sensing to measure diversity. Species richness can be measured using transect sampling, but when plot sampling is applied, caution needs to be taken in choosing sampling area especially with species rich forest type such as tropical forests. It is important to refer to the existing studies in different forest types for the concluded suggested sampling area. However, traditional sampling still has the problem of time-consuming and expensive. Fortunately, forest structure indicators are expected to be more cost-efficiently measured in the future with the development of remote sensing with UAVs in large areas. Functional traits can be investigated by using bioindicators such as birds, as they are probably the easiest and inexpensive taxa to study due to their high sensitivity to disturbance and the fact that they are well known (Ramírez-Soto et al., 2018). Soil parameters can also be used, but physical parameters and some chemical parameters that can be tested in the field would be the best choices as the access to laboratory is very much limited. Furthermore, the choice of indicators also depends on the needs and goals of restoration. For example, in habitats of endangered or keystone wildlife species, monitoring of the targeted species is important and should be considered (Hyde et al., 2022).

Participatory monitoring is a potential way to improve the efficiency of impact assessment. It can be a cost-effective way as it can lead to lower labor and transportation costs relative to professionally trained monitors (Evans et al., 2018). For example, community-based identification of trees in monitoring based on traditional sampling with plots can be done with quality and at around one-third of the cost in comparison to trained botanists (Zhao et al., 2016). The methods used should be easy, participatory, verifiable, and relatively accurate. Imagery monitoring using photos or remote sensing is also proved to be a practical and inexpensive way for different stakeholders to participate and can be discussed and analyzed collaboratively (Dickinson et al., 2016; Evans et al., 2018). Moreover, stakeholder involvement can facilitate long-term monitoring and increase personal interest and commitment in the project (Evans et al., 2018).

Despite the studies and suggestions in integrating non-carbon attributes into impact assessment, there are still rare implementation cases. The main obstacle in integrating this into the project protocol is the lack of motivation. There is no mandatory requirement to measure other ecosystem traits to generate carbon credits, and there is no reward either in doing so. In order to change this carbon-centered idea, recent studies suggest the development of wider restoration benefit markets, especially with biodiversity (Löfqvist et al., 2023; Morrell et al., 2023; Tedersoo et al., 2024). Incorporating biodiversity explicitly into carbon crediting schemes could incentivize actions that promote biodiversity alongside carbon sequestration, and help expand private-funding in restoration (Löfqvist et al., 2023; Tedersoo et al., 2024).

5 Conclusion

This review investigated the environmental impacts of forest carbon offset projects and gave a summary of the existing indicators and methods in assessing forest restoration success. Forest carbon offset projects have been doubted in their ability to truly curb deforestation and generate carbon credits with integrity. Criticisms also occur in regard of possible adverse impact on other attributes of ecosystem due to their carbon centric goals. Through literature search, it was found that there are few cases where forest carbon offset projects significantly decreased deforestation or increased forest cover. In most cases, they have rather minimal positive effect in forest protection and sometimes zero or even negative. As for the non-carbon environmental impacts, we still know very little about them. Most of the studies related to non-carbon impacts focus on socio-economic impacts while there are rare cases of studies on ecosystem composition, structure and function. This reflects the severe lack of attention in other ecosystem attributes under the implementation of the projects. In order to give some insight in developing protocols to assess these attributes, a review of the indicators and methods used in general forest restoration projects was done. It was shown that although there are many indicators that can be used to measure ecosystem composition, structure, and function, it is not easy to measure them as this usually is expensive and time-consuming. Currently, the biggest problems in integrating non-carbon attributes into impact assessment is probably the lack of cost-efficient ways to measure required indicators and the motivation in developing such protocols. Studies have suggested ways such as UAVs combined remote sensing and participatory monitoring to lower the cost and incorporating biodiversity into carbon credit schemes could potentially incentivize the development of such protocols.

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