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Forest carbon offset protocols in compliance carbon markets

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ABSTRACT

The forestry sector plays a significant role in nature-based climate solutions. This paper is a comparative review and analysis of forest carbon offset protocols in compliance carbon markets in Australia, California, China, New Zealand, and U.S. Northeast. Our results show variations in protocol designs, particularly in relation to additionality, permanence, non-leakage, and monitoring, reporting and verification (MRV), as well as regarding the fungibility between industrial carbon reduction and forest-based carbon offset. These results may have implications for national or subnational entities to build credible forest carbon offset protocols and programs.

1. Introduction

Nature-based solutions have been featured in many countries' Nationally Determined Contributions (NDCs) and large companies' plans to achieve climate change mitigation and adaptation (Seddon et al., 2019, 2020). The Glasgow Climate Pact also emphasizes the importance of nature-based solutions to achieve the 2 °C Paris Agreement temperature goal and addresses the role of forests acting as carbon sinks (UNFCCC, 2022). Among nature-based solutions, forests can act as carbon sinks to remove carbon emissions from the atmosphere, and offer substantive environmental co-benefits, such as enhancing air and water quality, supporting biodiversity and habitat for wildlife, and maintaining aesthetic values (Nowak et al., 2007). In comparison to other climate solutions, forest carbon sequestration is a cost-effective approach, with marginal costs varying across national and subnational contexts (Chu et al., 2022; Griscom et al., 2017). Afforestation, reforestation, improved forest management (IFM), and avoided conversion projects can enhance carbon sequestration and storage in trees and may generate additional carbon benefits relative to a business-as-usual (BAU) baseline. The amount of additional carbon stored/sequestered by forest projects can be verified and awarded as carbon offsets, which can be sold to enterprises to offset their greenhouse gas (GHG) emissions.

Compared to other types of carbon offsets, such as renewable energy offsets, forest carbon offsets are understudied (van der Gaast et al., 2018). In a few compliance carbon markets, emission trading schemes (ETS) or cap-and-trade markets – all three terms are interchangeable in literature – mandate emission reductions and impose quotas of maximum emission allowances on regulated enterprises. In these markets, the regulated enterprises may be allowed to purchase carbon offsets from projects outside the ETS capped sector, including forest projects. As a result, forest carbon offset initiatives increase forest land expectation value (Ekholm, 2020). Despite the potential benefits, integrating forest carbon offsets into compliance carbon markets has presented challenges, primarily from major barriers related to addressing forest projects' additionality, permanence, non-leakage, and monitoring, reporting and verification (MRV). Overcoming these challenges is essential to ensure the successful implementation of forest carbon offsets and have well-designed and efficient forest carbon policies (Gren and Aklilu, 2016).

The purpose of this paper is to review and compare the forest carbon protocols in compliance carbon markets. The few countries/regions/states whose compliance markets are currently active and include forest carbon offsets are New Zealand, Australia, California, China, and U.S. Northeast (Regional Greenhouse Gas Initiative or RGGI). The experiences of forest offset protocols in these markets may inform policymakers in other countries who are contemplating and developing protocols for forest offsets in their respective carbon markets. We employ a comparative case study approach and systematically compare how the protocols address additionality, permanence, non-leakage, and monitoring-reporting-valuation (MRV) of forest carbon offsets. The five protocols are fully implemented except for RGGI. We include RGGI here because it has a complete protocol, even though no forest project has been registered under it so far. Hopefully, this research offers insight for policymakers, practitioners, and landowners elsewhere who intend to design forest offset protocols or benefit from forestry offset projects.

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2. Literature review

Most countries have developed policy instruments to address environmental and climate issues, with rapid policy diffusion and learning across countries (Tews et al., 2003). Policy diffusion refers to the spreading process of policy innovations among countries due to communication rather than hierarchy or collective decision-making (Tews, 2005). The policy diffusion of carbon pricing, in the form of ETS or cap-and-trade, has been discussed as an example of policy diffusion (Gulbrandsen et al., 2017; Wettestad and Gulbrandsen, 2017). The European Union (EU) ETS, which has been in operation since 2005, is a frontrunner and a reference for other jurisdictions. Now, there are 25 ETS markets in operation out of which 16 allow forest carbon offsets, while 22 ETS under development (ICAP, 2022a).

New Zealand launched a national ETS in 2008, with a unique design of 'trading without cap' as there is no binding cap on the total volume of emissions allowed in New Zealand. Based on California's *Global Warming Act* in 2006, the California Air Resources Board (CARB) established a compliance carbon market with carbon offset allowance in 2012 and linked with the Quebec ETS in Canada in 2014 (CARB, 2015). Launched in 2009 with ten states and now extended to twelve, RGGI is another large mandatory ETS market in the United States. China has experimented with subnational ETS markets since 2013 which were influenced by the EU ETS designs and started to operate a national scheme since 2021. Rather than operating a nationwide ETS, Australia has operated the Emission Reductions Fund (ERF) since 2014, which is a government payment mechanism to finance forest carbon sequestration projects (Regan et al., 2020). Industrial facilities can purchase those credits to offset emissions to meet compliance obligations under a Safeguard Mechanism after 2021.

In the compliance carbon markets, regulated entities (e.g., industrial companies, organizations) are under mandatory obligations to reduce their GHG emissions. Through purchasing certified carbon offset credits, the regulated entities can reduce carbon emissions at lower costs than direct GHG emission reductions (Broekhoff, 2007). This allows the regulated entities to spend more resources on other climate actions and initiatives.

All forest carbon offset protocols have several fundamental components to ensure that carbon stored in forests is real, additional, permanent, and not causing leakage outside the project area (Merger and Pistorius, 2011). 'Additionality' requires a project to increase carbon sequestered by trees in addition to the BAU baseline scenario, demonstrating that this additional carbon sequestration would not have occurred in the absence of the project. 'Permanence' requires carbon stored in trees to be long-lasting and would not be released back into the atmosphere in the short term. 'Leakage' occurs when emission reduction activities in the project area simply shift emissions to another location, including increased deforestation in adjacent forests resulting from the displacement of activities or resources within the project area (i.e., activity-shifting leakage) and increased deforestation and emissions elsewhere when a project alters the timber supply and demand equilibrium (i.e., market-shifting leakage) (Murray et al., 2004; Wunder, 2008). Existing literature presents evidence highlighting the significant concern of carbon leakage within the forest sector, relative to that observed in other sectors (Pan et al., 2020). Protocols need to reduce leakages of forest carbon offsets to ensure net reductions of GHG emissions in the atmosphere. MRV requirements are important for demonstrating emission reduction and carbon sequestration by a project are real, quantifiable, and verifiable over time.

A number of studies have discussed the forest carbon offset protocols in Australia (Burke, 2016; Macintosh et al., 2022a, 2022b; Mummery, 2023; Regan et al., 2020), California (Badgley et al., 2022a, 2022b; Coffield et al., 2022; Lueders et al., 2014; Marland et al., 2017; Ruseva et al., 2017), and New Zealand (Birchall et al., 2015; Carver et al., 2022; Diaz-Rainey and Tulloch, 2018; Leining et al., 2019), but fewer studies have focused on those forest protocols in RGGI (Lamb et al., 2021; Lee et al., 2013) and China. As to China, although several studies have examined its carbon offset system – the China Certified Emission Reductions (CCERs) (Li et al., 2019; Lo and Cong, 2017; Wei and Xiao, 2022; Ye et al., 2021) – few have examined its forest carbon offsets.

From the global and comparative perspective, several studies have primarily compared voluntary protocols such as American Carbon Registry (ACR), Climate Action Reserve (CAR), and Verra Verified Carbon Standard (VCS) (see Table 1), but research has yet to be done on systematically reviewing and comparing various forest carbon programs/protocols across the compliance carbon markets.

3. Method and data

Our research method follows a small-N comparative case study design (Kaarbo and Beasley, 1999; Yin, 1992). A case study approach allows for the integration of diverse evidence sources to develop a thorough within-case understanding of each protocol, and a comparative case approach is suitable for analyzing the similarities and differences across protocols. Thus, we decided on the case selection, employing purposive sampling. The five compliance carbon markets selected have established forest carbon offset protocols, are prominently featured in the literature, are currently in force, and cover significant amounts of CO_2 emissions.

A comparative case study is often qualitative, exploring cases in depth from various aspects and collecting detailed information from a variety of data sources (Creswell and Creswell, 2017). It can make causal inferences or be descriptive without making any assertions about causal relationships (Gerring, 2004; Yin, 2018). This study is qualitative and descriptive, comparing the five cases from aspects of (1) basic designs of the forest carbon offset protocols, including eligibility of forestry projects, additionality/ baseline, permanence, non-leakage; (2) methodologies for accounting and MRV; and (3) purchasers of forest carbon offsets in the compliance markets.

To collect accurate information, we initially reviewed details on the design of protocols from the official websites of the five selected cases (Table 2). We also gathered official documents associated with protocol design within the cases, building the cases through document analysis – a widely recognized strategy for data collection and analysis in case studies (Priya, 2021). Subsequently, we conducted a purposive search of academic articles, targeting publications that discuss each protocol's practical application and outcomes, thereby providing a comprehensive view of their practices and challenges in real-world settings. Table 2 presents the official websites of the compliance carbon markets and forest carbon offset protocols and the regulatory design to oversee the

Table 1
Existing studies comparing forest-based carbon offset protocols.

Author (year)	Market	Specific protocols included	Key themes covered
Marino and Bautista (2022)	Voluntary and compliance forest carbon market	California, American Carbon Registry (ACR), Clean Development Mechanism (CDM), Verra Verified Carbon Standard (VCS).	Forest project categories; over-crediting bias.
Pan et al. (2022)	Voluntary forest carbon market	ACR, CAR, Plan Vivo, Verra VCS.	Additionality, permanence, leakage, co-benefit, MRV.
Haya et al. (2023)	Voluntary and compliance markets for improved forest management offsets	California, ACR, CAR, Verra VCS.	Additionality and baseline, permanence, leakage, carbon accounting.

Table 2
Key regulators, documents, and websites for forestry-based carbon offsets in compliance carbon markets.

Carbon markets	Regulator	Key regulations/ legislations/ documents	Key websites
New Zealand	Ministry for the Environment, Environmental Protection Authority, Ministry for Primary Industries (MPI)	• *Climate Change Response Act 2002.*	Ministry for the Environment. • https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/ets/ Environmental Protection Authority. • https://www.epa.govt.nz/industry-areas/emissions-trading-scheme/ Ministry for Primary Industries. • https://www.mpi.govt.nz/forestry/forestry-in-the-emissions-trading-scheme/
Australia	Clean Energy Regulator (CER)	• *Carbon Credits (Carbon Farming Initiative) Act 2011.* • *Carbon Credits (Carbon Farming Initiative) Regulations 2011.* • *Carbon Credits (Carbon Farming Initiative) Rule 2015.* • *Understanding your plantation forestry project.* Emissions Reduction Fund simple method guide for plantation forestry projects. • *FullCAM Guidelines for the 2022 plantation forestry method,* by CER.	Clean Energy Regulator. • https://www.cleanenergyregulator.gov.au/ERF
California	California Air Resources Board (CARB).	• *Global Warming Solutions Act 2006.* • *Assembly Bill 32 (AB 32)'s* cap-and-trade rule. • *California Cap on Greenhouse Gas Emissions and Market-Based Compliance Mechanisms* in *California Code of Regulations.* • *Compliance Offset Protocol: U.S. Forest Projects* on 20 October 2011, 14 November 2014, and 25 June 2015.	California Air Resources Board. • https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program
China	National Development and Reform Commission (NDRC); Ministry of Ecology and Environment (MEE)	• *Interim Measures for the Management of Voluntary GHG Emission Reduction Transactions*, by NDRC in 2012. • *Guidelines for the Validation and Certification of Voluntary Greenhouse Gas Emission Reduction Projects*, by NDRC in 2012.	Exchange Platform. • https://www.ccer.com.cn/
RGGI	RGGI, Inc.	• *RGGI Model Rule. Part XX CO_2 Budget Trading Program.* • *2005 RGGI Memorandum of Understanding.* • U.S. *Forest Projects Offset Protocol, by RGGI on 13 June 2013.*	RGGI. • https://www.rggi.org/allowance-tracking/offsets/offset-categories/forestry-afforestation.

protocols, including regulator(s) and regulations/legislations/official documents.

4. Analyzing designs of forest carbon offset protocols in compliance carbon markets

This section elaborates the five forest offset protocols in compliance carbon markets (Table 3). Information about how forest CCERs in China assure additionality, permanence, and non-leakage is quite limited.

New Zealand and Australia are unique in the way that they set no limitation on the number of offset credits that can be used by industrial entities, and in effect, they treat industrial carbon emission reduction and forest carbon offsets as identical. In other words, GHG emission reduction and carbon offset are fungible and are treated as substitutes. This is why there is only one carbon price in these two markets, respectively, and why their forest offset credit prices are much higher than those in other markets (Fig. 1). On the other hand, forest offsets are only allowed to be a small part of the carbon compliance markets in California, China, or RGGI, and there are a carbon allowance price and an offset price, which differ greatly (Fig. 1).

4.1. New Zealand

4.1.1. Protocol design

New Zealand ETS covers a wide range of sectors, including forestry, making it the only ETS market that engages forestry at the sector level. As noted above, New Zealand ETS does not differentiate between industrial CO_2 emission reduction and carbon offsets. In this ETS market, the New Zealand emission units (NZU, i.e., one ton of CO_2 emission, or the equivalent of any other GHGs) are traded through auctioning that are operated jointly by New Zealand Exchange and European Energy Exchange, or direct transactions between companies.

In New Zealand, forests are classified into pre-1990 forests versus post-1989 forests. Pre-1990 forest owners are subject to mandatory obligations under the ETS to keep their forests. Otherwise, they have to pay for the loss of carbon storage in the forests. Pre-1990 forests refer to those that existed as forest lands (with native and/or exotic tree species) on 31 December 1989 and remained as forest lands (with mostly exotic tree species) on 31 December 2007. Post-1989 forests refer to those being forested after 31 December 1989 and may include native, exotic, or mixed-species forests. Post-1989 forest owners can voluntarily participate in the ETS, and earn NZUs through afforestation,

Table 3
Protocols for forestry-based carbon offset protocols in compliance carbon markets.

Carbon markets	Offset credits	Eligible forest activities	Additionality	Permanence	Non-leakage
New Zealand	NZUs	Eligible forest activities earning NZUs (for post-1989 forest): • Afforestation, • IFM, • Reforestation.	Pre-1990 forest: • They face mandatory liabilities in the New Zealand ETS. Post-1989 forest: • Baseline is the initial carbon stocks (using stock change accounting), or the long-term carbon stock average over multiple rotations (using average accounting).	Minimum 50-year permanence period for permanent forests: • Permanent forests must not be clear-felled for at least 50 years. Otherwise, they must surrender NZUs and may face a penalty. No specific permanence period for standard forests.	Covering forestry at a sector level. Accounting for both deforestation and afforestation.
Australia	ACCUs	Eligible forest activities: • Afforestation, • Avoided conversion, • IFM.	Baseline varying with project types. Three project-level tests to ensure additionality: • Newness test • Regulatory additionality requirement test • Government programs test	Either 25-year or 100-year permanence period: • Discount in ACCUs payment for shorter permanent period • A reversal buffer pool to compensate for reversals.	Not available
California	CARB offset credits	Eligible forest activities: • Reforestation, • IFM, • Avoided Conversion.	Baseline: • Calculated through a 100-year projected baseline model. • Financially feasible. • Considering the initial carbon stocks and the common practice.	100 -year permanence period: • A reversal buffer pool to compensate for unintentional reversals. • Retirement of offset credit to compensate for intentional reversals.	• A default 20% activity-shifting leakage. • A default 20% market-shifting leakage.
China	CCERs	Eligible forest activities: • Afforestation, • IFM.	Baseline: business-as-usual scenario. Carbon stored in the forest above the baseline is considered additional.	Limited and weak permanence requirements. Permanence period same as the crediting period.	Not available
RGGI	CO_2 offset allowances	Eligible forest activities: • Afforestation (Connecticut only) • Avoided Conversion, • IFM, • Reforestation.	Baseline: 100-year baseline model. Two tests to assure additionality: • Legal requirement test, • Performance test.	100-year permanence period: • Compensation for intentional reversals and unintentional reversals.	• Activity-shifting leakage varying with project types. • A default 20% market-shifting leakage.

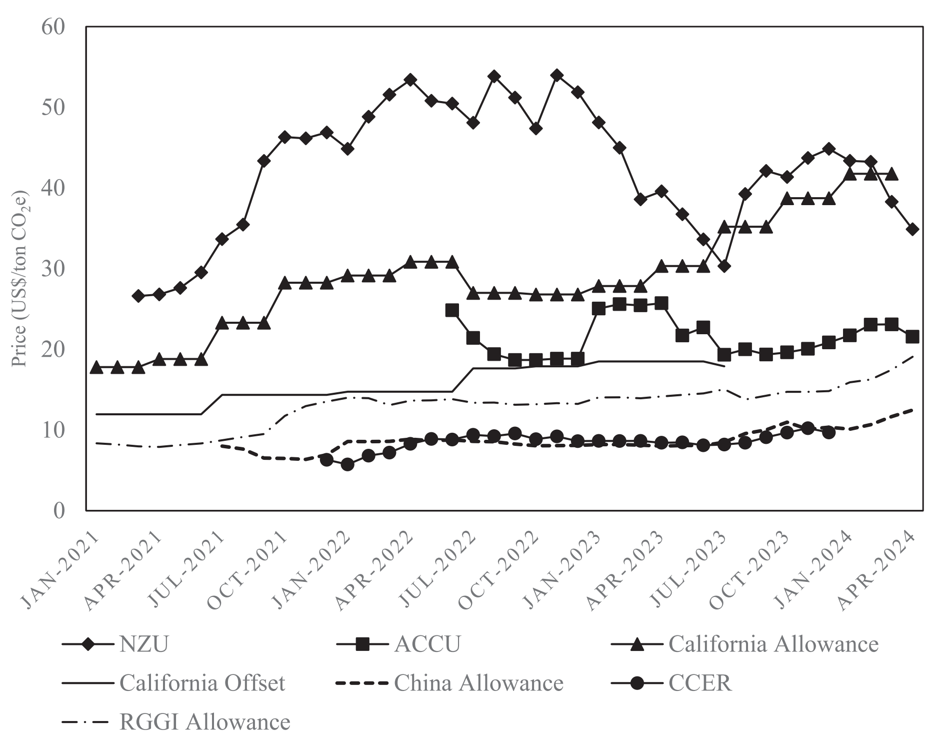

Fig. 1. Carbon offsets and allowance prices in the compliance carbon markets.
Note. RGGI offset price are not accessible.
Source: Bloomberg Terminal; CCER data is from the Fudan University's Research Center of Sustainable Development (https://rcsd.fudan.edu.cn/fdtjzs/zscx.htm).

reforestation or IFM activities. As such, there are no avoided conversion forest projects in the New Zealand ETS.

4.1.1.1. Additionality. Pre-1990 forest owners cannot earn NZUs from their forests but must pay NZUs if they deforest. In each reporting period, post-1989 forest owners can earn NZUs for additional carbon stock sequestered by their growing forests compared to the initial carbon stock at the beginning of that period and sell the NZUs to mandatory ETS participants for emission offsets. Post-1989 forest owners are required to pay NZUs when the carbon stored in trees decreases due to harvesting or deforesting, or when they withdraw from the ETS. In 2023, a different method – average accounting – was introduced, which sets the baseline according to a long-term average value of carbon stocks calculated over multiple rotations.

4.1.1.2. Permanence. The New Zealand ETS allows post-1989 forests to be registered as standard forests or permanent forests, with the latter category becoming available on 1 January 2023. Permanent forests may earn NZUs as the carbon storage in the forest increases and must pay NZUs when harvesting. The permanent forests cannot be clear-felled for at least 50 years. Permanent forest owners who deforest or change the use of their land within 50 years must pay NZUs to the government, up to the amount earned for that land. A penalty may apply depending on the value of the forest, and if the remaining tree crown cover after deforestation is 30% or lower. Nonetheless, for standard forests, there is no permanence period specified. A standard forest landowner who deforests their land must repay NZUs received for this land, but they won't face any fines or penalties.

4.1.1.3. Non-leakage. The New Zealand ETS addresses the leakage problem through coverage of forestry at the sector level and accounting for both deforestation and afforestation. As such, reduced deforestation activities in one place may not easily lead to deforestation elsewhere as both places are covered by the ETS (i.e., no activity shifting). With a

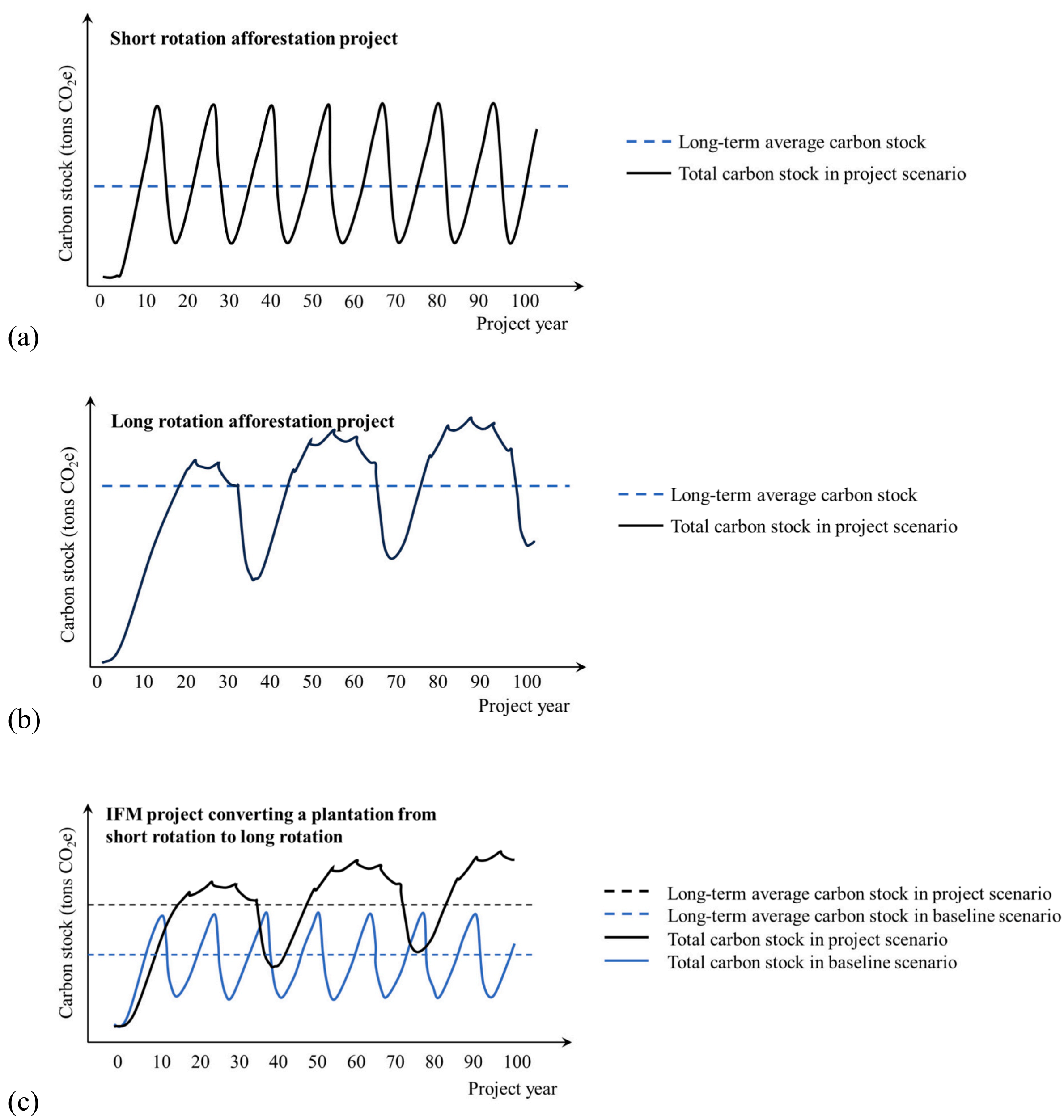

Fig. 2. Illustration of stock change accounting and average accounting methods: examples of afforestation and IFM projects.
(Source: Adapted from MPI (2023a) and CER (2022b).)

wide coverage of forest land, market leakage is thought not to be a big concern, either. By registering and covering both deforestation and afforestation activities, this scheme may provide symmetrical price incentives for afforestation and deforestation (Leining et al., 2019).

4.1.1.4. Accounting and MRV. In New Zealand ETS, forest owners need to regularly submit 'emission returns' which are reports that estimate changes in carbon stored by forest lands over time. An 'emission return' reports the amount of NZUs that a forest owner can earn or have to pay. Forest owners may face penalties if their emission returns are inaccurate or submitted late. For post-1989 forests, the accounting methods can be either average accounting or stock change accounting, as illustrated by Fig. 2.

The stock change accounting method requires post-1989 forest owners to regularly account for short-term changes in the carbon stored in trees. Fig. 2 illustrates the carbon stock in a short rotation afforestation project, a long rotation afforestation project, and an IFM project converting a plantation from short rotation to long rotation. As shown, the total carbon stock within the forest land relates to the tree growth in a rotation, experiencing an increase as trees grow and declining following tree harvesting activities. Under the stock change method, forest owners can either earn or pay NZUs contingent on the amount of carbon stored within the forest land at the time (Ministry for Primary Industries MPI, 2023b). For IFM projects, an augmentation in carbon stock can be achieved through converting the plantation cycle from short rotation to long rotation. As a result, the project owner becomes eligible to earn NZUs commensurate with the additional carbon stock. The permanent forestry category also follows the stock change accounting method. At the end of every mandatory emission return period (usually 5 years), the permanent forest owner needs to report emission returns and will be awarded or charged NZUs accordingly.

The average accounting method started to be available on 1 January 2023. Differing from the stock change accounting method, the average accounting method accounts for the long-term carbon stored in the forest (Fig. 2). The amount of long-term average carbon stock is estimated according to the average amount of carbon captured over multiple rotations of growth and harvest. A forest owner can earn NZUs until their forest reaches the average age, or the average of its long-term average carbon stock (represented by the dash lines in Fig. 2). After that, the forest owner can harvest their forest without paying NZUs as long as it is reforested. As illustrated in Fig. 2, a long rotation afforestation project exhibits a higher long-term average carbon stock than a short rotation project and is entitled for more NZUs. An IFM project achieves an increase in the long-term average carbon stock, resulting in the accrual of NZUs commensurate with the additional carbon stock.

4.1.2. Practices and challenges

As pre-1990 forest owners have to pay NZUs if they harvest more than 2 ha, Kim and Daniels (2019) argue that the New Zealand ETS relatively favors afforestation and reforestation but not the IFM of pre-1990 forests. Evison (2017) criticizes that the implementation of the ETS between 2008 and 2012 has not led to increased afforestation and even encouraged deforestation in some cases. It was because forest investment and policy risks were increased by the ETS, and forest owners were incentivized to deforest at times when the price of NZUs was very low. The considerable variability in carbon prices, coupled with extended periods of low pricing, challenge the effectiveness of New Zealand ETS as a policy instrument to encourage afforestation. Through an econometric model simulation of the New Zealand ETS, Adams and Turner (2012) show that a stable carbon price expectancy is essential for achieving the goals of increasing afforestation and reducing deforestation. Besides the above price issues, compliance and transaction costs—including the search costs to understand eligibility criteria for participation in the ETS—pose significant barriers that prevent landowners from registering new plantations in New Zealand's compliance market (Kaine et al., 2023; Roche, 2017).

4.2. Australia

4.2.1. Protocol design

Australia established an Emissions Reduction Fund (ERF) in 2014, operated by its Clean Energy Regulator (CER). ERF absorbed the legacy of the previous Carbon Farming Initiative that was designed for farmers to earn credit units (Mummery, 2023). Some scholars consider ERF as one of the largest payment schemes for carbon offsets (Hamrick and Gallant, 2017).

A registered emissions reduction project can be implemented through the ERF by submitting sealed bids, with the lowest bid per unit of abatement selected for contracts with the Australian Government (Burke, 2016; Regan et al., 2020). Thus, CER uses an inverse auction system and issues Australian Carbon Credit Units (ACCUs) for eligible projects, with each ACCU representing one ton of CO_2e not emitted into the atmosphere. Until now, the Australian government has been the major buyer of ACCUs. CER is the government agency carrying out the role of executing these purchases, accounting for around 95% of all ACCUs bought in 2019 (Climate Change Authority, 2020). From this perspective, ERF works like a 'subsidy' or a 'payment for ecosystem service' to registered emission reduction projects.

Besides governmental purchases, the demand for ACCUs also comes from industrial emitters having mandatory reduction targets under a Safeguard Mechanism in Australia. The Safeguard Mechanism, starting to operate in 2013, requires an industrial facility to limit its emissions under the prescribed emission caps, with the caps gradually lowered over time (Chubb et al., 2022). There are 212 industrial facilities covered under the Safeguard Mechanism. Facilities that emit beyond their baselines can purchase ACCUs to offset the emissions. Industrial facilities purchased about 380,000 ACCUs to offset emissions to meet their Safeguard obligations in 2016–17, and about 59,000 ACCUs in 2018–19 (Climate Change Authority, 2020). In this way, ERF credits industrial carbon emission reduction and carbon offset activities on a 1-to-1 basis, just like in New Zealand.

Forest projects accounted for around 80% of the total fund spent on all offset projects by 2020, and the majority are projects converting agricultural land to woody perennials (Regan et al., 2020). The 2022 plantation forestry methodology allows four types of forest activities (CER, 2022b): (1) afforestation (also mentioned as "establishing a new plantation" in ERF's protocol), (2) conversion of an existing plantation forest from a short to a long rotation, (3) avoided conversion to agricultural land through continuing plantation forestry activities, and (4) avoided conversion of a permanent (unproductive) forest to other land uses.

4.2.1.1. Additionality. ERF employs several mechanisms to ensure the additionality of carbon stored in forest projects. It requires projects to follow the *Full Carbon Accounting Model (FullCAM) guidelines* to estimate the baseline for crediting emission abatement, showing what level of carbon sequestration would be without the project. This baseline setting also varies with forest project types. For afforestation projects, the baseline assumption is that there is minimal or no carbon stock in the forest land. For IFM projects that extend forest rotations from short to long cycles, the baseline scenario assumes that forest management will continue with short rotations for 100 years. For avoided conversion projects, the baseline assumption is that the forest will be cleared in a single harvest event and converted to non-forest land use.

Furthermore, ERF designs three project-level tests, including the newness test, the regulatory additionality test, and the government programs test (CER, 2022b). The newness test requires that an ERF project must not have begun when it is registered. The regulatory additionality test requires that an ERF project cannot be required by or under a law of the Commonwealth, a State, or a Territory. It excludes forests that have already been protected from conversion to non-forest land. The government programs test requires that an ERF project cannot be likely to be implemented under another program or scheme of the Commonwealth, a State, or a Territory government.

4.2.1.2. Permanence. ERF requires a forest project to register for a 25- or 100-year permanence period during which the land-use change must be maintained. Compared to the 100-year permanence period, ACCU payments for projects that select the 25-year period will be reduced by 20%. ERF also ensures projects' permanence through applying a 5% reduction to all ACCUs payments to account for the risk of reversals and requires projects to compensate for losses caused by fire or other disturbances (Mummery, 2023).

4.2.1.3. Accounting and MRV. Accounting of ACCUs from forest projects follows the *Carbon Credits (Carbon Farming Initiative—Plantation Forestry) Methodology Determination 2022* or Full CAM models (CER, 2022b). A project needs to report its carbon abatement at regular intervals and submits an audit report that verifies the abatement achieved by the project (CER, 2023). Full CAM models help simulate the baseline, project, and long-term project scenarios to quantify the ACCUs that can be awarded to a forest project (CER, 2022a).

4.2.2. Practices and challenges

Despite mechanisms intended to ensure additionality, the Australian ERF has encountered criticism for its over-crediting among forest projects. Inaccurate baseline setting was one of the major reasons for this over-crediting. In practice, the actual baseline is uncertain and difficult to be accurately observed and measured (Haya et al., 2023). Macintosh et al. (2022a) argue that ERF's baseline assumption for avoided deforestation/conversion projects is flawed, which assumes that landowners will clear the land and that no carbon will be stored in trees. This faulty assumption resulted in credits being granted for forests that were unlikely to be cleared in the first place. Burke (2016) states that project owners are "committing to not clear land when there was no intention to clear." In other words, these avoided deforestation/conversion projects are awarded credits without taking any concrete actions to reduce deforestation.

Additionally, the credited afforestation projects include those in areas with existing mature vegetation in credit calculations. Macintosh et al. (2022a) state that "they are getting credits for growing trees that are already there." This has led to excessive crediting where the environmental abatement is neither real nor additional.

Another problem with the current protocol is that preventing leakage has not received much attention (Burke, 2016). Leakage is a significant concern. Evidence shows that afforestation and reforestation outcomes of the ERF's program have been compromised by rising deforestation in other regions of Australia (Evans, 2018). Warman and Nelson (2016), on the other hand, argue that conservation/avoided conversions of natural forests have resulted in minor leakage problems in Australia.

Therefore, ERF's forest carbon protocol design needs to be amended to correct the baseline setting and additionality measurement. The suggestions of Macintosh et al. (2022b) are to revoke the avoided conversion method and amend the afforestation method. For existing credited projects, there is a need to reevaluate and exclude credits from mature woody vegetation that was already present at the time of project commencement (Macintosh et al., 2022a). Equally important, prevention measures should be carefully designed and incorporated into the protocol to mitigate leakage risks for various forest project types.

4.3. California

4.3.1. Protocol design

California's cap-and-trade covers around 450 entities from power, industrial, building, and transportation sectors, covering about 80% of the total GHG emissions in California (CARB, 2015). It allows limited forest carbon offsets, with offset credits issued by CARB or a linked cap-and-trade (e.g., Québec, Ontario). It is considered as the first legally enforceable compliance forest carbon offset program in the United States (Anderson et al., 2017). Forest project types including IFM, avoided conversion, and reforestation are eligible for producing carbon offsets. However, afforestation projects are not eligible. IFM projects can include forest activities of increasing rotation ages, planting more trees, thinning diseased and suppressed trees, and managing brush and short-lived forest species. For 2013–2020 emissions, a regulated entity can offset up to 8% of its total compliance obligation through forest or other offset projects (CARB, 2015). The offset rate is reduced to 4% for 2021–2025 emissions and will be 6% for emissions from 2026 (ICAP, 2022a).

4.3.1.1. Additionality. To calculate additional carbon storage achieved, forest carbon offset project managers first need to estimate the conservative 100-year average baseline value for carbon storage in their forests in a BAU scenario. This baseline value calculation is based on regional average of U.S. Forest Service's Forest Inventory and Analysis data (Bechtold and Patterson, 2005). Forest owners can earn carbon offset credits for the difference between the actual carbon stored in trees and the BAU baseline value (CARB, 2019b). In addition, the annual inventory of carbon stored in trees must account for harvesting activities.

4.3.1.2. Permanence. California employs three mechanisms to achieve the permanence of forest carbon sequestration. First, forest projects need to make sure carbon will remain stored in trees for at least 100 years. Second, a reversal buffer pool is applied to compensate for unintentional risks of reversals. Projects are required to allocate a range of 2 to 4% of gross offset credits to the buffer pool to address wildfire risks, an additional 3% to account for disease and insect-related mortality risks, and a further 3% to mitigate other natural risks such as wind and flood catastrophic events (Badgley et al., 2022a). Third, for intentional reversals such as willful land use conversion, forest owners must retire offset credits equal to the number of offset credits that have been issued to the project, meaning that these credits are no longer eligible for sale, trade, or compliance purposes (CARB, 2019a; Ruseva et al., 2017). The forest owners may also be subject to penalties in cases of intentional reversals (ibid).

4.3.1.3. Non-leakage. Offset credit calculation in California intends to account for both activity-shifting leakage and market-shifting leakage. For activity shifting leakage, leakage equal to 20% of the difference between actual harvests and baseline harvests is deducted from carbon offset credits if actual harvests are less than baseline harvests (CARB, 2019b). For market-shifting leakage, a default 20% leakage is applied (ibid). This means that for every ton of reduced wood product harvesting in the project area, the market response will increase harvesting by 0.2 tons on non-project lands. These leakage factors were determined through a public process informed by available information.

4.3.1.4. Accounting and MRV. California incorporates accounting methods of CAR, one of the earlier carbon offset registries founded in 2008 under the California State Legislature (Lee et al., 2018). Quantification of carbon offsets follows six steps, including (1) estimation of total amount of carbon stored in a forest, (2) project baseline estimation, (3) accounting for annual harvesting, (4) estimation of the amount of carbon remaining stored in wood products over 100 years, (5) leakage estimation, and (6) verification of additional carbon stored in trees. California's offset protocol requires that GHG reductions and removal enhancements achieved by offset projects be verified by a CARB-accredited third party. Site visits are required to confirm inventory accuracy through sample remeasurement.

4.3.2. Practices and challenges

California's forest offset protocol has been extensively discussed in the literature. A few studies (Anderson et al., 2017; Kelly and Schmitz, 2016; Ruseva et al., 2017) argue that it pursues "stringent" additionality through multiple mechanisms, but the associated cost and complexity of compliance diminish the incentives for some landowners to participate in the offset market.

Conversely, many recent studies (Badgley et al., 2022a, 2022b; Coffield et al., 2022; Haya, 2019; Haya et al., 2023; Randazzo et al., 2023) criticize California's program for its over-crediting, due to issues like asymmetric information and adverse selection. The baseline for most projects in California is the regional average of surveyed forests that are classified as the same forest type. Randazzo et al. (2023) argue that using discrete classifications of forest types to determine baselines may introduce bias in baseline and additionality estimates, especially in areas with sharp geographical and ecological gradients. This bias explained the over-crediting of several forest projects they analyzed. Badgley et al. (2022b) also demonstrate that adverse selection problems occur because many project developers preferentially select forest lands that contain species with ecologically greater carbon stocks than the regional averages or the forest-type averages. They suggest a more refined way, which reflects species composition and ecological variables, is needed to accurately estimate the baseline. Coffield et al. (2022) examined 37 IFM projects in California, using remote sensing-based datasets to compare the carbon sequestered in these projects with a similar control group of lands. Their findings raise doubts about the claimed additionality of these projects. For instance, they observed that in many projects, the carbon sequestration did not increase, and/or the harvest rates did not decrease since the project initiation.

Besides criticism for its over-crediting, the buffer pool mechanism is not sufficient to ensure permanence in practice. Badgley et al. (2022a) conducted an actuarial analysis of California's buffer pool that is designed to ensure the permanence of stored forest carbon. They show that the number of credits set aside for risks such as disease, insects, and wildfires is not enough to counter the carbon losses from these risks at all. Wildfires have depleted around 95% of California's program-wide credit contributions intended to manage all fire risks for 100 years. Haya et al. (2023) argue that California's protocol, like many others, specifies the proportions of credits to allocate to its buffer pool, but it fails to account for the growing risks of reversal. They contend that this oversight could result in an insufficient buffer pool to compensate for carbon losses caused by future natural disturbances. Moreover, they point out that the quality of credits within the buffer pool, often being low, further undermines the guarantee of permanence.

California adopts a default leakage rate to account for leakage risks, but studies indicate that actual leakage rates may be higher and vary across locations, time horizons, scales, and project types. For instance, studies (Gan and McCarl, 2007; Murray et al., 2004) demonstrate that the leakage rates from forest offset projects in the U.S. can reach up to 78%, but with a large variation depending on the project contexts. Therefore, future research is needed to give a more refined and accurate understanding of leakage risks (Haya, 2019; Haya et al., 2023).

4.4. China

4.4.1. Protocol design

China established seven subnational ETS pilots in 2013–14 (Lo, 2012). They varied in sectoral coverage, emission caps, offset ratios, and carbon prices (Li, 2018; Li and Taeihagh, 2020; Liu et al., 2015). Learning from the subnational policy experiments, China started a national ETS in 2021.

China's carbon offset protocols allow eligible projects to register and earn the Chinese Certified Emissions Reduction (CCER) credits. CCER absorbs the legacy of Certified Emission Reduction (CER) credits under Clean Development Mechanism (CDM) and China was the largest producer of CER credits (Bayer et al., 2013). Like other ETS, the CCER system facilitates ETS participants to meet their compliance liabilities in more cost-effective ways (Ye et al., 2021). Regulated entities can use CCERs to offset up to 5% of their annual verified emissions for compliance (Ministry of Ecology and Environment (MEE) of China, 2020).

Eligible forest project types under the CCER program include afforestation and IFM. Unlike other offset protocols, the CCER allows bamboo forest projects, considering that China is a major bamboo-producing country (Gu et al., 2019). It has designed specific methodologies for both bamboo and other forest projects.

4.4.1.1. Additionality. For a project to be approved and registered with NDRC, a project developer must submit a CCER Project Design Document and demonstrate the project's additionality (Lo and Cong, 2017).

4.4.1.2. MRV. CCER program requires project developers to report carbon storage and emission reductions with validation and verification from a government-accredited third-party (Lo and Cong, 2017).

4.4.2. Practices and challenges

A few studies (Lo and Cong, 2017; Xu et al., 2022) report that forestry projects accounted for a small share of CCERs. CCER has not established precautionary measures to address leakage or reversal risks, nor has it set a clear permanence period requirement. Through a Delphi survey involving 17 CCER practitioners, Wei and Xiao (2022) suggest that program administrators need to enhance CCER's design by learning from other protocols and that substantial efforts are required to manage reversal risks and improve the quality of CCERs.

4.5. RGGI

4.5.1. Protocol design

The RGGI now covers Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia (RGGI, 2023a). RGGI, Inc. operates the regional cap-and-trade system. RGGI's offset mechanism allows offset credits to be used to meet up to 3.3% of regulated entities' compliance obligations, which is less than 0.01% of the total amount of CO_2 emission allowances issued by the program since 2009 (RGGI, 2023c). It allows CO_2 offset credits from forest projects, including reforestation, IFM, avoided conversion, and afforestation (only in Connecticut) (RGGI, 2023b). The offset project must be located within one of the participating states and fall into one of the state-approved project categories.

4.5.1.1. Additionality. RGGI employs a legal requirement test and a performance test for additionality (RGGI, 2013). The legal requirement test requires projects not to be legally covered under any ordinance, law, regulation, court order, or other mandates. The performance test requires forest projects to capture carbon beyond those that would have occurred under a conservative BAU scenario.

4.5.1.2. Permanence. After the award of any offset credit to a forest project, the project must continue to monitor, verify and report project data for a 100-year period. Besides the lifelong MRV requirements, offset projects must compensate for all intentional reversals through retirements of their CO_2 allowances, and adjust the number of offset credits awarded to the project to account for the risk of unintentional reversals.

4.5.1.3. Non-leakage. RGGI requires offset projects to account for both market-shifting and activity-shifting leakages. When quantifying the net change in carbon stored in harvested wood products, a default 20% market-shifting leakage factor is applied (RGGI, 2013). As to the activity-shifting leakage, each forest project needs to consider the changes in emissions from harvesting or clearing forests outside the project area. For example, a default 3.6% conversion displacement risk value is used to account for potential activity-shifting leakage for avoided conversion projects (ibid). For reforestation projects, RGGI requires them to assess project-specific activity-shifting risk factor.

4.5.1.4. Accounting and MRV. Forest owners need to estimate the primary and secondary effects of their projects. The secondary effects include increased combustion CO_2 emissions from site preparation activities, and increased CO_2 emissions caused by activity-shifting leakages (RGGI, 2013). So, the secondary effects are mostly negative when estimating the net GHG emission reductions.

Offset projects must submit monitoring and verification reports that contain a signed verification statement and report from an independent verifier. The independent verifier should be accredited by the participating state where the project is located.

4.5.2. Practices and challenges

Although a comprehensive forest project offset protocol is available on the RGGI's website, there is no evidence of projects registered under this protocol so far. This may be attributed to its low carbon price and insufficient political support for forest carbon projects among the participating states. Shrestha et al. (2022) state that the low carbon price in the RGGI market did not incentivize forest landowners to participate in offset projects. Lamb et al. (2021) examined governmental documents to review the climate mitigation plans of states participating in RGGI. They show that only four of the 12 participating states—Pennsylvania, Maryland, Connecticut, and Massachusetts—have included forest carbon sequestration through reforestation, afforestation, or conservation in their state-level climate plans.

5. Discussion

This comparative analysis generates a comprehensive picture of forest-based offset protocols in compliance carbon markets, meeting the demand for forest-based carbon offset programs across countries (ICAP, 2022a) and recent debates about the environmental integrity of forest carbon offsets (Jones and Lewis, 2023; West et al., 2023). Forest offset protocols in compliance carbon markets are still evolving. Besides the five protocol cases in this research, other compliance markets in Kazakhstan, Québec (Canada), Saitama (Japan), and South Korea are also on the way to institutionalizing forests carbon offset protocols (ICAP, 2022a, 2022b; Kim and Daniels, 2019; Ministry of the Environment and Fight Against Climate Change, 2023). For instance, the Québec cap-and-trade system introduced the forest offset protocol for afforestation and reforestation projects in November 2022, but limited information has been found about the forest projects registered (Ministry of the Environment and Fight Against Climate Change, 2023). On the other hand, the inclusion of forest carbon offsets in compliance carbon markets continues to be challenging, as illustrated by the EU ETS' refusal to allow transactions of forest carbon offsets on the EU ETS compliance market (Merger and Pistorius, 2011; van der Gaast et al., 2018). Against this background, an investigation into the designs of existing forest carbon offset protocols can shed light on the protocols under development.

This research contributes to the landscape of the market-based climate policy literature by presenting the status, design, implementation, and challenges of forest carbon offset protocols in compliance carbon markets. It adds to and compliments the works on voluntary forest carbon offset markets (Pan et al., 2022; Lee et al., 2018). No previous studies (e.g., Arup and Zhang, 2015) on compliance carbon markets have touched forest carbon offsets. Our work fills in this research gap. In particular, New Zealand and Australia are unique in the way that they set no limitation on offsets. Furthermore, New Zealand ETS distinguishes itself from other carbon markets due to its sectoral coverage of forestry, offering symmetrical incentives to reward forest landowners for increasing carbon sequestration and holding accountable those who deforest (Carver et al., 2022). Forest carbon offset programs in New Zealand and Australia could be valuable for other compliance carbon markets.

Our findings also reveal that there is no unique protocol design for forest carbon offsets, with some protocols more stringent than others. How the offset protocols are designed can influence the feasibility of forest projects, and the associated development and operational costs, thereby affecting the marginal costs and prices of offset credits. Due to variations in protocols, the five markets showed diverse offset price levels, with New Zealand and Australia exhibiting higher offset prices (as shown in Fig. 1). In addition, New Zealand (or Australia) maintains a consistent price for both industrial carbon reduction and forest carbon offsets, with no limitations on offset use, whereas the other three cases have distinct price structures for each category, imposing quantity restrictions on offset use. The latter practice is implemented to prevent a situation when industrial facilities, faced with higher costs for direct emission reductions, become reluctant to take impactful climate actions, and excessively rely on low-quality and less expensive forest carbon offsets. Hence, regardless of the price structures of carbon markets, it is crucial to enhance the design and implementation of offset protocols to safeguard the additionality, permanence, and non-leakage of the forest offset projects, therefore delivering real climate benefits.

This research also shows that there are implementation barriers that impede forest carbon projects from actually achieving additionality, permanence, and non-leakage of credited forest carbon sequestration. First, an accurate baseline setting is more challenging in practice than in theory. Information asymmetry between the program administrator/regulator and forest landowners is a barrier against accurate baseline setting and additionality measurement. Asymmetric information can enable forest landowners who have comprehensive information about their projects to report a low baseline carbon stock. This results in these low-quality projects receiving more credits than they should, leading to adverse selection. Flawed baseline scenarios in protocols, as observed in cases of Australia and California, can exacerbate the adverse selection problems and lead to over-crediting (Badgley et al., 2022b; Macintosh et al., 2022a, 2022b; Randazzo et al., 2023).

Second, while a 100-year permanence period theoretically benefits the safeguarding of long-lasting forest carbon credits, practical implementation can be difficult. For instance, California's protocol requires a forest project to maintain credited carbon sequestration for 100 years and a reversal buffer pool is implemented to account for unintentional reversals such as wildfire and disease. Yet, in practice, natural risks such as wildfires and disease outbreaks can use up all credits reserved for these risks, and previous studies have shown that California's buffer pool is insufficient to maintain the credited forest carbon sequestration for 100 years (Badgley et al., 2022a).

Third, leakage prevention is often pursued by applying a default leakage rate in estimating additional forest carbon sequestration. This default leakage rate used by California is 20%. In the real world, the leakage rates are likely to be higher than 20%. Based on a meta-analysis of 46 studies, Pan et al. (2020) estimate that the leakage rate in the forest sector is 39.6% at the global level. Moreover, the actual leakage rate differs across projects due to variations in factors like geographic locations, time frames, scales, and types of forest activities.

While stricter protocol designs to ensure additionality, permanence, and non-leakage serve climate goals, but may increase transaction costs, such as information and search costs, compliance costs associated with MRV rules, and operational costs related to forest land management for carbon sequestration. These, in turn, are likely to diminish landowners' willingness to participate in forest carbon offset programs, consequently resulting in a shortage of supply of offset credits. Furthermore, considering the nature of the "compliance" market, governmental involvement in designing protocols introduces policy risk and uncertainty for participants in the market (Kelly and Schmitz, 2016). These factors can deter forest landowners from engaging in the market.

To handle these barriers and challenges, we propose the following policy suggestions. First, we suggest that forest carbon offset programs reevaluate and enhance their baseline setting methods to ensure the additionality of credited forest carbon sequestration. Second, forest carbon offset programs may consider carefully adjusting both the quantity and quality of credits allocated to the buffer pool to effectively address reversal risks. Third, forest carbon offset programs may need to tighten the default leakage rate and consider implementing varying leakage rates for different types of forest projects. Fourth, enhancing governance arrangements by engaging the public and independent researchers is beneficial for the integrity of forest carbon offset systems. Public engagement could be a way to mitigate information asymmetry, adverse selection, and potential risks of deforestation and leakages, by disclosing which forests are being credited and providing the public with the ability to review project baselines and audit reports detailing the project's carbon sequestration (Macintosh et al., 2022a). This level of openness ensures that decisions are well-informed and subject to public scrutiny. Finally, while introducing strict requirements to safeguard additionality, permanence, and leakage prevention, decision-makers have to balance the integrity of forest carbon offsets with the transaction costs.

Future studies could be directed to more empirical studies on the effectiveness and real climate impacts of these protocols. One area of focus could be the implementation barriers establishing accurate baselines to mitigate adverse selection and asymmetric information issues. Additionally, it would be beneficial to investigate the practical effectiveness of various tests and mechanisms to safeguard additionality. Future research could also explore how credit allocations to buffer pools can be calibrated to manage reversal risks, and how leakage rates can be appropriately applied in carbon credit calculations. Another valuable research direction could involve examining empirical data within or across programs to understand what factors drive forest landowners' participation in a forest carbon offset program.

6. Conclusion and policy implications

In this paper, we document variations in forest carbon offset protocol designs in terms of additionality, permanence, and non-leakage, and MRV in compliance carbon markets. Also, we discuss practices and challenges involved in effectively achieving these goals. The policy and practical implications of this paper are threefold. The most important implication of this research is whether to treat industrial carbon emission reduction the same as forest-based carbon offsets in the compliance market. If yes, the regulatory market will differ between carbon reduction and offsets, have no limit on the use of carbon offset credits, and only have a single carbon price, such as in the cases of New Zealand and Australia. If not, the regulatory market will limit the use of carbon offset credits and, in effect, have two carbon markets and two prices, one for carbon reduction and the other for carbon offsets. The extreme case is that forest carbon offsets are not allowed in compliance markets.

The second is that there are various ways of designing forest carbon offset protocols to assure the quality of carbon offsets. For policymakers to better learn from the experiences of other regulatory carbon markets, it would be beneficial to document the transaction costs involved in generating and receiving carbon credits within these five markets. The third is that there are many testable hypotheses that could be generated from all protocols reviewed in this study, the most important being the real impact of implementing these protocols on climate change mitigation. Other study topics include the changing risk-return profile of forest investment in New Zealand because of the front-load nature of its carbon payments, and the logic of a 20% discount between the 25- and 100-year contract in Australia.

It is well known that setting an overall cap in a cap-and-trade system is critical in ensuring that the system works. Yet, no country has set their Nationally Determined Contributions as legally binding. As such, it is possible that New Zealand and Australia periodically adjust their caps.

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CRediT authorship contribution statement

Lili Li: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Daowei Zhang:** Conceptualization, Funding acquisition, Project administration, Resources, Software, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the data source of Figure 1 in the Figures.docx file.

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