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REVIEW ARTICLE

Key challenges and approaches to addressing barriers in forest carbon offset projects

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Abstract Forest carbon offset (FCO) projects play an increasingly important role in mitigating climate change through market mechanisms in both compliance and voluntary markets. However, there are challenges and barriers to developing an FCO project, such as carbon leakage and cost-effectiveness. There have been few attempts to summarize and synthesize all types and aspects of existing challenges and possible solutions for FCO projects. This paper systematically reviews and discusses the current challenges involved in developing FCO projects, and then draws on the experience and lessons of existing projects to show how those challenges were addressed in world-leading voluntary carbon standards, namely the Verified Carbon Standard, the American Carbon Registry, the Climate Action Reserve, and Plan Vivo. These voluntary markets have rich experience in FCO projects and are responsible for a significant share of the market. From the 53 publications used in this analysis, three broad thematic categories of challenges emerged. These were related to methodology, socio-economic implications, and implementation. Methodological challenges, particularly additionality, permanence, and leakage, were the focus of 46% of the selected research papers, while socio-economic challenges, including transaction, social, and opportunity costs, were addressed by 35%. The remaining 19% of the research articles focused on implementational challenges related to monitoring, reporting, and verification. Major voluntary standards adequately addressed most of the methodological and implementational barriers by adopting various approaches. However, the standards did not adequately address socio-economic issues, despite these being the second most frequently discussed theme in the papers analyzed. More research is clearly needed on the socio-economic challenges involved in the development of FCO projects. For the development of high-quality forestry carbon offset projects, there are many challenges and no simple, universal recipe for addressing them. However, it is crucial to build upon the current science and move forward with carbon projects which ensure effective, long-term carbon sinks and maximize benefits for biodiversity and people; this is particularly important with a growing public and private interest in this field.

Keywords Forest carbon · Offset schemes · Market mechanisms · Challenges · Opportunities

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Introduction

Forests have always been a valuable natural asset, sequestering carbon from the atmosphere and providing numerous essential ecosystem services and functions, including biodiversity, soil, and water conservation (Jenkins and Schaap 2018). However, as the climate change crisis worsens, global governments, citizens, and enterprises have been giving increasing attention to the generation, preservation, and protection of forest resources (Hamrick and Gallant 2017). Forestry is crucial in mitigating climate change, primarily through the ability of forests to sequester carbon, which can be significantly enhanced through appropriate management. Such projects to capture and store carbon rely on financial investments and incentives, and, as a result, the first standardized forest carbon offset (FCO) project was created in 2006 under the Clean Development Mechanism (CDM 2021). FCO projects can now be traded in either the compliance emission trading market to meet required obligations or the voluntary carbon market for purposes such as the completion of environmental, social, governance and sustainability commitments.

There are 24 compliance emission trading systems (ETS) in force globally, including the European Union's ETS, California's Cap-and-Trade Program, China's National ETS, and New Zealand's ETS (ICAP 2021). Offset quality and regulation are among the most critical factors at the designing stage of ETS (Riehl et al. 2016; Pan et al. 2021), and forestry offsets play an essential role in both mandatory and voluntary carbon markets (Shrestha et al. 2022). Most compliance programs accept the forestry sector for offsetting, although the European Union's ETS does not offset forestry credits due to the uncertainties with permanence and market supplies (Hamrick and Gallant 2017). However, numerous voluntary standards deal with the forestry sector, with the Verified Carbon Standard (VCS) being the largest. The American Carbon Registry (ACR), Plan Vivo, and Climate Action Reserve (CAR) are also responsible for significant market share (Hamrick and Gallant 2017). The share of the offset market held by voluntary standards increased significantly between 2015 and 2019, with the percentage of total offset credit increasing from 17 to 65% (World Bank Group 2020). In addition, the global trend of shifting towards nature-based climate solutions has allowed the forestry sector to become the primary component of the voluntary offset market.

From 2015 to 2019, FCO projects contributed 42% of global total offset credits, with half coming from voluntary programs (World Bank Group 2020). Voluntary FCO projects have gained a significant market share thanks to their flexibility in project type and price (Hamrick and Gallant 2017). In addition, most existing FCO methodologies, including afforestation and reforestation (AR), improved forest management (IFM), and reduced emissions from deforestation and forest degradation (REDD), were initially explored and implemented under voluntary standards before being gradually adopted by the compliance market (Hamrick and Gallant 2017; van der Gaast et al. 2018). The voluntary market will continue to play an essential role in the future as the global voluntary carbon credit demand is estimated to scale up by 15 times by 2030 and 100-fold by 2050 (Blaufelder et al. 2021). Interestingly, FCO projects continue to dominate and are growing rapidly in the voluntary markets (Maguire et al. 2021), contributing 46% of the total credits issued to date (Mitchell-Larson and Bushman 2021). Among the different FCO standards, VCS, ACR, Plan Vivo, and CAR continually dominated the voluntary FCO market throughout the past decade, sharing 63% of voluntary FCO projects in 2012 (Peters-Stanley et al. 2013), 91% in 2016 (Hamrick and Gallant 2017) and 97% in 2019 (Maguire et al. 2021), signifying their global importance. Therefore, it is crucial to understand the lessons learned from these voluntary FCO standards.

The prospects and potential for well-designed and properly regulated FCO projects are boundless, as a growing number of countries are developing quality offset standards and platforms. For instance, Singapore plans launched the Climate Impact X (CIX), global exchange and marketplace for transparent, high-quality, and high-integrity carbon offset credits in March 2022, incorporating advanced technological back-up, including satellite monitoring and machine learning (Climate Impact X 2022). The United Kingdom established the Voluntary Carbon Markets Integrity Initiative (VCMI) in 2021 to provide guidance for companies and businesses trying to achieve carbon-neutrality through credible and high-integrity offsets (Voluntary Carbon Markets Integrity Initiative 2021). However, as FCO projects develop over time, multiple challenges and barriers are being reported and discussed, including additionality, permanence, leakage, and monitoring, reporting, and verification (MRV) (Poudyal et al. 2011; Gren and Aklilu 2016; Carton and Andersson 2017). Richards and Huebner (2012a, b) summarized how different standards address additionality, permanence, leakage, wood products, and verification but with limited scope to other key issues such as monitoring and reporting. Howard et al. (2015) focused on the issues related to benefit-sharing; Wise et al. (2019), on the other hand, addressed how to optimize participation for small landowners. While these early studies have attempted to address FCO project challenges, their extent has been limited and has not covered all the uncertainties and challenges associated with FCO projects. To address this gap, this paper first systematically reviews and discusses the current challenges and barriers involved in developing FCO projects, and then draws on the experiences and lessons to show how those challenges were addressed in world-leading voluntary carbon standards, namely the Verified Carbon Standard (VCS), the American

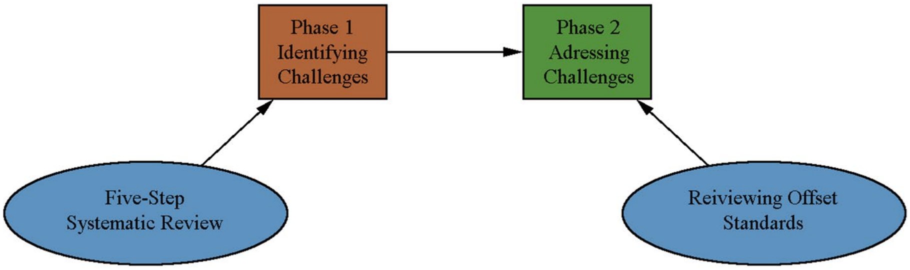


Fig. 1 Visualization of the methodology used in this study

Table 1 The five-step systematic review structure (Khan et al. 2003)

Step	Description of each step
I	Framing the question
II	Identifying the relevant publications
III	Assessing the study quality
IV	Summarizing the evidence
V	Interpreting the findings

Carbon Registry (ACR), the Climate Action Reserve (CAR), and Plan Vivo.

Material and methods

This work was undertaken in two phases. Phase 1 identified and summarized the existing challenges involved in the development of an FCO project based on a systematic review. Phase 2 identified solutions to these challenges by drawing on the lessons learned from the implementation of voluntary carbon offset standards (Fig. 1).

A systematic review involves a comprehensive and unbiased synthesis (Aromataris and Pearson 2014). The analysis was based on the 'Five-step Systematic Review' developed by Khan et al. (2003) during phase 1 (Table 1).

Step 1 involved stating the research question clearly and unambiguously. The research question, put simply, was "what are the existing challenges involved in the development of an FCO project?". In step 2, the Clarivate Analytics Web of Science (WoS) was used as the primary source for locating relevant peer-reviewed literature. It is acknowledged that some important results might have been overlooked while relying only on WoS search. However, as the pioneer and leading multidisciplinary bibliographic database system, WoS offers a vast amount of peer-reviewed scholarship in carbon forest challenges globally. Thus, the comprehensive literature review in WoS captures most of the emerging themes of carbon forestry challenges and represents a valuable reflection of current forest carbon offset program practices. As the oldest database system, it also overlaps with the interest in searching literature since the start of the Kyoto Protocol in 1997. A large volume of grey literature is associated with both regulated and voluntary carbon markets, with major variations in accuracy and reliability. Restricting the analysis to peer review literature in the WoS database reduces some of these uncertainties. Hence, the intersection of forest and offset was searched as the topic (TS). Further, abstract (AB) requirements were included to collect all possible studies for forest carbon offsets. The timespan, 1995–2021, inclusive of the date of the Kyoto Protocol, was chosen, and a total of 166 publications were located.

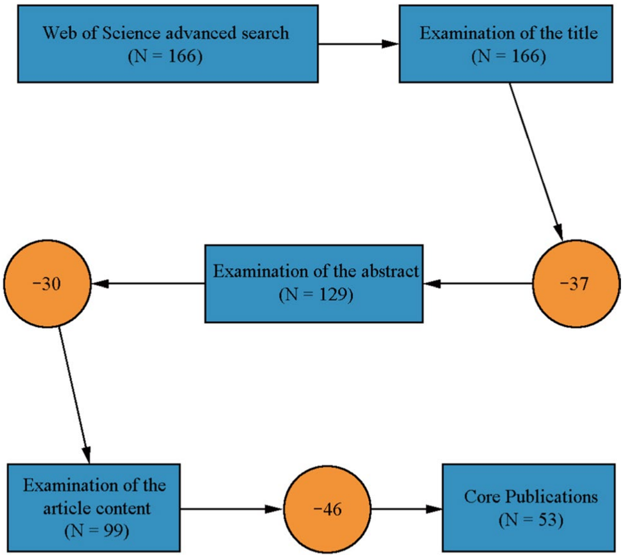


Fig. 2 Sub-steps for assessing the study quality

Several sub-steps were used to assess the study quality (Step 3) (Fig. 2). First, 37 papers based on their lack of relevance to the topic were removed, as indicated by the title of the paper (despite containing keywords 'forest' and 'offset'). For example, one such study was related to municipal wastewater management analysis. A further 30 papers were excluded based on their lack of relevance, as indicated by their abstracts. These 30 papers had some connections with FCO projects but were not relevant to the question. One article, for example, focused explicitly on the ocean carbon sink, while others focused on agriculture. The remaining 99 articles were imported into NVivo, a computer-assisted qualitative analysis software, for immersive reading (Woolf and Silver 2017), and a further 46 articles were excluded as they did not directly discuss the challenges of developing an FCO project. For instance, the main body of these papers discussed economic models for FCO project values, while others focused on the carbon sequestration of different harvesting plans, carbon stock potentials, and the future of timber markets and wood energy consumption. This reduced the final number of publications used in the analysis to 53.

To proceed with Step 4, summarizing the evidence (Table 1), guidelines recommended for conducting a trustworthy thematic analysis were used (Fig. 3) (Nowell et al. 2017). This approach enables the synthesis and analysis of the broader topic under different themes, allowing research questions to be answered with functional patterns (Braun and Clarke 2012). A rough node structure was created for the coding framework as the reading proceeded (Fig. 4a). All relevant information was coded to the respective node. For example, NVivo recorded the number of articles, hence the frequency, of discussing particular nodes. Three broader themes were inductively created, the financial, implementation and methodological challenges, and individual challenges were assigned to their themes (Fig. 4b). However, there were difficulties in distinguishing between the nodes, 'land right' and 'social cost,' as there was overlapping information. Also, it was noticed that the information about 'measurement' and 'monitoring' could be merged as there were considerable overlaps. The final thematic framework merged 'land right' and 'social cost,' and 'measurement' and 'monitoring' (Fig. 4c). In addition, the 'financial' theme was changed to 'socio-economic,' as it contained social costs. Microsoft Excel and NVivo were then used to prepare the data and produce the results. Step 5 is integrated with the findings and is addressed in later sections of this paper.

In phase 2, FCO standards were reviewed, including the Verified Carbon Standard (VCS), the Climate Action Reserve (CAR), Plan Vivo, and the American Carbon Registry (ACR), to analyze how these standards sought to address the critical issues identified in phase 1. For this part of the analysis, the "grey literature" was included, as this is where considerable information about voluntary standards is published.

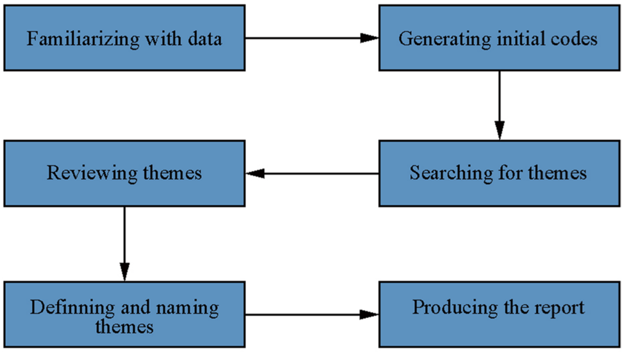
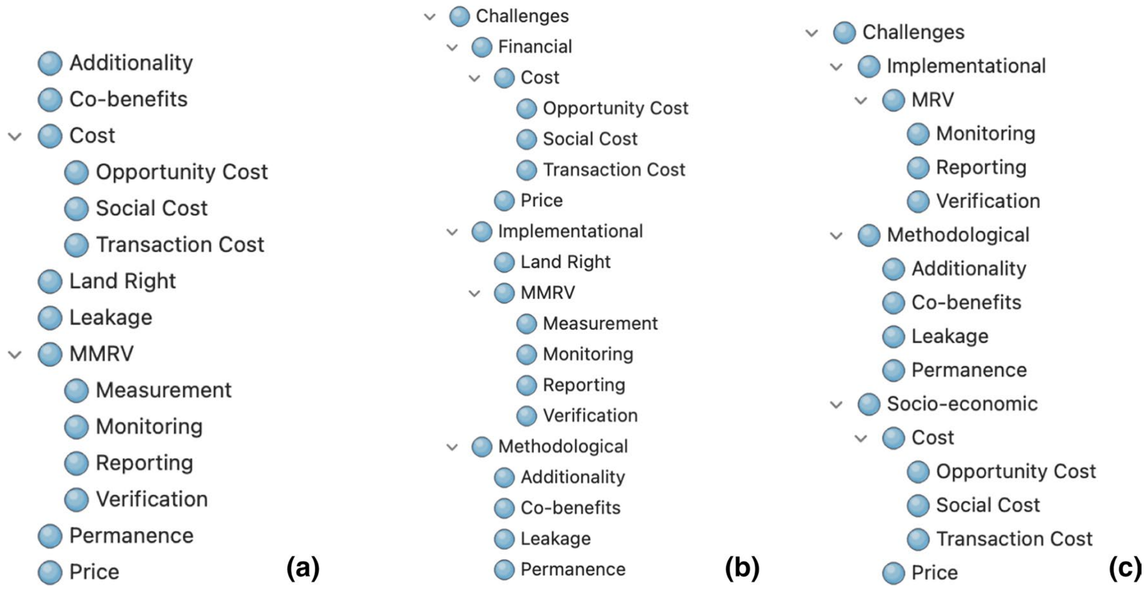


Fig. 3 Steps towards the trustworthiness of thematic analysis (Nowell et al. 2017)



- Additionality
- Co-benefits
- Cost
  - Opportunity Cost
  - Social Cost
  - Transaction Cost
- Land Right
- Leakage
- MMRV
  - Measurement
  - Monitoring
  - Reporting
  - Verification
- Permanence
- Price

(a)

- Challenges
  - Financial
    - Cost
      - Opportunity Cost
      - Social Cost
      - Transaction Cost
    - Price
  - Implementational
    - Land Right
    - MMRV
      - Measurement
      - Monitoring
      - Reporting
      - Verification
  - Methodological
    - Additionality
    - Co-benefits
    - Leakage
    - Permanence

(b)

- Challenges
  - Implementational
    - MRV
      - Monitoring
      - Reporting
      - Verification
  - Methodological
    - Additionality
    - Co-benefits
    - Leakage
    - Permanence
  - Socio-economic
    - Cost
      - Opportunity Cost
      - Social Cost
      - Transaction Cost
    - Price

(c)

Fig. 4 Screenshots of the node structures created on NVivo

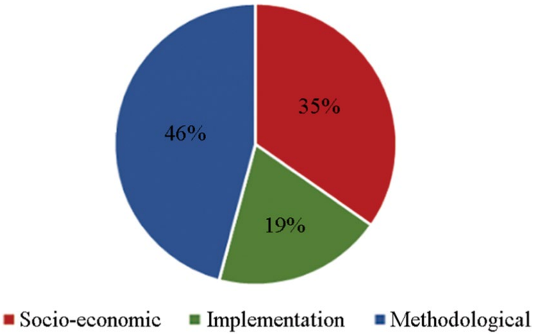


Fig. 5 The three frequently discussed challenges expressed as percentages

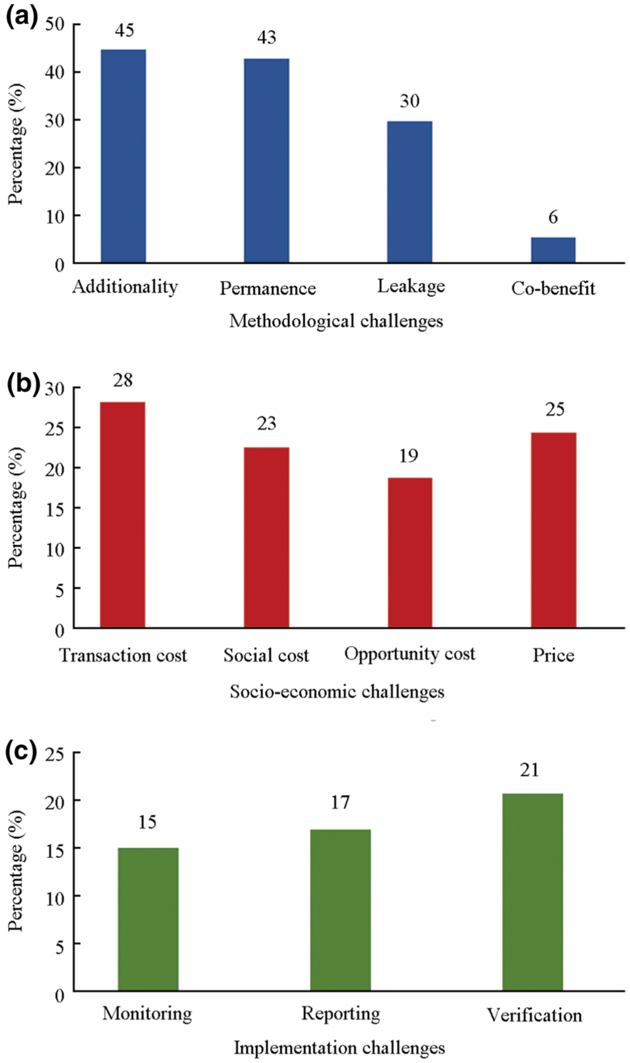


Fig. 6 Themes frequently discussed within each main challenge: **a** methodological challenge; **b** socio-economic challenges; and **c** implementation challenges, expressed as percentages

Results and discussion

Existing challenges to FCO projects

Three broad thematic categories of challenges emerged from the review process: methodological, socio-economic, and implementation difficulties. Among the 53 reviewed papers, methodological challenges were discussed the most frequently (46% of papers), followed by socio-economic (35%) and implementation (19%) challenges (Fig. 5).

Among the methodological challenges, additionality (45%) and permanence (43%) were the most frequently discussed, followed by leakage (30%) (Fig. 6a). The co-benefit-related issue was less commonly reported (6%) (Fig. 6a). Four themes, namely transaction, social, opportunity costs, and price, were highlighted within socio-economic difficulties, ranging in frequency from 19 to 28% (Fig. 6b). For the implementation challenges, processes of monitoring (15%), reporting (17%), and verification (21%) (MRV) were significant barriers to FCO project implementation (Fig. 6c).

Methodological challenges

The three most analyzed methodological challenges to FCO projects were additionality, permanence, and leakage. Additionality is a principal condition for the eligibility of an FCO project. A project is additional if: (1) the reduction in GHG emissions would not have occurred without the project; and (2) the project could not have happened without the offset credits (Richards and Huebner 2012a). However, proving additionality can be challenging, as different projects can have distinct conditions, including species compositions, habitats, and ecosystems (von Hedemann et al. 2020). Developing a baseline scenario, sometimes called "business-as-usual," is a critical step in determining additionality. However, the baseline scenario is also distinct and unique to the specific project, and it can be time-consuming and inefficient to develop (Kelly and Schmitz 2016). For example, if project promoters determine additionality, a new baseline scenario needs to be developed every time a project is started. This can deter FCO participation. Such a baseline can be inaccurate over the long- term, as the conditions present in a natural ecosystem vary over time and are inherently unstable, especially given the impacts of climate change (Ristea and Maness 2009). Furthermore, the verification process can be complicated and challenging if the project promoters develop the baseline by themselves, as there may be information asymmetry between them and the verifiers. With this in mind, project developers have an incentive to exaggerate the project's ability to sequester carbon (Dutschke et al. 2005; Malmsheimer et al. 2011).

Non-permanence is another primary methodological challenge. This refers to reductions in the ability of the project to sequester and store carbon, primarily due to natural or anthropological disturbances (Charnley et al. 2010; Malmsheimer et al. 2011; Kang et al. 2012). As a result of climate change, nature is becoming less stable, leading to more frequent and unpredictable natural events such as forest fires, flooding, and wind damage. For example, a massive fire near the Colville Indian Reservation in Washington State and Bootleg near Klamath Falls in Oregon State, USA, destroyed part of several forest carbon offset projects, reducing the value of those offsets (Hodgson 2021). Similarly, a forest can be subject to harmful insect species and disease outbreaks, and climate change may further exacerbate the situation by affecting long-term carbon sequestration. In some cases, project trees may be intentionally logged for timber sales to make illegal profits (Gren and Aklilu 2016), resulting in a compromise in the permanence of the FCO project. In addition, a future government may alter their climate change policy and harvest the forest, although it is an FCO project (St-Laurent et al. 2017). Even if there is no intentional logging, project developers may give insufficient attention to the project once they have obtained the credits, and there are few disincentives for cheating (Richards and Andersson 2001).

Leakage is a frequently discussed methodological challenge and refers to unexpected increases in carbon emissions outside the boundaries of the offset project and directly related to the implementation of the project (Ristea and Maness 2009; Malmsheimer et al. 2011). Carbon leakage can be challenging to identify and quantify, as leakage can result from an activity shift and market behavior (Richards and Andersson 2001). An activity shift refers to the existence of an FCO project that results in the original activity shifting to somewhere outside the project area (Poudyal et al. 2011). For instance, if the land was previously used for harvesting and was later registered for the FCO project involving an IFM project, the landowner may directly shift the previously planned harvesting from that land to another area (Poudyal et al. 2011). On the other hand, market behavior refers to a project that leads to a change in supply that would induce carbon emissions (van Kooten and Johnston 2016). For example, some afforestation projects may convert cropland to forest land, and as a result, total crop production may decline (van Kooten and Johnston 2016). Other landowners then have an incentive to deforest outside the project area to increase crop production.

Apart from these three primary challenges, there are concerns about the degradation of the environment and ecosystem co-benefits as a result of FCO projects (Dargusch et al. 2010). In the majority of cases, the primary management goal of an AR FCO projects is to maximize carbon sequestration and storage. When this takes the form of a monospecific or fast-growing plantation, it can lead to biodiversity loss and even soil moisture depletion (Carton and Andersson 2017). However, a large number of publications outside the FCO literature demonstrate a positive relationship between carbon storage and biodiversity (Magnago et al. 2015; Deere et al. 2018; Matos et al. 2020; Osuri et al. 2020). It is important to align and synergize the various conservation goals, including carbon sequestration, species richness, and water conservation, while developing forest carbon offsets (Larsen et al. 2011).

Socio-economic challenges

Numerous studies have shown that various high costs associated with FCO projects, including opportunity, social, and transaction costs, could deter FCO projects from being implemented successfully. Opportunity costs are defined as the cost of forgoing the benefit of the original land use in order to support a carbon offset project (Dargusch et al. 2010). A carbon forest that has a lower return than other land-use options, such as agriculture and timber production, may lead to a lesser willingness for landowners to participate (Aggarwal 2020; Regan et al. 2020). For example, Boucher (2015) concluded that deforestation and forest degradation drivers would generate significantly more economic benefits than managing a REDD project. The total value, hence, the opportunity cost of those drivers, including timber, pulp, paper, beef, leather, soy, and palm oil, was estimated to be ten times higher than the total funding of an offset project. Similarly, the likelihood of converting an orchard to a forest project in the United States was found to be extremely low due to the high economic returns associated with orchards (Nelson and Matzek 2016; Oeba et al. 2017). Similarly, when the income from wood production is more than the price of offset credits generated from carbon forestry, it leads more investors to opt for timber investments (Oeba et al. 2017). However, in other cases, income from carbon credits and other co-benefits as compensation to local communities in exchange for differing livelihood benefits were incentives to strengthen carbon storage benefits and motivation to participate in the FCO (Chhatre and Agrawal 2009). Hence, different incentive structures that ensure co-benefits beyond environmental and social safeguards should be considered, depending on the context while developing FCO (Maraseni et al. 2014; Pelletier et al. 2016).

Social cost is another challenge for FCO project implementation. The public, investors, landowners, and local communities may have limited and asymmetric knowledge and understanding of the concept of carbon offsets, resulting in uneven participation and less successful FCO projects (Laing et al. 2016; Holmes et al. 2017; Kelly et al. 2017; St-Laurent et al. 2017). Land rights issues are the main social cost component. Farmers who have the rights to the land will have less control once it is turned into an FCO project. This loss of security could lead farmers to participate less effectively (Aggarwal 2020). For instance, in Guangdong province, China, FCO project developers unilaterally decided the benefit-sharing and tree species, which left farmers no voice in the negotiation process (Zhou et al. 2017). Also, these farmers would receive no income from credit sales. Instead, they own the planted trees, but these will provide lower economic returns compared to species that they would normally plant. Similarly, Indigenous rights, including the benefit-sharing and adequate participation in decision-making, often receive little attention when developing REDD projects in developing countries, discouraging the Indigenous Peoples from participation (Lyster 2011). In some cases, the Indigenous Peoples and local people have been evicted from the forests and acts of violence and lawsuits have contributed to the conflict, negatively impacting their livelihoods (Alusiola et al. 2021). Although most projects have some provisions for protecting local Indigenous tenure rights, the protection is often insufficient without broader land tenure reform (Larson et al. 2013).

The increased transaction costs of FCO projects have also been listed as a major challenge. These are essentially the costs from information and search to project design and the complete monitoring, reporting, and verification system (Milne 1999; Cacho et al. 2013; van Kooten 2017; Guadalupe et al. 2018). For example, Pearson et al. (2014) found that the transaction costs of developing an FCO project could be as high as $7.71 per ton of carbon dioxide, which would be about 270% of the expected project income. The situation could worsen if it is a small-scale FCO because the ultimate credit gained is limited, and at the same time, the fixed transaction costs are too high to be profitable (von Hedemann et al. 2020). Hence, project developers and landowners would have little incentive to participate due to high starting costs (Charnley et al. 2010; Dargusch et al. 2010; Aggarwal 2020).

Apart from the various costs discussed above, current low and unpredictable carbon prices are also an important socio-economic challenge to FCO projects. Due to the nature of carbon price fluctuations, if the carbon price is reduced, the chance of developing an FCO project will be negligible because of the high transaction costs (St-Laurent et al. 2017). In most cases, the project will only be financially attractive when the price of carbon reaches at least US $14 per ton (Vázquez-González et al. 2017). Aggarwal (2020) has estimated that forest carbon credits can only be sold at 25–50% of the expected market value while prices remain low, potentially blocking many newcomers from entering the field. Another critical challenge identified is the stability of carbon prices. Unstable carbon prices increase the risk and uncertainty on investment returns and deter investors if they foresee a high risk (Funk and Kerr 2007; Coleman 2018). Furthermore, the forestry carbon offset market uses the ex-post payment scheme (i.e., payments made after the offset has been generated); with the uncertainty in future prices, project proponents could be further deterred from such a system (St-Laurent et al. 2017).

Implementation challenges

FCO projects rely on the MRV of claims for carbon emissions avoided or carbon sequestered. Monitoring is the periodic measurement of stored carbon stocks by the project and changes to these amounts throughout the project period (Grimault et al. 2018; Nature Conservancy, Conservation International and Wildlife Conservation Society 2010). However, this vital monitoring step is important that challenge successful FCO projects need to address. It involves field measurements, modeling, and application of GIS and remote sensing, adding costs and complexity (Birdsey et al. 2013). Pearson et al. (2014) reported that monitoring in FCO projects ranges from 3 to 42% of the total project expenses. The high costs of some monitoring could significantly deter FCO projects from entering the market. For example, northeast forest landowners in the United States are reluctant to develop an FCO project because there will be high 100-year monitoring costs following the transaction under the Air Resource Board guidelines (Kerchner and Keeton 2015). Further, in some afforestation projects, farmers may not conscientiously follow tree planting guidelines, and, as a result, more costly and rigorous monitoring is required (Carton and Andersson 2017). Similarly, farmers may fail to maintain the proper spacing and the suggested thinning process, ultimately impacting the overall effectiveness of emission reductions (Carton and Andersson 2017).

The reporting process—the recording and gathering of the collected data and communication with the project authorities—can also be challenging (Grimault et al. 2018). Moreover, the verification process, referring to the identification and detection of errors and potential fraudulence in the reporting by accredited third-party verifiers, could also act as a barrier (Grimault et al. 2018), particularly in terms of the cost involved. For instance, in CAR and ACR carbon projects, verification for individual landowners can cost a minimum of US $15,000 for initial field verification, regardless of the size of the forest (Northwest Natural Resource Group 2014), posing challenges for the viability of FCO projects (Poudyal et al. 2011). If the frequency of verification is rigorous, increasing costs will deter participation, as every verification exercise is costly. Moreover, project developers and verification agencies can present information unevenly, such that third-party verifiers cannot properly validate the projects based solely on data reported by the developers (Richards and Andersson 2001). Agencies are less likely to meticulously review every detail when they have a significant number of projects to verify. The cost related to verification is also considerable.

Approaches to address key issues by four standards

Drawing on four global standard protocols, namely VCS, CAR, Plan Vivo, and ACR, the following sections review and synthesize best practices on how these standards have addressed FCO project challenges related to methodology, finance, and implementation (Tables 2 and 3). All the standards present various ways to address methodological and implementation challenges, but there have been limited discussions of the socio-economic challenges.

Methodological challenges

In all four standards, demonstration of additionality is one of the critical requirements for an FCO project. Project developers must conduct multi-step assessments to ensure that their activities will demonstrate additionality. The legal requirement/regulatory surplus test commonly adopted by all standards requires proof that the project is not legally bound by existing laws, regulations, and other regulatory frameworks (Plan Vivo 2015a; Nickerson et al. 2019; American Carbon Registry 2020). The legal requirement test hypothetically regards the forest situation under national or local laws as the baseline, and the proposed FCO project must reduce more GHG than the baseline (Nickerson et al. 2019). The test is included in step one of VCS, determining the alternative land-use scenarios, including the pre-project land-use, the land-use without the project, and legal requirements (Verified Carbon Standard 2012). This step asks the project proponents to determine the credible alternative baseline and projects that can be shown to reduce more carbon than this baseline can pass this step. CAR adopts a performance test with a similar purpose of identifying alternative scenarios (Nickerson et al. 2019). These steps are essential as they directly show that proposed projects are genuinely additional. There are also tests designed to demonstrate additionality indirectly.

The implementation barrier test is commonly used to ensure FCO project additionality in all the standards except for the CAR. It asks project proponents to use transparent evidence to show that at least one type of barrier is present, including financial, institutional, and technological barriers, to implement the project if the project is not for credit sales (Verified Carbon Standard 2012). VCS requires the project developers to show that the identified barriers would not prevent the alternative scenarios identified in step one from happening, indicating that these barriers are only affecting the proposed project (Verified Carbon Standard 2012). In contrast, Plan Vivo adds up more viability perspectives and strictly asks the project developers to provide solutions to all the barriers identified (Plan Vivo 2015a), while ACR requires addressing only one (American Carbon Registry 2020). The barrier test may be ineffective as the barriers

Table 2 Summary of the approaches and solutions to critical methodological challenges cited by four major standards

Program name	Additionality	Permanence	Leakage	Co-benefit
Verified carbon standard	Alternative scenario identification, investment test, barrier test, and common practice test	Non-Permanence Risk Analysis and Buffer Determination	Leakage factor from activity-shifting and market effect	Must not negatively impact the surrounding environment and community
Climate action reserve	Legal requirement test and performance test	Buffer account and reversal risk rating	Leakage factor, as the secondary effect, in the carbon credit calculation	Sustainable harvesting strategy and natural forest management
Plan vivo	Regulatory surplus assessment and barrier analysis	Risk assessment and a risk buffer of at least 10% (20% typically)	Identify all potential sources of leakage	Socio-economic baseline to demonstrate a positive impact on local livelihood and community
American carbon registry	Regulatory surplus assessment, barrier test and common practice test	ACR Tool for Risk Analysis and Buffer Determination	Monitor the leakage due to activity-shifting and estimate the leakage due to market effect	Environmental and community impact assessment

Table 3 Summary of the approaches and solutions to critical implementational challenges cited by four major standards

Program name	Monitoring	Reporting	Verification
Verified carbon standard	Monitoring plan and monitoring report	Contiguous reporting period	Stringent processes with verification bodies
Climate action reserve	Annual monitoring report over the 100 years after issuance	Contiguous reporting period	Stringent processes with verification bodies by the end of each reporting period
Plan vivo	Monitoring plan, including the performance indicator, monitoring duration and frequency	Annual report	First verification within the first five years and at least every five years afterwards by third-party
American carbon registry	Monitoring plan, including carbon stocks and emission sources	Contiguous reporting period	First verification within the first five years and at least every five years afterwards by verification bodies

could come from an invalid story, making the standards difficult to investigate (Richards and Huebner 2012a). Additionally, the investment analysis, the second step of VCS, analyzes whether the project is less economically beneficial to the scenarios determined earlier if there is no revenue from the project (Verified Carbon Standard 2012). This step serves a similar purpose to the barrier test because the investment challenge can be one financial barrier. Moreover, the common practise test required by both VCS and ACR identifies similar previous or ongoing activities, predominantly penetrates the market, and shows an essential distinction between similar activities and the proposed project (Verified Carbon Standard 2012; American Carbon Registry 2020). In addition to the various tests described above, applying an upscaling baseline will help prevent non-additionality because project proponents may try to take advantage of information asymmetry (Gren and Aklilu 2016). Also, an optimal contract scheme, aiming to identify the project type, opportunity cost, and so on, would prevent buyers from purchasing non-additional offsets and would minimize the overall cost (Mason and Plantinga 2013). However, a rigorous additionality test could prevent potential climate mitigation projects from entering the market (Ruseva et al. 2017).

Within each standard, project developers must conduct a permanence-related risk assessment and determine the buffer amount to demonstrate the permanence against any unintentional carbon losses in their credit calculation. VCS asks the proponents to run a non-permanence analysis, including internal, external, and natural risks based on the score rating. This is used to assess the transient and permanent losses that could potentially happen over the next 100 years (Verified Carbon Standard 2019a). VCS's risk analysis is the most comprehensive and inclusive of the four standards examined in this study, although they all adopt similar mechanisms (Plan Vivo 2015b; Nickerson et al. 2019; American Carbon Registry 2020). There are sub-categories under each risk category with VCS; for example, there are project management, financial viability, and opportunity cost sub-category analyses under internal risk (Verified Carbon Standard 2019a). The sum of each sub-category rating score, the overall risk rating, cannot surpass a particular threshold (60); regardless of the calculation, the minimum is 10. VCS determines that internal and natural risks cannot exceed 35, while external risks cannot exceed 20. Between 10 and 60, the overall risk score will be directly converted to a percentage, and this percentage of total credit will be transferred into the buffer account. However, although natural external risks can be well estimated, none of the standards adequately address the issue of deliberate reversal, consistent with the findings of Richards and Huebner (2012a). For instance, there is no measure that accounts for a landowner's direct non-permanence actions.

The four standards commonly address leakage by requiring project proponents to involve leakage factors in the FCO credit calculation from two angles, the activity shifts and the market effects. VCS is often the favoured standard because it addresses leakage from both on at least a national scale with a range of available leakage assessment tools, including direct monitoring, leakage factors and modelling (Henders and Ostwald 2012). However, no standard covers all types of FCO projects and addresses leakage from both activity shifts and market effects. For example, although VCS has well-developed strategies for leakage, it does not have guidelines for AR projects. The CAR and Plan Vivo do not have the clear guidelines that are included in VCS and ACR. ACR requires that the project developer conduct a survey or a different approach to determine whether the activity will shift to new forested locations outside the proposed AR project area (American Carbon Registry 2020). Otherwise, if there is no such survey, ACR will automatically consider that there is an activity shift. ACR does not account for AR projects that will cause leakage from market effects (American Carbon Registry 2020). VCS addresses leakage from activity shift for REDD projects by requiring a series of calculations (Verified Carbon Standard 2020). And if possibilities are leading to lower production of timber or fuelwood, the market effect must be considered. On the other hand, ACR takes a surveying and monitoring approach to determine the potential cause and scale of leakage from an activity shift and location replacement for market effect estimation (American Carbon Registry 2020).

VCS and ACR state the leakage calculations for IFM projects. VCS determines 'that leakage due to activity shifting is zero if the decrease in wood production of the proposed IFM project is less than 5% compared to the baseline scenario (Verified Carbon Standard 2013). If the percentage is larger than 5, the project proponents must demonstrate that there will be no leakage. The guidelines from ACR are similar but less rigorous than VCS. They do not specify the percentage decrease in production (American Carbon Registry 2020), leaving more opportunities to the project developers if they have entire activity shifts. On the other hand, VCS asks the project proponents to provide a leakage assessment from market effects if the rotation is increased by more than ten years or the harvest is decreased by more than 25% (Verified Carbon Standard 2013). ACR takes a stricter position: if the yield is reduced by more than 5%, the leakage due to market effects needs to be calculated (American Carbon Registry 2020).

All four standards require the project to consider the proposed impact on the surrounding environment, but the depth and degree differ. CAR has the most rigorous guidelines for addressing co-benefits. Every FCO project under CAR must satisfy comprehensive natural forest management criteria, including native species composition, age class distribution, and structural elements (Nickerson et al. 2019). Native species must make up at least 95% of the project within 50 years. The use of monodominant stands is restricted, consistent with the literature, which increasingly shows that mixed species composition can be more productive than monospecific stands (Standish and Hulvey 2014). Secondly, stands less than 20 years old cannot surpass 40% of the area, and the project needs to fulfill this criterion within 25 years. Deadwood needs to be maintained at a sufficient level because of its value as a wildlife habitat. If any of the above criteria are not met, the project account will be suspended. Plan Vivo stipulates that any project must not adversely affect the livelihoods of local people and the community (Plan Vivo 2013). It further emphasizes maintaining and improving local biodiversity by planting native species and identifying a socio-economic baseline. VCS requires that proposed projects do no harm to the environment and that any negative impacts are adequately addressed (Verified Carbon Standard 2019b). In addition to VCS's requirement, ACR further asks the project proponents to conduct an environmental and community impact assessment, which can be undertaken by globally reputed schemes, including the World Bank Safeguard Policies and the Climate Community and Biodiversity Alliance (CCBA) Standard (American Carbon Registry 2020). ACR requires that the net environmental and community impact of the FCO project should be positive (American Carbon Registry 2020).

Implementation challenges

All standards explicitly require that project proponents develop specific monitoring plans. For example, CAR, ACR and Plan Vivo have specific times for annual monitoring throughout the crediting period, while VCS requires a monitoring assessment every five years. Plan Vivo is among the least strict. CAR has the most comprehensive monitoring guidelines and requires an annual monitoring report over the 100 years after issuing credits (Nickerson et al. 2019). The report must include a project calculation worksheet to reflect the carbon stocks, harvest volumes, leakage, and permanence buffer (Nickerson et al. 2019). ACR also requires a similar annual monitoring report, including the confirmation of ownership, updates covering environmental and community impacts, and permanence (American Carbon Registry 2010). Plan Vivo does not have a strict rule for monitoring but allows the project developers to decide the monitoring approach, frequency, and duration (Plan Vivo 2017). Monitoring strategies could include permanent sample plots, which are cost- and time-efficient to monitor and estimate carbon dynamics throughout the credit period (Brown 2002). Field sampling is adequate for smaller projects, but remote sensing is favoured when the project area is more extensive, especially for IFM and REDD projects (Grimault et al. 2018). An integrated approach, combining remote-sensing, modelling, and field data measurements, is gaining increasing recognition in the field of carbon monitoring (Birdsey et al. 2013). For instance, the Improved Forest Management Through Extension of Rotation Age methodology, developed by VCS, monitors the carbon stock not only by remote sensing but also by modelling and field site measurements, with allometric equations being utilized (Grimault et al. 2018).

The reporting process is commonly undertaken at the end of each monitoring period. CAR stipulates that the first reporting should be within a year from the project start date, and the following reporting period must cover 12 months (Nickerson et al. 2019). There should be no gaps between reporting periods. Similarly, Plan Vivo sets the reporting frequency annually (Plan Vivo 2017). VCS and ACR only ask the project proponents to have continuous reporting periods with no time gaps and with no reporting frequency requirements (American Carbon Registry 2020; Verified Carbon Standard 2013). The verification process requires third-party verifiers to check and authenticate the monitoring reports and ensure that the FCO projects are still valid for credits (Verified Carbon Standard 2019b). Projects should also update their information, including the buffer amount, at each verification cycle. After the first verification within the first five years, both ACR and Plan Vivo require a complete verification at least every five years, including carbon stock measurements, risk of reversal, and buffer amount updates (American Carbon Registry 2010; Plan Vivo 2017). CAR uses stricter measures, requiring the verification process within one year after each reporting period (Nickerson et al. 2019). Each annual monitoring report should be authenticated by the verification bodies. VCS requires verification every five years and focuses more on forest parameters, including diameter at breast height, tree height, and information related to deadwood (Verified Carbon Standard 2013). Monitoring data must be retained for two years after the end of the project period. The verification is often accompanied by a site visit to check the consistency between the project monitoring report and the accuracy of the field data (Grimault et al. 2018).

Socio-economic challenges

Most of the standards offer standalone certifications or additional eligibility requirements to address social cost challenges in their FCO projects; however, none have explicit approaches to address the issues of cost-effectiveness identified in phase 1.

VCS paired with climate, community, and biodiversity standards (CCB) to ensure the rights of the Indigenous Peoples and local communities, improve livelihoods, protect traditional culture, and ensure project benefit sharing with the communities. More than 80% of the VCS credits transacted so far have added the CCB (Maguire et al. 2021). ACR requires the FCO projects "do no harm" to communities by identifying community risks of the projects and how those will be avoided, reduced, mitigated, or compensated, and by establishing proper mechanisms to address community grievances and communication issues (American Carbon Registry 2020). Plan Vivo emphasizes the flow of benefits to the communities to deliver at least 60% of the credit sales to the relevant communities. Plan Vivo standards are based on free, prior, and informed consent (FPIC), ensuring the community's leading role in developing FCO projects and managing their land according to their needs and priorities (Plan Vivo 2013). CAR standards provide opportunities for local stakeholder consultation, and during the protocol development process, the potential social impacts of project activities are assessed, and protocols that may harm will not be adopted (Climate Action Reserve 2021). The Mexico Forest Protocol of CAR provides prescriptive guidance about obtaining free, prior, and informed consent; meeting notification, participation, and documentation; and project governance to ensure local community participation (Climate Action Reserve 2021).

Since the standards do not explicitly address issues related to cost-effectiveness identified in phase 1, the following is therefore based on an examination of the peer-reviewed literature. Maintaining the carbon price at a high level is important in addressing socio-economic challenges associated with FCO projects, as high prices mean that there will be more likelihood for economic benefits from credit sales. Consequently, it has been argued that standards should seek ways to maintain or increase the carbon price by negotiating with local governments to implement policy tools that lead to this outcome (St-Laurent et al. 2017). However, manipulating the price level is not always an optimal strategy as prices also depend on market mechanisms.

Transaction costs can be reduced through various means, including information, contracting, and adopting efficient MRV. The development of program standard documents and program guidance is essential for reducing information costs, especially for small projects (Cacho et al. 2013). Further, when specific methodologies are available, small-scale project developers can apply them at the lowest cost (Cacho et al. 2013). It has been recommended that programs should disseminate related information and knowledge to the public while targeting smallholders (Milne 1999). Contracting costs can be high when purchasing an entire set of IT infrastructure, making cost-sharing and funding extremely important (Cacho et al. 2013). Linking smallholders to local entities or institutions already equipped with the facilities could significantly reduce contracting costs (Cacho et al. 2013).

Similarly, aggregated forest carbon offset projects incorporating a range of small forest landowners and coordinated by, for example, an NGO could address costly MRV and other transaction costs, potentially increasing the willingness of small-scale forest holders to participate (White et al. 2018). Providing opportunities for funding to reduce transaction costs is important, especially in relation to MRV costs. For example, most voluntary carbon projects in China are eligible for government subsidies covering MRV costs that ensure the smooth implementation of the project (Lin and Lin 2015). New technologies, including LiDAR (satellite-based, drone-mounted, or hand-held), could significantly reduce monitoring costs (Sedjo and Macauley 2012; Ruseva et al. 2017). Similarly, community-based monitoring could be more affordable and efficient and result in more co-benefits than conventional monitoring by experts (Skutsch 2005).

Conclusions

This paper has identified and summarized the barriers and challenges of developing forest carbon offset projects based on a systematic review of peer-reviewed literature specifically mentioning forest carbon offsets. The literature identifies three broad categories of challenges: methodological, socio-economic, and implementation. Additionality, permanence, leakage, and co-benefits are methodological challenges and feature in 46% of the selected research papers.

Socio-economic challenges, including carbon pricing, and transaction, social, and opportunity costs, were emphasized in 35%, and implementation challenges associated with MRV were featured in 19%. Examining how four major voluntary standards have dealt with these challenges revealed that, while some are more robust than others, all the standards have adopted similar solutions to challenges associated with methodology, implementation, and the social cost portion of socio-economic challenges. However, the standards do not explicitly address cost-effectiveness issues of socio-economic challenges. This remains an area where further research would be welcome, mainly focusing on the inclusion of voluntary carbon offset standards addressing the cost-effectiveness of FCO projects. There are many challenges for developing high-quality forestry carbon offsets and no universal, straightforward approach for addressing them. However, it is crucial to build upon current knowledge and move forward with carbon projects and standards that result in effective and long-term carbon sinks, ensuring social justice, equity, and preservation of biodiversity. This is particularly important with growing public and private interests in this topic.

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