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Review

The status of forest carbon markets in Latin America

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ABSTRACT

Tropical rainforests of Latin America (LATAM) are one of the world's largest carbon sinks, with substantial future carbon sequestration potential and contributing a major proportion of the global supply of forest carbon credits. LATAM is poised to contribute predominantly towards high-quality forest carbon offset projects designed to reduce emissions from deforestation and forest degradation, halt biodiversity loss, and provide equitable conservation benefits to people. Thus, carbon markets, including compliance carbon markets and voluntary carbon markets continue to expand in LATAM. However, the extent of the growth and status of forest carbon markets, pricing initiatives, stakeholders, amongst others, are yet to be explored and extensively reviewed for the entire LATAM region. Against this backdrop, we reviewed a total of 299 articles, including peer-reviewed and non-scientific gray literature sources, from January 2010 to March 2023. Herein, based on the extensive literature review, we present the results and provide perspectives classified into five categories: (i) the status and recent trends of forest carbon markets (ii) the interested parties and their role in the forest carbon markets, (iii) the measurement, reporting and verification (MRV) approaches and role of remote sensing, (iv) the challenges, and (v) the benefits, opportunities, future directions and recommendations to enhance forest carbon markets in LATAM. Despite the substantial challenges, better governance structures for forest carbon markets can increase

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the number, quality and integrity of projects and support the carbon sequestration capacity of the rainforests of LATAM. Due to the complex and extensive nature of forest carbon projects in LATAM, emerging technologies like remote sensing can enable scale and reduce technical barriers to MRV, if properly benchmarked. The future directions and recommendations provided are intended to improve upon the existing infrastructure and governance mechanisms, and encourage further participation from the public and private sectors in forest carbon markets in LATAM.

1. Introduction

The Glasgow leaders' declaration on forests and land use has been endorsed by 144 countries to date, covering 91% of the world's forests, with a commitment to halt and reverse deforestation and land degradation by 2030 (Messetchkova, 2021). This declaration intends to accelerate action on goals within the Paris Climate Agreement, which aims to substantially reduce the severity of climate change by limiting global average temperature increases to 1.5 °C above pre-industrial levels (Hoegh-Guldberg et al., 2018). Yet, deforestation and forest degradation continue to take place at alarming rates, and 11 million hectares (ha) of tree cover were lost in the tropics in 2021, resulting in 6.3 Gt of carbon dioxide (CO_2) emissions (World Resources Institute, 2022). Agricultural expansion-driven deforestation and forest degradation remains relatively high for South America with 2.60 million hectares of forest area lost per year from 2010 to 2020, significantly increasing biodiversity loss and CO_2 emissions (FAO and UNEP, 2020). In addition to releasing large quantities of greenhouse gasses (GHG), tropical deforestation threatens the rights, culture, and livelihood of indigenous peoples and local communities (IPLC) (Ometto et al., 2022).

Forest landscape restoration involving afforestation, reforestation, agroforestry, and natural regeneration is promoted as a cost-effective nature-based solution to climate change mitigation, due to its potential for increased carbon sequestration and storage (Mohan et al., 2021a). Evidence suggests that the world is not on track to meet the target of the United Nations strategic plan for forests to increase forest cover by 3% worldwide by 2030 through various forest restoration and protection approaches (FAO and UNEP, 2020). Through legally binding international treaties such as the Paris Climate Agreement, countries are encouraged to take concerted and immediate action in delivering what they have pledged through Nationally Determined Contributions (NDCs), which include reductions in deforestation and forest degradation-related emissions (Lucatello and Flores, 2022). The growing establishment of carbon markets is an innovative market-based climate change mitigation approach, which is expected to mobilize finances at a greater scale and incentivize forest protection, restoration, improved climate-smart management, and climate-resilient development, especially in the global south (Keohane and Seymour, 2021).

Carbon markets or carbon pricing instruments (CPIs) consist of two market types, namely, the compliance and voluntary carbon markets. Compliance carbon markets (CCM) such as emissions trading systems (ETS) and carbon taxes are regulated by mandatory national, regional, or international carbon reduction regimes while voluntary carbon markets (VCM) enable private investors, organizations, governments, and businesses to purchase carbon offsets on a voluntary basis without much regulation (Streck, 2020; Sullivan et al., 2021; Andersen et al., 2022). Businesses can play a crucial role in climate mitigation by first setting science-based net-zero targets, defining a mitigation hierarchy, and then engaging in the VCM for "beyond value chain mitigation" (Science-Based Targets Initiative (SBTi), 2021). Thus, CCM and VCM are important complementary mechanisms for global climate action (Sousa et al., 2020; Sullivan et al., 2021; Pullins, 2022).

The tropical rainforests of LATAM are one of the largest carbon sinks, with a substantial carbon sequestration and storage potential of 121.03 Gt C (Saatchi et al., 2011). The Amazon forest region alone contains 31.5 Gt of carbon stock that once lost through deforestation and forest degradation, cannot be recovered by 2050, the time frame that global emissions must reach net-zero to achieve climate goals to avoid the most negative effects of climate change (Noon et al., 2022). Thus, the forests of LATAM are of global importance and have a high potential for carbon market projects. In general, forest carbon markets generate offsets mainly through three types of forest management activities: afforestation/reforestation (A/R), avoided conversion, and improved forest management (Yankel, 2018). The LATAM region is the second largest supplier of voluntary credits in the world, and carbon markets in the region are dominated by REDD+ (Reducing emissions from deforestation and forest degradation, and conservation, sustainable forest management and enhancement of carbon stocks) projects, followed by renewable energy, restoration of native forests, energy efficiency, and fuel switch projects, respectively.

Forest degradation is land degradation that occurs in forest land, defined as a "negative trend in land condition, caused by direct or indirect human-induced processes including anthropogenic climate change, expressed as long-term reduction or loss of biological productivity, ecological integrity or value to humans" (Olsson et al., 2019). In particular, anthropogenic climate change-driven wildfire is a major driver of land degradation across vegetation types (Shabbir et al., 2020, 2023). Throughout this manuscript "degraded forests" refers to forests that have lost carbon or some other intrinsic value but remain a forest, whereas "secondary forest" refers to forests that are developing after a forest was totally cleared, usually for agriculture or cattle farming. Planted trees (especially with non-native species), fiber farms, and biomass plantations are recognized as "plantations."

CCMs are essential parts of policy frameworks and low-carbon emission pathways, where polluting industries are held responsible for the environmental cost of their emissions, and are incentivized to adopt low-emissions technologies and shift away from fossil fuel use (International Energy Agency, 2021; Sullivan et al., 2021). However, CCMs such as the ETS that aggregates all sectors, are complex, expensive, fragile, and technically difficult to implement (Oliveira et al., 2019; Sullivan et al., 2021; Andersen et al., 2022). Securing financing to start the process of allocating emissions, financing bonds, and other design issues on implementation and technical cooperation to follow up on eligible projects for ETS is challenging (Lucatello and Flores, 2022). LATAM countries such as Mexico, Chile, Colombia, Argentina and Brazil are frontrunners in the CCMs and have many established national and sub-national carbon taxes in various jurisdictions (Sullivan et al., 2021; ICAP, 2023; World Bank, 2023a). The ETS, though widely adopted and mandated, is mostly still under consideration, under development and/or in pilot phases in these countries (Stevens, 2021; Sullivan et al., 2021; ICAP, 2023; World Bank, 2023a).

In contrast, Brazil and Peru have no set date for compliance CPIs to be implemented but have the largest carbon credit supply in the VCM in LATAM, with 16 and 14 million carbon credits issued in 2021, respectively (Sullivan et al., 2021). Credits are mainly generated through REDD + projects, and together with Colombia, they are the largest VCM credit suppliers, representing more than 80% (71 $MtCO_2e$) of the region's carbon credits retired in the VCM till 2021 (Sullivan et al., 2021). Overall, carbon market initiatives are expanding in the LATAM region due to adoption at national and subnational levels, and government incentives promoting investment in low-carbon technologies and existing renewable energy infrastructure (Oliveira et al., 2019; Sullivan et al., 2021; Pullins, 2022).

The implementation of forest carbon projects requires extensive capacity building from sectoral participants and extensive reviews and revisions to support adaptive management (Sullivan et al., 2021). IPLCs are disproportionately vulnerable to inequitable benefit sharing in carbon projects, which is mainly attributable to poor recognition of their land tenure rights, particularly in the global south (Streck, 2020; Guido, 2022). Concerns around the inequitable participation of IPLCs and the lack of access of these groups to carbon markets highlight the risks involved in carbon markets and REDD + initiatives in achieving desired environmental, social, and economic goals (McAfee, 2016). Furthermore, there is a lack of transparency and credibility throughout the process. Key issues to the expansion of the forest carbon markets in LATAM include variations in measurement, reporting, and verification (MRV) regulations between countries, attempts at corporate greenwashing and concerns about the quality and integrity of carbon credits.

Despite the potential of the LATAM region for developing carbon markets with high quality and integrity, there exist very few reviews that have summarized the state of these markets in this region in peer-reviewed literature: Grieg-Gran et al. (2005) and Louman et al. (2011) previously explored preliminary results and the development of carbon markets in LATAM. Thus, the main aim of this review paper was to build upon these previous studies, investigate the growth and status of the forest carbon markets in LATAM, and provide a benchmark resource. Specific aims of the review were to examine: 1) the status and recent trends of forest carbon markets, 2) the interested parties and their roles in forest carbon markets, 3) the MRV approaches and role of remote sensing, 4) the challenges and 5) the benefits and opportunities during the adoption, design and implementation of various forest carbon market types in different jurisdictions in the LATAM region. We propose future directions and recommendations to improve the quality and integrity of forest carbon markets to encourage more participation from public and private sectors.

2. Methods

We reviewed peer-reviewed scientific articles as well as non-peer-reviewed gray literature, including technical reports, conference papers, and blogs related to forest carbon markets in LATAM. “Forest carbon markets” encompass tropical rainforests, seasonally dry forests, and other forest biomes in LATAM. The review focused specifically on results from January 2010 to March 2023. Existing literature were explored using the Google and Google Scholar search engines and Scopus and Web of Science databases based on keyword combinations in the search expression presented in Table 1.

In the Google and Google Scholar search engines, we examined the first ten pages of 100 results per page giving a total of 1000 articles, because no relevant article is usually retrieved after an initial screening of the next 500 articles (Ewane et al., 2023a). Relevant articles were further verified by the following keywords: “carbon markets,” “REDD,” “REDD+,” “carbon credits,” “carbon trading,” “carbon offset,” “forest carbon,” “forest carbon offset program,” and “offset credits,” which returned the initial pool of results from each database, as reflected in Fig. 2. Articles were determined to be relevant by first reading the abstract and methods section and later verified by reading the entire paper using the eligibility criteria for exclusion or inclusion presented in Table 1.

Table 1
Search expressions used in the literature review for querying the search engines and databases.

Criteria	Search Expression
What	“Carbon Markets” OR “REDD” OR “REDD+” OR “Carbon Credits” OR “Carbon Trading” OR “Carbon Offset” OR “Forest Carbon” OR “Forest Carbon Offset Program” OR “Offset Credits”
AND	“Latin America” OR “Argentina” OR “Bolivia” OR “Brazil” OR “Chile” OR “Colombia” OR “Costa Rica” OR “Cuba” OR “Dominican Republic” OR “Ecuador” OR “El Salvador” OR “Guatemala” OR “Haiti” OR “Honduras” OR “Mexico” OR “Nicaragua” OR “Panama” OR Paraguay” OR “Peru” OR “Uruguay” OR “Venezuela”
When	January 1, 2010 to March 31, 2023

The primary selection included 358 articles, of which 144 were removed after filtering for duplicates. The remaining 214 articles were assessed for eligibility and seven non-English articles were excluded for the systematic review data analysis (Ewane et al., 2023a). In addition, we excluded 23 articles from the 214 articles that focused on other types of carbon projects, such as renewable energy, community projects, and blue carbon projects involving seagrass and tidal marshes. While English is generally accepted as the international language of science and research, we acknowledge that most LATAM countries communicate in non-English languages, which can be the focus of future studies. Following this manual screening, we conducted a code-based literature search using Python to confirm these results, utilizing the same keywords on Google Scholar. The code-based search returned 283 articles, of which 253 were removed as duplicates or as sources that did not focus on forest carbon markets, resulting in an additional 30 articles. Finally, 120 articles were added throughout the writing process from supplementary searches through the citations, references and complementary studies network. This resulted in of 334 references (including results from the initial manual review and Python-based search), out of which 35 were excluded because they were published before January 2010 or after March 2023. The final list included 299 articles, out of which 177 were peer-reviewed and 122 were gray articles (Fig. 1).

Out of the countries surveyed in LATAM, Brazil returned the greatest number of results, followed by Colombia, Peru, and Mexico (Fig. 2). We observed an increase in the total results of perceived published articles from 2018 to 2021, and sharp increase in gray literature in 2021 and 2022, which were the only years that returned more gray literature than peer-reviewed literature (Fig. 3).

3. Extent of forest carbon markets in LATAM

3.1. Existing forest carbon markets and pricing initiatives

Forest carbon markets are being increasingly adopted at both national and subnational levels in some countries of LATAM, exemplified in Fig. 4, to meet their NDCs and other environmental, social, and economic goals in general (Pullins, 2022; Sullivan et al., 2021). A detailed comparison of the various modes of forest carbon markets for all the studied LATAM countries is presented in Table 2. The LATAM region holds the second largest collection of subnational jurisdictions that have net-zero commitments in the world, with 209 cities across five regions (Pullins, 2022; Sullivan et al., 2021). Since 2021, the region has implemented four federal carbon taxes, three subnational carbon taxes and one national ETS (BNAmericas, 2021). Mandatory ETSs tend to be colossal in market size and value when compared to their voluntary counterparts. Globally, mandated carbon markets were valued at US$ 800bn in 2020 (Nordeng, 2022), whereas the combined worth of VCM was US$ 1bn in 2021 (Ecosystem Marketplace, 2021).

The growth of CPIs in the LATAM region is substantial but intermittent, and implementation varies by country (Table 2) - Mexico, Colombia, Chile, and Argentina are at the forefront of implementation of carbon taxes, while it is under consideration and in the early stages of the process in Brazil and Peru (Sullivan et al., 2021; World Bank, 2023a, b). Mexico is the first country to have an ETS in operation in LATAM and the only country that has implemented both the carbon taxes and the ETS of the compliance carbon market (CCM) by 2023. Chile, Columbia, and Argentina have implemented carbon taxes and/or are considering ETS. Brazil and Peru are exploring options and considering the implementation of both carbon taxes and ETS of the CCM, with some government planning phase underway. All the other LATAM countries included in this study have not yet considered carbon taxes or ETS implementation (Table 2). Carbon pricing initiatives are considered “scheduled for implementation” once “they have been formally adopted

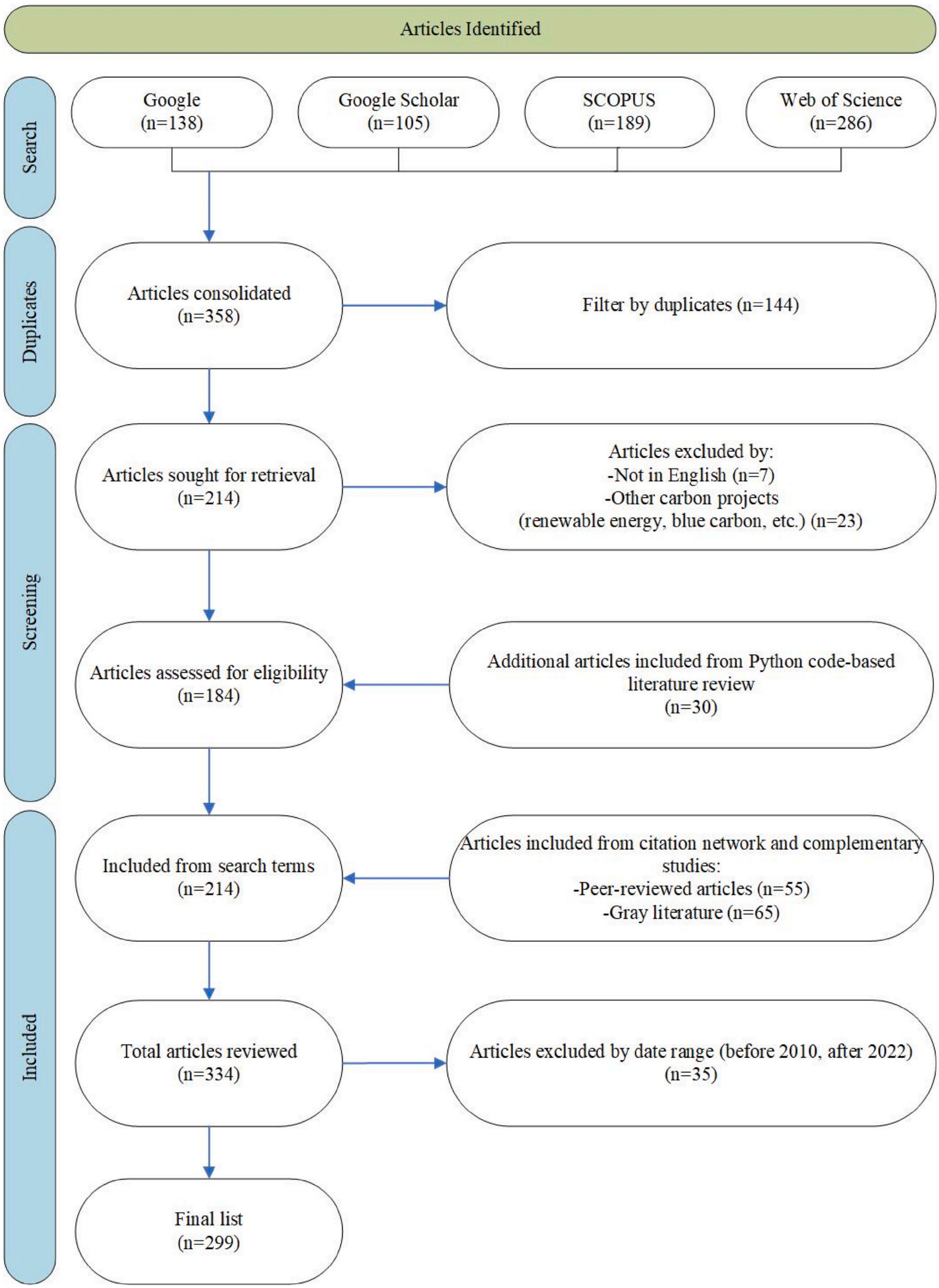

Fig. 1. Workflow representing the systematic literature review process from January 2010 to March 2023.

through legislation and have an official, planned start date". Carbon pricing initiatives are categorized as "under consideration" if "the government has announced its intention to work towards the implementation of a carbon pricing initiative and this has been formally confirmed by official government sources" (World Bank, 2023a). The data for the carbon taxes and the ETS of the compliance carbon market (CCM) and voluntary carbon market in Table 2 has been mainly compiled from Sullivan et al. (2021), World Bank (2023a), and International Carbon Action Partnership - ICAP (2023).

The VCM has been more extensively adopted and implemented by all

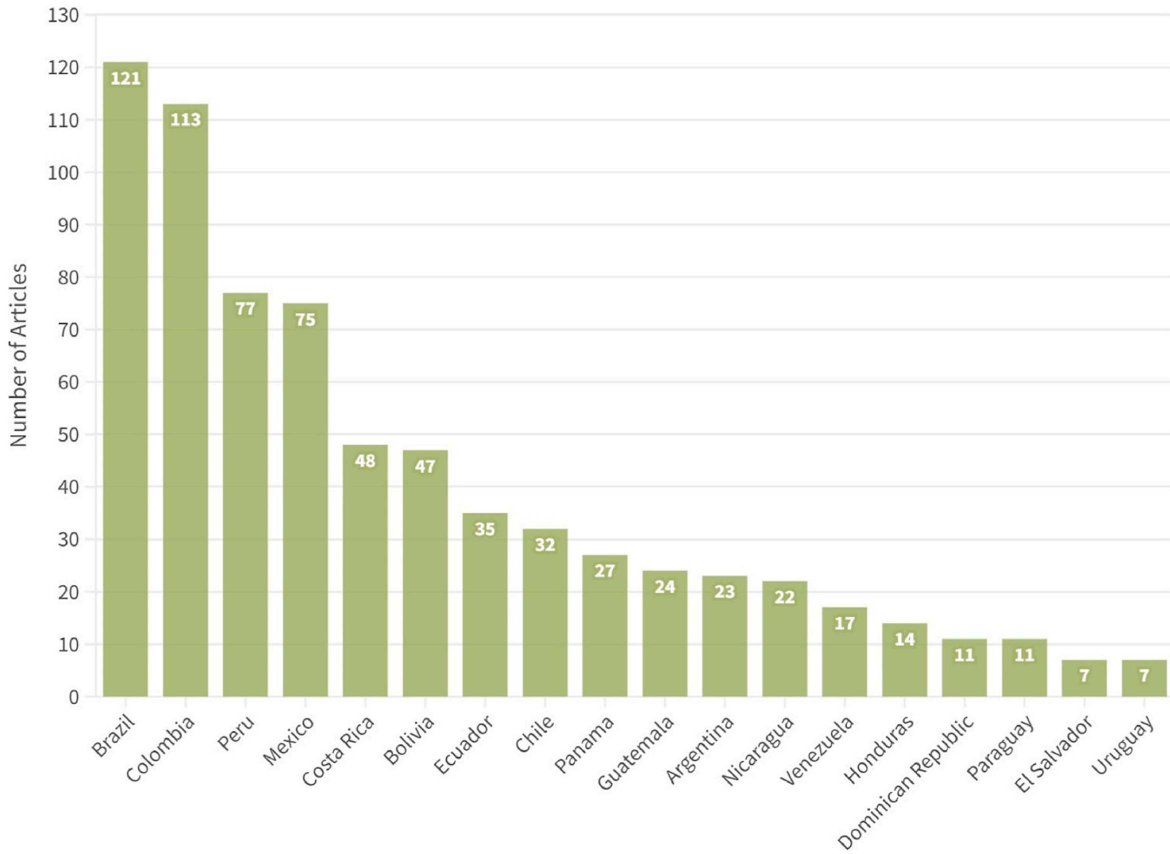

Fig. 2. Number of publications for the various LATAM countries over time (January 2010 to March 2023). Some global and regional studies include multiple countries within LATAM, increasing the number of article counts per country mentioned, especially for Brazil, Colombia, Peru and Mexico.

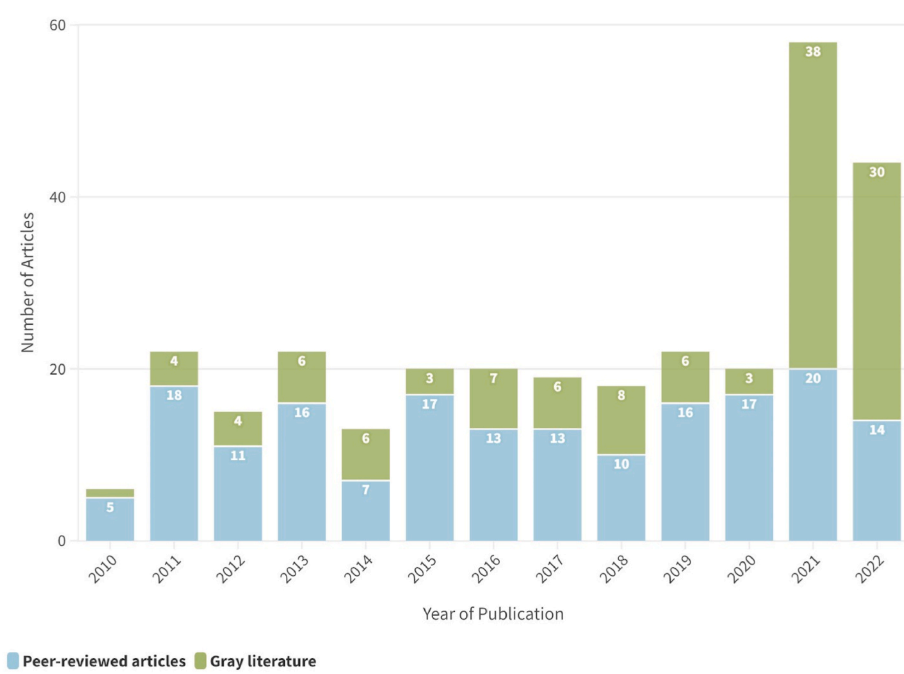

Fig. 3. Number of gray literature and peer-reviewed articles by year of publication (January 2010 to March 2023).

the LATAM countries through various REDD + projects and national carbon exchange programs (Table 2). Suriname, Guyana, and Belize have also contributed substantially to the growth of forest carbon markets in the LATAM region, though these are predominantly English-speaking countries and thus do not fall under traditional definitions of LATAM. REDD + projects in Belize kicked off the creation of multilateral development funds such as the Forest Carbon Partnership Facility, among others (Sullivan et al., 2021). Suriname has achieved net zero

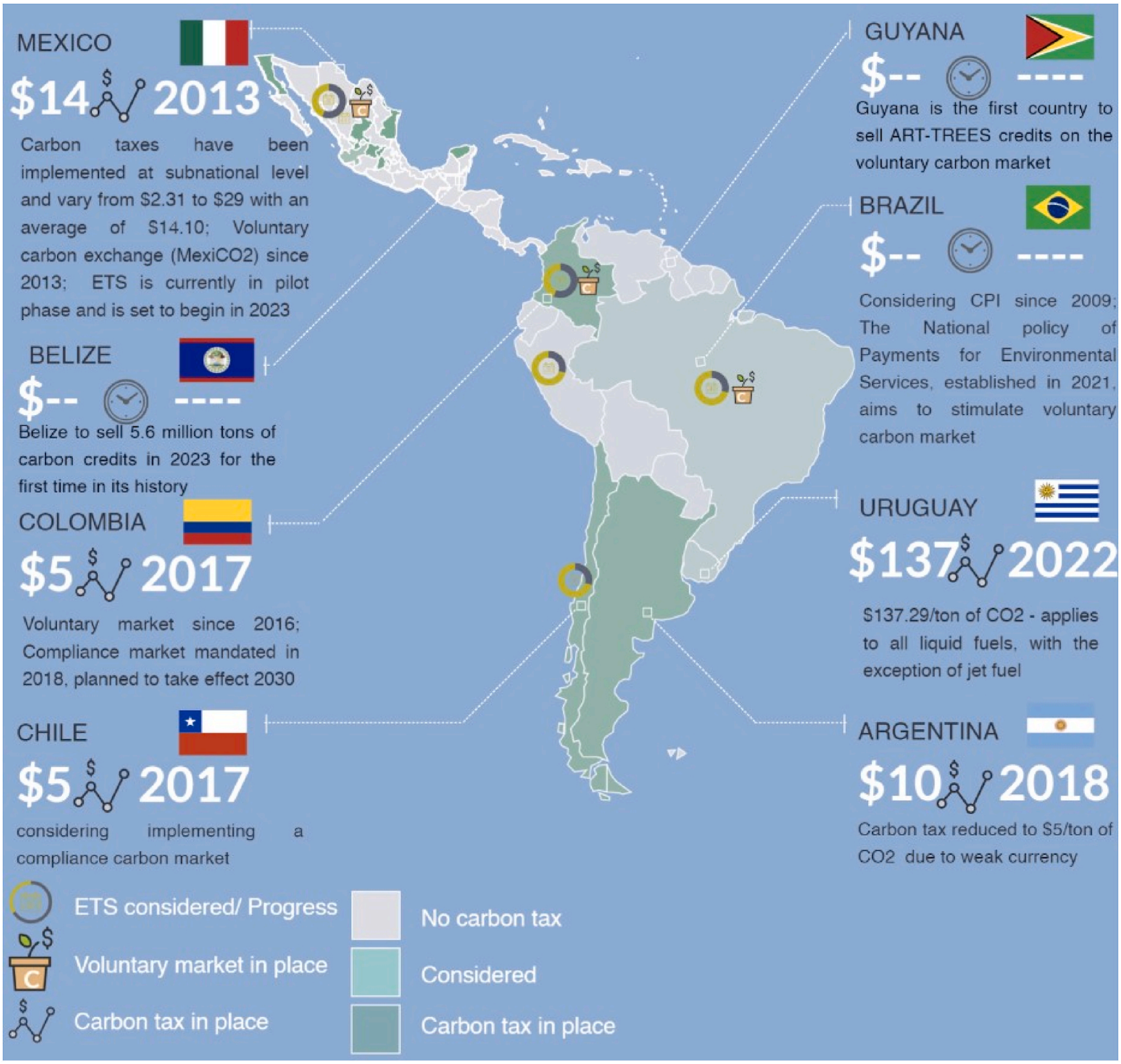

Fig. 4. Graphical illustration summarizing the top countries implementing carbon market and pricing initiatives in Latin America.

carbon emission in terms of deforestation-driven carbon emissions (BNAmericas, 2021). Guyana has implemented a jurisdictional forest carbon credit program on a national scale, which enables the high forest cover and low deforestation (HFLD) country to fund low-carbon development priorities. The program encompasses all 18 million ha of forest in the country - approximately 85% of Guyana's territory - and REDD + carbon credits are generated and verified through Architecture for REDD + Transactions (ART) - The REDD Environmental Excellence Standard (TREES). Between 2016 and 2020, Guyana was issued 33.47 million ART-TREES credits for results achieved (Natural Climate Solutions Alliance, 2023).

The LATAM countries receive the support of several initiatives and platforms in planning, designing, and implementing CPIs, such as Carbon Pricing Leadership Coalition, Pacific Alliance, Carbon Pricing in the Americas, and the Latin American and Caribbean Carbon Forum (Sullivan et al., 2021). The World Bank's Partnership for Market Readiness (PMR) is another regional initiative, which expedited the implementation of CPIs in Colombia, Brazil, Chile, and Mexico (PMR, 2019). PMR explored options for various types of carbon systems to determine suitable CPIs and to build MRV facilities in Brazil (PMR, 2019). In 2009, the National Climate Change Policy conceptualized the Brazilian Market for Emission Reductions (UNFCCC, 2022). The Ministry of the Environment established the Forest + Carbon Program in 2020 (Biofilica Ambipar Environment, 2020), and the National Payment Policy for Environmental Services in 2021 (Amaral et al., 2021). Chile introduced a tax on carbon emissions in 2017 and signed an agreement with the Forest Carbon Partnership Facility (FCPF) unlocking US$ 26 million to increase sequestration and reduce emissions (World Bank, 2019).

Colombia developed the Low Carbon Development Strategy, including a domestic offset system, carbon tax and market-based programs, such as the Mechanism for Voluntary Greenhouse Gases Emissions (Alarcon-Diaz and Lubowski, 2018). In 2013, Mexico established a carbon tax (Averchenkova and Guzman Luna, 2018) and complementarily launched MexiCO2, a voluntary ETS (MexiCO2, 2016). The Secretariat of Environment and Natural Resources (SEMARNAT) set a mandatory ETS for 2023 (International Carbon Action Partnership - ICAP, 2018; 2023), which affects small-scale forest owners (REDD + Costa Rica, 2013). Seven ground rules were agreed upon at the 2010 United Nations climate summit to safeguard these communities and biodiversity (UN-REDD Programme, 2022). In Chile, the Emission Reduction Payment Agreement (ERPA) mandates social safeguards via its National Strategy for Climate Change and Vegetation Resources (World Bank, 2019).

Table 2
Comparison of various modes of forest carbon markets for all the studied Latin American countries.

Country	Compliance carbon market		Voluntary carbon market (Government-enabled and supported)
	Carbon tax	Emission trading systems	
Mexico	Implemented since 2013	Implemented or in force (Operational phase started in 2022)	Mexico Carbon Exchange Platform (MexiCO2) established since 2013
Colombia	Implemented since 2017	Under Development (Climate Action Law in 2021 with a goal to fully implement ETS by 2030)	Colombian Voluntary Carbon Market Platform in 2016. Carbon neutrality voluntary program (tax reduction incentives based on "levels of effort" to reduce emissions) - $5/ton of CO_2e
Chile	Implemented since 2017	Under Development (Pilot ETS for the energy sector from 2022 to 2026)	AFOLU projects mainly (32 % of all VCM in 2021). Emission Reduction Payment Agreement (ERPA) - $5/ton of CO_2e
Argentina	Implemented since 2018	Not under consideration	12 projects have been registered linked to renewable energies and forestry offsets ($10/ton of CO_2e - now $5 due to weak currency)
Brazil	Under consideration	Under consideration	REDD+ is the main project type (16 million carbon credits in the VCM H1 2021 alone). Forest+ (2020) and National Payment Policy for Environmental Services (2021) established
Peru	Not under consideration	Not under consideration	REDD + projects (42.5 million for the Cordillera Azul National Park, The Madre de Dios Amazon and Alto Mayo projects). National Registry of Mitigation Actions (RENAMI) to open registration for initiatives to participate in carbon markets
Costa Rica	Not under consideration	Not under consideration	REDD + payments exist; intends to establish a Domestic Carbon Market to meet neutrality objectives
Belize	Not under consideration	Not under consideration	5.6 million tons of carbon credits sold in 2023 in REDD + projects for the first time
Guyana	Not under consideration	Not under consideration	33.47 million tons of carbon credits sold in the ART-TREES program from 2016 to 2020. Jurisdictional forest carbon credit program
Uruguay	Not under consideration	Not under consideration	National carbon market (carbon tax on emissions created from gasoline combustion set at $135/ton CO_2e) - applies to all liquid fuels, with the exception of jet fuel
Suriname	Not under consideration	Not under consideration	REDD + projects (4.8 million $MtCO_2$e credits sold in 2021 (about $50 million worth of carbon credits)
Bolivia	Not under consideration	Not under consideration	No VCM program under REDD+ (Reluctant to engage in REDD + mechanisms, they prefer "non-market measures")
Cuba	Not under consideration	Not under consideration	No REDD + program (Reluctant to engage in REDD + mechanisms, they prefer "non-market measures"). Demonstrated interest in selling carbon credits on potential international market
Dominican Republic	Not under consideration	Not under consideration	REDD + Emission Reductions Payment Agreement program to reduce 5 million tons of forest-related carbon emissions in 2021
Ecuador	Not under consideration	Not under consideration	Voluntary carbon zero program (tax reduction incentives based on "levels of effort" to reduce emissions)
El Salvador	Not under consideration	Not under consideration	REDD + projects under the Emissions Reduction Payment Agreement Program
Guatemala	Not under consideration	Not under consideration	REDD + projects under the Emissions Reduction Payment Agreement Program
Haiti	Not under consideration	Not under consideration	Carbon savings initiative exist under the Brazil Amazon REDD + project
Honduras	Not under consideration	Not under consideration	REDD + mechanism supported by the InfoCarbonoHonduras 2022 initiative. A national moratorium on the sale of forest carbon credits was imposed by the government
Nicaragua	Not under consideration	Not under consideration	REDD + projects under the Emissions Reduction Payment Agreement Program
Panama	Not under consideration	Not under consideration	National carbon market program called "reduce your carbon footprint", with around 71 companies are registered. Exploring implementation of Panamanian Carbon Exchange Platform
Paraguay	Not under consideration	Not under consideration	First national regulation regulating the voluntary carbon market approved in 2023
Venezuela	Not under consideration	Not under consideration	No program under REDD+ (Reluctant to engage in REDD + mechanisms, they prefer "non-market measures")

3.2. *Compliance versus voluntary carbon markets*

Compliance Carbon Markets, also called cap-and-trade programs, represent a mechanism for eliminating carbon emissions, and mitigating their impacts (Ferguson et al., 2021). Colombia, Chile, and Mexico are leading in the adoption of carbon markets, their instruments, and regulations for implementing carbon taxes (Pullins, 2022). In 2016, the World Bank report stated that solid cooperation between LATAM regions through carbon trading could reduce 32% of the global climate change impacts by 2030. Thus, in 2017, the Declaration on Carbon Pricing in the Americas was created, which stimulated cooperation and commitment among regions to periodically discuss the status, design, and implementation of new CPIs. Countries such as Brazil, Mexico, Colombia, and Chile are already exploring and/or are building their national cap-and-trade programs (Sullivan et al., 2021, ICAP, 2023). Brazil's national climate change policies have evolved over the last decade after the National Climate Change Policy was adopted in 2009. Since then, the country has established frameworks for voluntary and compliance carbon markets through the Forest + Carbon program and the National Payment Policy for Environmental Services (Ribeiro, 2022).

Consequently, there has been substantial growth in national carbon compliance programs and in their regulatory jurisdictions over the last four years, fostering more elevated CPI and its potential impact on the Brazilian economy. Simultaneously, in 2018, Mexico established its regulation of carbon markets, formally initiating the pilot phase of carbon compliance instruments and reaffirming its commitment to the Paris Agreement and Kyoto Protocol. Colombia has also launched effective compliance pilot systems for a better green path by 2023 (Sullivan et al., 2021). In Chile, the legislative debate around Climate Change and CCM continues. Chile's nationally determined contribution (NDC) committed the country to reduce greenhouse gas emissions by 30% from 2007 levels by 2030; in 2020, the country updated this NDC to reduce annual emissions to 95 MtCO2e by 2030, a 27.5% reduction from the previous NDC (Leprince-Ringuet, 2020).

Complementing the CCM, the VCM Voluntary Carbon Market allows players such as private investors, governments, non-governmental organizations, and companies to purchase carbon credits to offset their emissions. The VCM such as the Verified Carbon Standard (VCS) Program is the most widely used GHG crediting program in the world where carbon credit buyers and sellers get registered and the projects and their activities are publicly available on the Verra Registry. The VCS provides finance toward activities that reduce and remove GHG emissions, improve livelihoods and protect nature (Verra, 2022). This market is still relatively nascent and small compared to the CCM, and its value is equivalent to US$ 300 million, which is a fraction of the regulatory market size (Ecosystem Marketplace, 2021). LATAM has the potential of becoming the global leader in supplying carbon credits in VCM. According to the Development Bank of LATAM (CAF), LATAM and the Caribbean represent 40% of the potential global VCM share on the supply-side. Countries such as Argentina, Brazil, Chile, Colombia, Costa Rica, Peru, and Mexico have received assistance to promote this market (Sullivan et al., 2021). Benefit-sharing mechanisms and feedback and grievance mechanisms (FGRMs) for carbon projects remain scant among LATAM countries; Chile, Costa Rica, and Mexico have designed both of these systems, although none of these countries have operationalized benefit-sharing. Only Costa Rica has clearly defined carbon rights in addition to a national benefit-sharing system (Rights and Resources Initiative, 2018).

The VCM has four primary certification standards, each of which has a specific focus and distinguishes indications and limitations. These four carbon market standards, along with the total carbon credits issued in LATAM from 2010 to 2021, include the 1) Verra Verified Carbon Standard (VCS) (151.7 $MtCO_2e$), the 2) Gold Standard (16.7 $MtCO_2e$), 3) American Carbon Registry (ACR) (4.6 $MtCO_2e$) and the 4) Climate Action Reserve (CAR) (0.3 $MtCO_2e$) (Pullins, 2022). REDD + credits certified by Verra represent over 70% of all credits retired (the key indicator of demand in the VCM) in the region in 2020–2021 (Ecosystem Marketplace, 2021).

3.3. Applications of carbon taxes

Carbon taxes, according to many economists, are the most effective and economical strategy to avert climate change (Calderón et al., 2016; Diniz Oliveira et al., 2021; Sullivan et al., 2021). Properly implemented environmental taxes and spending can support several macroeconomic outcomes, including greater employment, economic diversification, and improved domestic industry competitiveness. Carbon taxes impose a cost on GHG emissions, which incentivizes businesses to invest in transitions to cleaner energy sources, or improve energy efficiency, and propels further technological advancement (Calderón et al., 2016). Introducing carbon taxes, abolishing subsidies for fossil fuels, and accelerating initiatives for green infrastructure and renewable energy developments can improve nations' capacity to achieve their NDCs and net-zero targets.

For example, Colombia enacted a tax in 2017 to encourage a low-carbon growth path and uses the proceeds to pay for investments in technical innovation, adaptation, and low-carbon initiatives (Sullivan et al., 2021; ICAP, 2023; World Bank, 2023a). The tax reforms brought nearly US$ 250 million in its first year, where 30% of the proceeds were used to establish a national environmental fund for protecting coastal areas, preventing deforestation, monitoring forested areas, and preserving water sources and other strategic ecosystems. In Costa Rica, a special tax on the sale of fossil fuels serves as the primary funding source for the Forestry Environmental Services Program (FESP). More than a third of tax income, or 5% of gasoline sales, is set aside for investments in reforestation, sustainable forest management, and forest preservation. It is important to note that revenues from carbon taxes are not used exclusively to offset emissions or for purposes of climate change mitigation. In Argentina, for example, tax income from fossil fuels is directed toward social and infrastructure development, including transport infrastructure investments, support for the national housing fund, and the social security system (Sullivan et al., 2021). Unlike Colombia, Costa Rica, and Argentina, revenues raised by the carbon taxes are not earmarked in Chile yet, but tax reforms approved directing tax incomes for education and health initiatives (Sullivan et al., 2021).

3.4. Offsets from afforestation and reforestation

There is compelling evidence that the world is not on track to meet the target of 3% increase in forest area worldwide by 2030 as set by the United Nations strategic plan for forests through the various forest restoration approaches (FAO and UNEP, 2020). Droughts, forest fires, and other disturbance events are becoming more frequent across LATAM in addition to high rates of deforestation, particularly in Amazonia, which further degrades these key forest ecosystems and their ability to sequester carbon (Cardil et al., 2020; Lefebvre et al., 2021). Therefore, it is important to identify conservation needs and prioritize restoration action. A value-focused approach to restoration goal setting could help conservation teams clearly define what they aim to improve through its strategies, and develop a set of actionable objectives (Martin, 2017). These include increased resilience, reduced threat of natural disasters, opportunities for local communities, and a substantial contribution to climate change mitigation (Mohan et al., 2021b).

To meet the ambitious restoration goals in A/R projects as a nature-based solution, the entire pipeline of activities including seed gathering, nursery care, outplanting, direct seeding, and post-planting activities needs to be scaled up (Fargione et al., 2021; Mohan et al., 2021b). Investing in assisted natural regeneration techniques to remove or reduce barriers to regeneration and promote natural regeneration could be more cost-effective and successful than A/R in many places (Shono, 2007). As carbon markets in LATAM mature, investments in A/R projects in the form of advance purchases to meet future net zero targets is key to ensuring that forest cover, biodiversity gains, and carbon stocks are permanent. However, in some ecosystems maximizing carbon storage is incompatible with habitat restoration needs for certain species. As an example, attempts of A/R in natural savannas and grasslands could lead to a loss in biodiversity and ecological function. Thus, it is important to evaluate carbon and wildlife trade-offs, and apply a climate adaptation lens to restoration planning (Littlefield & D'Amato, 2022). This further implies that forest restoration needs to explicitly consider future environmental conditions rather than being informed by past conditions only.

3.5. Overview of forest carbon fluxes in Latin America countries

The estimated forest carbon fluxes and the total carbon storage by country from 2001 to 2022, which was sourced from the Global Forest Watch database (country dashboard) (Global Forest Watch, 2023) is shown in Table 3. The forest carbon fluxes are sorted in a descending order by country in terms of net removals. The forest of Chile had the highest net carbon removals (−236 $MtCO_2e$/year) from 2001 to 2022. This was followed by Brazil (−149 $MtCO_2e$/year), Mexico (−143 $MtCO_2e$/year), Venezuela (−115 $MtCO_2e$/year), Argentina (−112 $MtCO_2e$/year), and Colombia (−110 $MtCO_2e$/year) from 2001 to 2022. These countries are also at the upper end of deforestation-driven emission of CO_2 and other greenhouse gases, and conversely, conservation, afforestation and reforestation-driven CO_2 removals in $MtCO_2e$/year. The forest of Brazil removes and emits the highest amount of carbon per year, driven by shifting cultivation, urbanization, logging, commodity export and wildfire, similar to deforestation-driven emissions in all the LATAM countries. The amount of CO_2 emissions and removals in $MtCO_2e$/year is closely associated with the forest area of each country. Deforestation-driven emissions in Belize, Nicaragua and Guatemala surpass removals by their forest, by, respectively, 1.22, 9.88 and 3.98 $MtCO_2e$/year". Overall, the forests of most countries in the LATAM are net carbon sinks over this period. The total forest carbon storage per country included carbon that is stored in the above ground biomass (AGB), below ground biomass (BGB) and soil in 2022.

4. Interested parties and their role

4.1. Role of international organizations

LATAM has received assistance from several international organizations in the development of carbon markets in the region, in the form of financial support, technical knowledge, and networking (Duque et al., 2017; Recio, 2018; Wallbott and Florian-Rivero, 2018). As a strategic partner, the World Bank has established initiatives such as the PMR, which has provided input around the construction of CPI policies in Brazil and Chile. In Colombia, the PMR assisted government agencies have designed a carbon tax and linked this with the ETS. The German Agency for International Cooperation (GIZ) has contributed to the World Bank initiatives (Sullivan et al., 2021). The World Bank Forest Carbon Partnership Facility (FCPF) and the REDD + partnership have developed capabilities within many LATAM countries for participating in global carbon markets. Recio (2018) points out that more than half of the multilateral financing in 2016 went to LATAM and the Caribbean. The World Bank's Prototype Carbon Fund has founded Brazil's Plantar project and contributes to REDD + policies on readiness activities (Wittman, 2012; Wallbott and Florian-Rivero, 2018).

The Inter-American Development Bank (IADB) has played a crucial role in LATAM. The IADB administers the Fondo Colombia Sostenible (conservation programmes, REDD+) and developed the Forest Investment Attractiveness Index for investments in responsible forestry business (Boscolo et al., 2010; Gilbertson, 2021). Tyukavina et al. (2015) and Tridgell (2016) stress the need to support the welfare of indigenous landowners through forest carbon initiatives including the United Nations Framework Convention on Climate Change (UNFCCC) and REDD+. These initiatives include the Amazon Indigenous Fund, a fund that allows indigenous people to access REDD + funds. Other international financing opportunities for LATAM nations include the Japan Bank for International Cooperation, Fund of the United Nations for Global Environment Facility (GEF), and Latin American Carbon Program (LACP) (Duque et al., 2017). These organizations with their global presence and networking capabilities support the development of carbon markets in LATAM.

Table 3
Estimated forest carbon fluxes and total carbon storage for all the studied Latin America countries. Data for this table was sourced from the Global Forest Watch database (country dashboard) (Global Forest Watch, 2023).

Country	Estimated forest carbon fluxes from 2001 to 2022			
	Removals	Emissions	Net removals/ Net carbon sink	Total forest carbon stored in 2022
Chile	−275 $MtCO_2e$/year	39.0 $MtCO_2e$/year	−236 $MtCO_2e$/year	9.88 Gt
Brazil	−1.79 $GtCO_2e$/year	1.64 $GtCO_2e$/year	−149 $MtCO_2e$/year	126 Gt
Mexico	−228 $MtCO_2e$/year	85.3 $MtCO_2e$/year	−143 $MtCO_2e$/year	15.1 Gt
Venezuela	−164 $MtCO_2e$/year	48.7 $MtCO_2e$/year	−115 $MtCO_2e$/year	15.2 Gt
Argentina	−184 $MtCO_2e$/year	71.4 $MtCO_2e$/year	−112 $MtCO_2e$/year	18.3 Gt
Colombia	−241 $MtCO_2e$/year	131 $MtCO_2e$/year	−110 $MtCO_2e$/year	24.7 Gt
Peru	−170 $MtCO_2e$/year	111 $MtCO_2e$/year	−59.5 $MtCO_2e$/year	27.5 Gt
Ecuador	−63.1 $MtCO_2e$/year	27.6 $MtCO_2e$/year	−35.5 $MtCO_2e$/year	6.31 Gt
Guyana	−40.4 $MtCO_2e$/year	7.09 $MtCO_2e$/year	−33.3 $MtCO_2e$/year	5.19 Gt
Bolivia	−177 $MtCO_2e$/year	150 $MtCO_2e$/year	−27.3 $MtCO_2e$/year	13.6 Gt
Cuba	−29.1 $MtCO_2e$/year	7.41 $MtCO_2e$/year	−21.7 $MtCO_2e$/year	1.54 Gt
Suriname	−28.3 $MtCO_2e$/year	7.81 $MtCO_2e$/year	−20.5 $MtCO_2e$/year	3.83 Gt
Uruguay	−38.2 $MtCO_2e$/year	21.5 $MtCO_2e$/year	−16.7 $MtCO_2e$/year	1.49 Gt
Paraguay	−89.9 $MtCO_2e$/year	77.6 $MtCO_2e$/year	−12.3 $MtCO_2e$/year	4.04 Gt
Costa Rica	−17.4 $MtCO_2e$/year	6.40 $MtCO_2e$/year	−11.0 $MtCO_2e$/year	1.17 Gt
Panama	−22.5 $MtCO_2e$/year	12.0 $MtCO_2e$/year	−10.6 $MtCO_2e$/year	1.70 Gt
Dominican Republic	−12.0 $MtCO_2e$/year	7.13 $MtCO_2e$/year	−4.89 $MtCO_2e$/year	672 Mt
Honduras	−33.7 $MtCO_2e$/year	29.0 $MtCO_2e$/year	−4.64 $MtCO_2e$/year	1.92 Gt
El Salvador	−4.87 $MtCO_2e$/year	1.58 $MtCO_2e$/year	−3.29 $MtCO_2e$/year	244 Mt
Haiti	−4.69 $MtCO_2e$/year	1.54 $MtCO_2e$/year	−3.15 $MtCO_2e$/year	296 Mt
Belize	−4.77 $MtCO_2e$/year	6.00 $MtCO_2e$/year	1.22 $MtCO_2e$/year	24.7 Gt
Guatemala	−31.3 $MtCO_2e$/year	35.3 $MtCO_2e$/year	3.98 $MtCO_2e$/year	1.80 Gt
Nicaragua	−32.4 $MtCO_2e$/year	42.3 $MtCO_2e$/year	9.88 $MtCO_2e$/year	2.02 Gt

4.2. Investment motives for companies

According to a survey conducted in 2022, which gathered information from senior managers from over 500 medium to large companies in the UK, USA, and Europe, the vast majority of businesses (92%) recognize the urgency to reduce emissions, with 79% of them already having climate goals set for their company. Investment in carbon credits was stated as valuable by 89% for accelerated climate action (Conservation International, 2023). Companies whose supply chains rely on the sustenance of tropical forests are more likely to invest in carbon markets and secure their supply chain (Zaballa Romero et al., 2013). In some cases, companies invest in carbon markets to offset their carbon emissions, which does not necessarily mitigate climate impacts. Marriott International purchased REDD + credits, and also invited its guests to donate funds via its website to offset their carbon emissions.

Companies from various countries, such as Mexico, the UK, and Switzerland, provided funds to the project operators of the Carbon Sequestration in Communities of Extreme Poverty in the Sierra Gorda of Mexico project to compensate for their emissions and improve their eco-image (Zaballa Romero et al., 2013). The Bolsa Floresta (BF) program in Brazil, which started with the Juma Sustainable Development Reserve Project, received initial investments from the government of the state of Amazonas, Bradesco Bank, and Coca-Cola Company (Rival, 2013). Additionally, another sort of motive can also be influenced by popular perceptions of the relationship between forests and water provision and the desire of companies to improve their eco-image. For example, Mexican pharmaceutical companies invested in national payments for ecosystem services policies to improve their eco-image (Shapiro-Garza, 2013).

Private companies represent the largest group of buyers, accounting for 40% of carbon credit purchases in LATAM, Asia and Africa (Phan et al., 2017). Companies participating in these markets to manage their impact on climate change, improve their image and reputation, take advantage of technological innovations to reduce greenhouse gas emissions, prepare for future regulations, and potentially profit from carbon credit trade (Paiva et al., 2014). In addition to private companies, other players such as banks, commodity trading firms, energy companies, and investment funds also benefit from transnational carbon markets (McAfee, 2016). In Argentina, companies like Genneia and YPF Luz have substantial participation in the carbon credit market, with Genneia having issued over a million credits from wind and solar energy projects, and YPF Luz having issued 601,000 credits from a wind farm project (Lewkowicz, 2022). Arcor, the largest food company in Argentina, has also entered the VCM, replacing fossil fuels with sugar cane waste in its production process, with an aim to achieve accredited actual emissions reductions of 600,000 tons of CO_2 by the end of 2022 (Lewkowicz, 2022).

However, many medium to large companies who recognize the importance of VCM, are concerned and shying away from further investment in carbon markets due to concerns such as greenwashing (Conservation International, 2023). There is a reputational risk for corporations associated with investing in low-quality tropical forest carbon credits, and with the increasing demand for carbon offsets globally, the supply of low-quality carbon credits in the market is on the rise (TFCI Guide, 2023). Thus, responsible business leaders are expecting non-state actors focused on policy aimed at achieving high-quality credit supply, such as the Integrity Council for the Voluntary Carbon Market Initiative (VCMI), and demand, such as the Voluntary Carbon Market Initiative (VCMI), to develop guidelines and address these challenges and help facilitate further investment in the VCM (Conservation International, 2023).

4.3. Impact of carbon markets on indigenous peoples and local communities (IPLC)

Carbon markets in Latin America vary in terms of design and project development and this may affect how the IPLCs benefit. Brazil, Chile, and Colombia connect the land ownership of residents to their carbon rights (Rights and Resources Initiative, 2018). IPLCs and local communities are custodians of numerous expansive carbon sinks that contribute to carbon markets globally. IPLCs manage land holding approximately 300 billion metric tons of carbon, equivalent to 33 times the global energy emissions in 2017 (Rights and Resources Initiative, 2018; Sirica et al., 2018). Thus, carbon markets expanding in LATAM should bring positive effects to IPLCs. The advantages may include economic support for conservation, recognition of human rights, and improved livelihoods. Local communities received benefits from mitigation activities in the forest sector (Larson et al., 2013), retaining legal ownership of 10% of the circa 300 billion tons of carbon from their forests (Pearce, 2021).

Implementing frameworks for carbon markets are key to IPLC support. Mexico introduced a carbon tax in 2013 alongside MexiCO2, a voluntary exchange for carbon credits - in 2019, amendments to the General Climate Change Law mandated an ETS program, which is currently in a pilot phase. Brazil's National Climate Change Policy led to the development of a voluntary carbon market, with plans to create a national carbon market announced in 2022. Colombia has a carbon tax - it is developing an ETS through the National Program of Greenhouse Gas Tradable Emission Quotas. Chile implemented a carbon tax in 2017, with plans to increase it and achieve net carbon neutrality by 2030 under a new legal framework (Pullins, 2022).

Many carbon sinks affected are in lands where indigenous or local rights are minimal (Rights and Resources Initiative, 2020). Some examples include the establishment of palm oil plantations in various regions in LATAM (Ramos-Castillo et al., 2017); the Mapuche people in Chile claiming pollution from forest plantations (Reinao, 2008); and the Kichwa people claiming their government sold credits from the Peruvian Cordillera Azul National Park without consultation (Forest Peoples Programme, 2021). These consequences heighten the drawbacks already faced by local communities, including human rights transgressions, prejudice, and deprivation (Chatty and Colchester, 2002; Dowie, 2009; United Nations, 2009).

Local communities are disproportionately vulnerable to the impacts of climate change, which include famine, displacement, and infrastructural changes, and this stresses the need to provide adequate support to IPLCs to ensure effective stewardship of these lands (Ford, 2012; Williams, 2012; Lynn et al., 2013). In Ecuador, IPLC lands span 29% of the total land area, and 64% remain relatively untouched, indicating good ecological conditions. However, development pressures persist, as 31% of IPLC lands are subject to active oil and gas concessions. This lack of recognition of IPLC rights may diminish their influence in decision-making processes related to potential development pressures. Recognizing and respecting their rights could double protected or conserved lands in Ecuador from 22% to 44% (WWF et al., 2021).

4.4. Empowering indigenous peoples and local communities (IPLC)

IPLCs have criticized carbon markets for oversimplifying ecosystems and neglecting the socio-economic, political, and institutional importance of carbon sequestration for their communities (Schroeder, 2010). Therefore, equitable participation of IPLCs in decision-making around land management and ensuring they have direct access to carbon markets is imperative for successful functioning of high-integrity carbon markets (TFCI Guide, 2023). A range of actors, from energy companies to drug traffickers, claim, inhabit, or want custody of lands occupied by indigenous people. Strategies to persuade and grant the legality of their tenancy appear arduous and require state provision, and there is a belief that REDD + initiatives can reinforce their rights through subsidies.

One example of successful intervention is the Coordinating Body of Indigenous Organizations in the Amazon Basin (COICA) proposing a model founded on their priorities. COICA advocates for the principle of Free, Prior, and Informed Consent (FPIC), affirming the rights of indigenous communities to participate in decision-making processes that directly impact their lands and resources (Food and Agriculture Organisation of the United Nations (FAO), 2016). Through holistic management plans, they ensure livelihoods, titles, consolidation, and rights in Aboriginal territories. COICA campaigns for global carbon funds for indigenous communities to safeguard the many parts of their ecosystems (Vásquez et al., 2014).

Despite significant challenges, indigenous peoples in the Amazon have successfully repelled external threats to their lands (FAO, 2016). The Kichwa people of Sarayaku in Ecuador successfully fought against oil companies and the government's encroachment on their lands without their consent. They engaged in negotiations, sought assistance from organizations like the Pachamama Foundation and the Center for Justice and International Law, and pursued accountability through the Inter-American Court of Human Rights (IACtHR) through FPIC (Pueblo Kichwa Sarayku, 2018).

A high-integrity carbon market should recognize human well-being outcomes. Within such a market all stakeholders must make concerted efforts to secure the legal recognition and protection of the land, forest, and territorial rights of IPLCs, including the carbon stored and the ecosystem services they provide. Robust safeguards must be adopted to protect human rights, including their rights to FPIC, and access to independent legal counsel and grievance mechanisms. Ideally, direct financing support should be available for community-led initiatives, needs and priorities, including capacity building, natural resources governance and local livelihoods (Aguilar-Støen, 2017).

The decarbonization of global supply chains and changes in the incentives that drive deforestation and forest degradation must be aligned with binding commitments to respect forest and land rights. These binding commitments are necessary to protect the world's forests and the IPLCs that live in or near them. Human well-being and conservation impact on IPLCs are difficult to measure. Measuring equitable participation, empowerment, accessibility, and accountability with regard to human well-being outcomes poses particular difficulties. Consequently, operational understandings of how this relates to interventions need to be figured out early in the process, to define metrics and measurable attributes.

5. Measurement and verification using remote sensing

5.1. Measurement, reporting, and verification (MRV)

The Article 6 rulebook adopted at UKCOP26 describes that participant countries need to regularly collect and report data on their GHG emissions and mitigation performances (UNFCCC, 2021). Robust MRV systems are a core component of carbon markets and are required to overcome concerns around credibility in producing high-quality carbon offsets (Fankhauser et al., 2022; World Bank, 2022). Digital MRV (D-MRV) technologies are increasingly being used over conventional MRV systems to streamline MRV processes, and reduce cost and time (World Bank, 2022). The MRV approach provides baseline or reference level data against which performance in carbon accumulation is measured periodically based on standard accounting methodologies (for example, developed by the Forest Carbon Partnership Facility) used to calculate forest-related emission reductions at different spatial scales.

The most reliable and widely used continuous dataset for MRV systems are repeated measurements from satellite imagery. Long-term monitoring using remote sensing technologies is the most effective method for identifying deforestation and discriminating anthropogenic impacts from seasonal changes (Miettinen et al., 2014) and tree mortality resulting from climate change-induced drought (Ewane et al., 2023b). Observations from multiple satellites, with a regular revisit frequency, can be used to create a time series that can track forest disturbance. One of the most widely used satellites in this capacity is Landsat imagery which has an extensive archive (Wulder et al., 2019) and has been widely used for MRV systems (Tabor and Connell, 2019). Image data from Sentinel 2, which is of a higher resolution than Landsat, complement this data source. When used separately, or in combination, imagery from these satellites provides a useful tool for establishing baselines and forming time series that can be used to detect subtle changes and provide alerts in near real-time (Mitchell et al., 2017).

Most remote sensing systems in LATAM used to detect deforestation utilize moderate resolution, multispectral satellite data with regular revisit imagery such as Landsat (Tabor and Connell, 2019). Within Brazil, the Deter-B system classifies land into several classes, including clear-cut and degradation features from two satellites (CBERS-4, AWiFS). After these data are georeferenced, the fraction of soil, vegetation and shade components are estimated using a linear spectral mixing model (LSMM), and these fractions are subsequently used to define eight deforestation and degradation classes. Within these classes clearcut features show well defined boundaries between the bare soil and the forest matrix while degradation features are associated with the presence of gaps, bare soil, and secondary vegetation (Diniz et al., 2015). In Colombia, the national forest monitoring system for REDD + annually monitors forest change and carbon stocks using top-down satellite monitoring that produces quarterly deforestation alerts (The World Bank, 2017a). This approach incorporates the mapping methods described by Hansen et al. (2013), and these maps are validated using local field data provided by trained staff (Tabor and Connell, 2019). The Mexico National Forest Monitoring System operated by the National Forestry Commission (CONAFOR) combines satellite remote sensing with field-based estimates for carbon inventory (World Bank, 2017b). Since 2017, deforestation within Peru has been monitored using imagery from Landsat 7 and 8 that is further processed using the direct spectral unmixing method (Vargas et al., 2019).

Many other forms of remotely sensed data have been used within LATAM to assess forest cover and changes in carbon stock over time. These include light detection and ranging (LiDAR), synthetic aperture radar (SAR), interferometric SAR (InSAR) and high-resolution stereo-photogrammetry (Goetz and Dubayah, 2011; Ene et al., 2012; Pham et al., 2019). However, there are few examples of these technologies being adopted within national reporting schemes as they are often costly to scale. SAR is a useful addition to existing satellites such as Landsat and Sentinel 2. Data from Sentinel 1 is free and in contrast to optical satellite imagery, SAR from Sentinel 1 can be used to monitor damage during the frequent overcast conditions that characterize tropical rainforests (Mitchell et al., 2017). However, the number of Sentinel 1 satellites have been recently reduced from 2 to 1, which has resulted in coverage gaps. Guyana has developed an advanced MRV for REDD + that captures change at a 1 ha level. The detection framework adopted in the MRV integrates Sentinel 2, Landsat and SAR obtained from Sentinel 1 (Watt et al., 2020).

Multi-temporal community-based monitoring, mapping, and measuring (CBM) can be useful and cost-effective to understand the local drivers of land use and has been found to provide accurate carbon stock measurements. However, it has been stressed that local communities should receive benefits and compensation to participate in CBM for sustainable and long-term monitoring (Torres and Skutsch, 2015; McCall et al., 2016).

5.2. Role of remote sensing for improving monitoring reporting verification systems

Several ongoing and upcoming satellite launches - such as NASA-ISRO SAR (NISAR) - are likely to substantially improve MRV systems. Data from these satellites can be used to improve estimates of emissions from deforestation and degradation and will also be useful for assessing gains in forest carbon stocks. Improved quantification of these attributes may mean that countries participating in REDD + will become eligible for increasing existing forest carbon stocks through management and A/R as well as performance-based payments around emission reductions (through avoiding deforestation and degradation) (Goetz et al., 2022).

NASA's Global Ecosystem Dynamics Investigation (GEDI) was launched in 2018 and is attached to the International Space Station. GEDI is a laser-based instrument, developed based on the principles of LiDAR that acquires discontinuous data along tracks with a footprint size of 25 m (Dubayah et al., 2022). Through fusing GEDI data with information from other earth observation satellites (e.g., Landsat 8 OLI) global wall to wall maps of canopy height at fine spatial resolution have been produced and similar maps for aboveground biomass density (AGBD) are underway that will provide a global benchmark with well-characterized uncertainty (Potapov et al., 2021; Lang et al., 2022). GEDI data and products are freely available and cover all tropical forests and >90% of the temperate forest biome (Dubayah et al., 2022).

Two SAR missions with launch dates scheduled for 2023/2024 have substantial potential to further improve REDD + estimates of carbon dynamics by providing open access global, sub-weekly observations at sub-hectare resolution. The NASA-ISRO L-bandSAR (NISAR) mission has a high return frequency and can be used to estimate forest biomass stock. Although estimates of AGBD using SAR often saturate at moderate to high values of biomass, the use of machine learning and physically based models, which are trained on the plethora of GEDI data, could be used to extend the range of this SAR data source (Khati et al., 2021). A complementary mission, administered by the European Space Agency, called BIOMASS, has been developed primarily for mapping and monitoring of forest biomass in tropical forests. This mission will be the first that uses a longer P band wavelength that is capable of deeper penetration, than L band into forest canopies. The estimates of AGBD from this mission will be calibrated using GEDI data (Banda et al., 2020).

When used in combination, GEDI, NISAR and BIOMASS data will provide accurate wall-to-wall AGBD maps (Silva et al., 2021). Time series from these data sources can directly contribute to REDD + needs by quantifying AGBD losses associated with degradation and deforestation at a high enough temporal resolution to capture these changes before vegetation regrows (Huang et al., 2022). Field inventory data will be required to calibrate predictions of many metrics from these satellite data, and carefully designed inventory programs should be implemented to maximize the effectiveness of these data (Huang et al., 2022).

6. Challenges

6.1. Need for transparency and standardization

One of the criticisms of carbon markets, and especially VCM, is the use of net zero pledges that makes corporate greenwashing possible, where non-state actors claiming to be “net zero” continue to invest in fossil fuel supply or other environmental destructive activity (United Nations, 2022). Carbon markets are often considered fragile because they are influenced by political decisions, which can be perceived by the population as damaging or unfair, and might be rejected someday (Andersen et al., 2022). Thus, improving corporate accountability and transparency is important for ensuring credibility within carbon markets. This could be achieved through validation of corporate emission reduction targets beyond value chain mitigation (BVCM) by Science-Based Targets initiative (SBTi), and by defining a mitigation hierarchy to ensure carbon offset investments complement and do not substitute decarbonization plans for the company (The SBTi, 2023; TFCI Guide, 2023; United Nations, 2022).

Having a robust MRV process is integral for a high-quality carbon market; this is the source data used to evaluate project success. Improvements should be made to the MRV process through maintaining transparency and standardization throughout data collection protocols and ensuring that reference datasets are available (Morales-Barquero et al., 2019). There are valid concerns and evidence of malpractices around carbon monitoring that include faulty additionality calculations, systematic measurement biases, inaccurate baselines, and intentionally overstated impacts on avoided deforestation (Rifai et al., 2015; West et al., 2020, 2023). Transitioning towards a compatible D-MRV system would improve the credibility and transparency of carbon markets through storage of raw data in the cloud, which would ensure full data traceability during verification and prevent data tampering (World Bank, 2022). Automation of data collection and analysis by incorporating AI and machine learning would standardize the MRV process in a D-MRV system, and further improve the credibility and transparency of credits (World Bank, 2022).

Carbon market intermediaries play an important role in VCMs, connecting buyers and sellers of carbon credits in a decentralized marketplace, but often act with little transparency in revealing the commissions and profits they make during these exchanges (Dufrasne, 2023). However, it is important to have this financial transparency in carbon markets, to be aware of how much money flows through the system to support on-the-ground climate action and climate resilient development in the region.

6.2. Implementing sustainability measures in ongoing- and post-conflict zones

Due to historical colonial land policies, the LATAM region has suffered numerous conflicts of interest and internal confrontations due to poor recognition of human rights and violations of the principles of freedom and knowledge. As a result, there is a growing demand for land and its natural resources, which has resulted in escalating land conflicts and violence with IPLCs fighting for land tenure rights. This instability has aggravated forest conservation challenges, as local communities are losing land tenure rights, resources, and territories due to various political factions in LATAM (Streck, 2020). According to Cabrera et al. (2020), the forests most threatened by deforestation are small and medium-sized forests with up to 100,000 inhabitants, as confrontations expand local economic growth at the cost of extensive natural forest destruction.

In Colombia, post-conflict groups have emerged since the government and the Revolutionary Armed Forces of Colombia (FARC) began discussing potential peace agreements in 2012. Since then, radical groups have taken advantage of the legal clefts, causing several adverse environmental effects and disrupting the sustainable development of these territories (Cabrera et al., 2020). The Colombian post-conflict context related to the power vacuum left by the FARC illustrates how political instability can influence forest conservation challenges. Extremist groups in Colombia, such as the Clan del Golfo and Los Puntilleros, used the power void left after FARC’s withdrawal to increase control over land in post-conflict zones and foster farming speculation and natural resource extractions. As mentioned above, the peace accord with the FARC has directly impacted and restructured the socio-ecological politics of forest rights, boosting the deforestation models of the country. Hence, all these factors reaffirm that fragile and conflict-affected states face the greatest challenges in achieving global climate goals and SDGs (Rodríguez-de-Francisco et al., 2021; United Nations, 2022).

Another substantial conflict that aggravates violence between communities and promotes deforestation in Amazonia is cocoa cultivation, which has increased considerably during the last few decades (Castro-Nunez et al., 2017; Rodríguez-de-Francisco et al., 2021). The historical circumstances create political and social brutality and aggravate the situation between influential actors competing with IPLCs for land and local resources. Consequently, governments are implementing regulatory policies that limit growers who expand into new lands and cause deforestation. New socioecological models that contribute to peacebuilding by reducing deforestation and promoting sustainable development are designed to foster better management of natural resources (Cabrera et al., 2020). Therefore, programs such as REDD Early Movers (REM) and other sustainable models, if well executed, are vital for social, ecological, and economic growth as they incentivize countries in the global south to reduce deforestation. Despite all the challenges and conflicts throughout LATAM, the expansion of carbon markets including REDD+ and carbon taxes could have the potential to reconfigure the socio-ecological dynamics of this region and reduce deforestation rates (Sierra et al., 2017).

7. Benefits, opportunities, and future directions

7.1. Increasing opportunities for involvement

As more companies make commitments toward net-zero targets, and environmental, social, and governance initiatives in general, increasing opportunities for investment and employment continue to emerge in the LATAM region. With one of the world's largest carbon sinks, and future sequestration potential, companies with ambitious climate goals, particularly within the hydrocarbon, energy, finance, consumer goods, and insurance industries, have collectively driven a substantial increase in participation in both the CCM and VCM in LATAM (Pullins, 2022). Demands from investors and consumers to achieve these climate goals have positioned the VCM in LATAM for a ten-to 30-fold increase by 2050, which represents key opportunities for further involvement and investment in the region's forest carbon markets (Sullivan et al., 2021).

This expansion of forest carbon projects would also result in additional employment and participation opportunities for IPLCs, who often serve as stewards of the forests involved in these projects. Boscolo et al. (2010), found that sustainable small-scale forestry initiatives in the region resulted in an estimated one job created for every 10 ha of planted forest, as well as additional opportunities for private-private partnerships and increases in capacity building, governance, and awareness. Additionally, forest carbon projects in LATAM can produce alternative employment opportunities, reducing reliance on livestock grazing or the production of food crops, and increasing the potential for afforestation/reforestation (A/R) projects and the growth of secondary forests, wooded areas that have regenerated after degradation due to human activities or natural phenomena. While A/R projects require skilled professionals such as tree planters and operators of heavy machinery, they would also employ and train local people and enhance local revenues through microlending and investment in infrastructure (Zaballa Romero et al., 2013).

Further opportunities are driven by government programs; Colombia has created the "Sustainable Colombia Fund," which supports sustainable projects initiated and maintained by marginalized groups such as women, black communities, and indigenous peoples, using revenues generated from carbon taxes (Sullivan et al., 2021). Guyana's jurisdictional REDD + program has dedicated tens of millions of dollars to the country's 235 indigenous communities through the Amerindian Titling Program, which enables these communities to accelerate the acquisition of legal land titles (Natural Climate Solutions Alliance, 2023).

The VCM in LATAM is the result of a complex value chain that incorporates registries and standards, project originators, project developers, financers, and buyers. Standard bodies including Verra and Gold Standard, as well as alternatives such as Puro.earth and universal initiatives like the World Bank's Climate Warehouse, make up a complex network of registries, and regulatory bodies such as the Integrity Council for the Voluntary Carbon Market (ICVCM), which created the Core Carbon Principles (Prather, 2023). Companies that utilize these marketplaces to purchase forest carbon credits include the oil and gas (e.g., Shell, Ecopetrol), transportation (e.g., Uber), airline (e.g., Delta), and finance (e.g., Credit-Suisse, BlackRock) industries, among many others (Pullins, 2022). In 2019, the majority (63%) of companies purchasing LATAM carbon credits were European, followed by North American corporations (Sullivan et al., 2021). In addition to purchasing carbon credits to offset their own emissions, companies such as Amazon, Unilever, Salesforce, AirBnB, and Nestle mobilized $1 billion in financing using architecture for REDD + transitions as part of the Lowering Emissions by Accelerating Forest Finance (LEAF) coalition (Selibas, 2021).

7.2. Transition into regenerative forest markets

As the United Nations declared 2021 to 2030 as the Decade for Ecosystem Restoration, A/R projects in LATAM and other regions have additional potential to complement REDD + projects. Similar to initiatives occurring across the world, tree reforestation initiatives are gaining momentum in the LATAM region. Ecosia, a reforestation search engine, has planted over 100 million trees in LATAM countries including Mexico, Guatemala, Brazil, Bolivia, Colombia, Peru, and Nicaragua (Lefebvre et al., 2021). However, it is important to protect these restored forests to avoid re-clearing and to ensure potential benefits are sustained over the longer-term. Schwartz et al. (2020), found that forest cover gains recorded in many reforestation projects that occurred in LATAM and Caribbean during the early 2000s were subsequently lost by 2014, and this reversal is ten times more common than sustained regeneration.

Trends in deforestation and the status of restoration projects over time are effectively assessed through D-MRV systems using remote sensing data, integrated with machine learning and AI-enabled platforms (World Bank, 2022). Between 2000 and 2010, a net gain in forest cover of 360,000 km^2 was recorded across Latin America and the Caribbean (Schwartz et al., 2020). Failure rates of tropical restoration projects are high, as young tree mortality often occurs when there is a lack of protection and management (Lefebvre et al., 2021; Ewane, 2023). Hence, restored forests must be protected by incentive frameworks to encourage landowners to act post-restoration (Chazdon et al., 2016). In addition, mangrove forest restoration and conservation initiatives provide viable opportunities for carbon offset programs of the compliance and voluntary carbon markets to industries contributing to GHG emissions (Rondon et al., 2023).

Carbon sequestration potential of A/R are calculated in advance, based on projected results, which may allow corporations to inflate premature capture values to skew public perception of their impact, contributing to "corporate greenwashing" (Lefebvre et al., 2021). But concerns around overstated results are not limited to A/R efforts; many voluntary REDD + projects calculated based on ex ante historical trends provide cause for skepticism around the validity and environmental integrity of the offsets (West et al., 2020). Certification bodies often require that A/R projects meet certain requirements; Gold Standard, for example, requires that trees reach a minimum height of 2 m (Gold Standard, 2013), while Verra projects define trees as perennial woody plants with a diameter at breast height (DBH) greater than or equal to 5 cm (Verra, 2021). Ex-ante forest carbon projects may also have special requirements for the estimation of tree biomass. Verra projects may estimate the carbon stored in pools other than trees as zero (Verra, 2021), while Gold Standard includes non-tree biomass and standing dead wood as part of the baseline carbon pool (Gold Standard, 2013). Landowners and other stakeholders interested in tree planting and other restoration projects should consult these platforms' standard processes before initiation to ensure the resulting secondary forests meet the necessary requirements.

7.3. Environmental, economic, and social implications of recent trends in forest carbon markets

Carbon trading has the potential to achieve co-benefits substantially and progressively for the environment, economy and people involved, indicating that the benefits extend beyond the GHG mitigation impacts of this policy (Sullivan et al., 2021). The expected key environmental benefits of the forest carbon markets include mitigation of GHGs and improved forest management that increase biodiversity and habitat conservation, and reduce the impact of natural disasters (Yankel, 2018). Forest carbon markets can enhance environmental integrity through the development of robust national MRV systems that can track changes in aboveground biomass density (AGBD) and company emissions (Sullivan et al., 2021).

Most LATAM countries have made substantial progress toward achieving their targets for NDCs. In Brazil, for example, the share of emissions from the land use, land use change and forestry sector has decreased from 2004 to 2016, and these changes strongly contribute to the achievement of NDC target GHG emission reductions of 37 and 43% in, respectively, 2025 and 2030, compared with 2005 levels (UNFCCC, 2021). The observed reduction in deforestation and forest degradation related emissions in LATAM countries could be partly attributable to the growing number of certified REDD + projects under the VCM in Brazil, Peru, and Colombia (following a record 71 $MtCO_2e$ emission reduction in the year 2021), and expansion of CPIs in Argentina, Mexico, Chile and Colombia (Sullivan et al., 2021).

Carbon markets can strongly contribute to the achievement of various SDGs. This occurs through mobilization of funding from the global north to the global south, to support investments in environmental, economic, technological advancement, and social development at national and sub-national levels. There is growing evidence of the progressive distributional impact and outcomes of carbon trading revenue to lower-income countries in market-based climate change mitigation policies, but this has a relatively larger impact on the budget of higher-income households and groups (Dorband et al., 2019; Ohlendorf et al., 2020). Thus, there are still concerns regarding revenue flow and expected provision of employment opportunities, poverty alleviation, and climate-resilient local economic development for IPLCs (Sullivan et al., 2021). Therefore, market-based climate change mitigation policies such as the CPIs must be economically and socially efficient, acceptable, and sustainable. Reward systems should be designed to provide equitable benefits for all the stakeholders involved, and in particular, safeguard the economic and social interests of IPLCs. For example, an agreement between the World Bank and Dominican Republic on a REDD + project will mobilize 25 million USD to support the country's vision to reduce 5 $MtCO_2$ of emissions from 2021 to 2025, and fund high-impact projects with socio-economic benefits (Sullivan et al., 2021).

7.4. Contribution to UN sustainable development goals (SDGs)

The operation of well-planned, high-quality carbon markets with high integrity in LATAM has the potential to reduce GDP losses and result in long-term favorable improvements for people and the environment, supporting SDGs at all scales including SDG 7 - Affordable and Clean Energy, SDG 11 - Sustainable Cities and Communities, and SDG 13 - Climate Action (Calderón et al., 2016; Sousa et al., 2020). Numerous carbon projects assert that they go beyond lowering or eliminating greenhouse gas (GHG) emissions to positively impact SDGs (In and Schumacher, 2021). The spread of low-carbon technology, technical innovation, greater health due to lower air pollution, less reliance on imported fuels, less traffic congestion, and increased net trade-in technologies and services are just a few of these positive impacts of carbon markets on SDGs. The range of benefits includes capacity addition of 1200 MW resulting in approximately 2.89 million MWh of renewable energy generation per annum, improved air quality for about 1.31 million people, more than 14,000 additional jobs per region, 1.39 million people benefitted from improved energy efficiency measures and services, 8.74 million people potentially gaining access to stable and reliable energy, improved education facilities for more than 8,500 children, reduced traffic congestion and upgraded urban transport services, and close to 40,000 people gaining access to health services (Asian Development Bank, 2017).

Sustainable carbon projects that have long-term beneficial effects have an integrated perspective on many outcomes. They optimize advantages that range from improving biodiversity and coastal habitats to lowering poverty and assuring access to clean electricity and water. In other words, they are more worthwhile initiatives that demand greater funding. The integration of environmental and socioecological priorities in carbon market design has the potential to facilitate the wellbeing of IPLCs and reduce conflicts related to land tenure rights, power disparities, and corrupt regional issues, and directly supports SDG 16 ″peace, justice, and strong institutions" (Rodríguez-de-Francisco et al., 2021).

7.5. Governance implications of the recent trends/applications of forest carbon markets

Good governance systems and associated technical infrastructure are required for successful carbon pricing planning and implementation in carbon markets. Governance systems such as a carbon market registry for transactions of allowances and/or carbon credits to be registered and an auctioning platform for offsetting allowances are required. These systems need to be backed by well-developed rules and regulations to provide an enabling marketplace for participants to trade carbon offset allowances. Stakeholder capacity building is invaluable for successful planning and participation in forest carbon markets for all parties. Front-running LATAM countries in the various carbon markets have developed and implemented capacity building and stakeholder engagement activities to enable participants to understand how forest carbon market policies work and how these affect them and their responsibilities (Sullivan et al., 2021). There is a great opportunity for knowledge sharing around lessons learned about carbon pricing planning and implementation within LATAM countries.

All the forest carbon markets front-runners in LATAM have prioritized capacity building through studies describing policy design options, impact assessment through MRV and stakeholder engagement processes to secure co-benefit outcomes for all the parties involved. For example, Chile has initiated studies on policy coherence of CPIs, international carbon markets, and MRV systems for carbon markets, implemented through working groups and dialogue with different stakeholders to provide inputs on the development of a CCM. Brazil has undertaken studies on design options, economic and regulatory impact assessments, and stakeholder engagement and communication activities on carbon pricing, implemented through seminars to raise awareness and discuss carbon pricing (Sullivan et al., 2021). Colombia has completed studies describing the impact of an ETS, sectoral competitiveness and design options for a mandatory GHG reporting program implemented through in-country and virtual courses on ETS, simulations exercises on ETS, and study tours (World Bank, 2020). Mexico has undertaken studies on design elements, options, and interactions, as well as communication and stakeholder engagement throughout the carbon pricing planning and implementation process. Peru has put considerable effort into developing foundational carbon pricing MRV, infrastructure and national rules to participate in international carbon markets under the Paris Agreement (Sullivan et al., 2021).

7.6. Future directions towards a high-integrity carbon market

Businesses can play a critical role in transitioning carbon markets in the LATAM region to higher integrity by making investment choices based on the quality, impact, and scale of carbon offsets, aligned with Tropical Forest Credit Integrity (TFCI) guidance (TFCI Guide, 2023). "Beyond value chain mitigation" investments in the VCM should only be considered after taking necessary actions to abate their own value chain emissions, following a "mitigation hierarchy" defined through SBTi-validated emission reduction targets (The SBTi, 2023). This approach to carbon market investments would minimize the opportunity for corporate greenwashing, as halting investment in fossil fuels and other environmentally destructive activities would come first in the mitigation hierarchy, before claiming beyond value chain mitigation credits (UN News, 2022). Companies should also do the necessary due diligence to ensure the rights, traditions, and culture of IPLCs, women, and other underserved communities are respected, which can be achieved through the purchase of carbon credits with higher social integrity and transparent benefit sharing mechanisms (TFCI Guide, 2023).

Transitioning to jurisdictional-scale crediting from stand-alone, project-scale crediting is another central requirement for a carbon market with high environmental integrity and impact. This would incentivize climate actions and policy changes to address the systematic drivers of tropical deforestation and risks of leakage (Schwartzman et al., 2021; TFCI Guide, 2023). Similarly, companies should invest in carbon credits generated from HFLD jurisdictions, such as Colombia, Peru, Suriname, Ecuador, Panama, Guyana, and Venezuela in LATAM due to their importance as intact forests with a carbon sink of global importance (Schweikart et al., 2022; TFCI Guide, 2023; Dixon, 2021). However, further studies to refine the guidance on carbon credits attached to HFLD credits are needed.

Future studies should focus on ways to transition into a more robust D-MRV process, integrating machine learning and AI algorithms into remote sensing to expand its scalability. This would facilitate the analysis of massive multi-source heterogeneous data, and take full advantage of blockchain, cloud computing, and the internet of things (IoT) to at least partially automate data recording, storage, and processing to improve the scalability, transparency and credibility of carbon credits generated (Chen, et al., 2021; World Bank, 2022). As standards around human well-being outcomes evolve, the MRV process should integrate measurable attributes and conduct timely, and precise assessments against social standards (TFCI Guide, 2023).

8. Conclusion

As the second-largest provider of carbon credits, LATAM is poised to become a leader in carbon markets that benefit the climate, people and biodiversity. With substantial natural resources and one of the world's largest carbon sinks, our findings revealed that carbon markets continue to expand in the region, driven by increased adoption at the national and sub-national levels, government incentives, and public demand. We found that Colombia, Mexico, Chile, Brazil, Peru, and Argentina lead the region in carbon tax adoption and the development of voluntary and compliant carbon markets. Brazil, Peru, and Colombia contribute the greatest number of voluntary credits. Through this increased adoption and participation, the voluntary carbon market in LATAM is poised to grow substantially, which represents or provides ample opportunities for investors.

These opportunities, however, are threatened by challenges such as increased natural disasters borne from climate change, the complexity of CPI implementation, corporate greenwashing, corruption, undefined or poor governance of carbon projects, lack of transparency, and further marginalization of fringe communities and IPLCs. To address these challenges, the implementation of forest carbon projects should ensure equitable participation of IPLCs at all levels of negotiation, planning, and implementation, and should provide opportunities for employment and capacity building. LATAM countries that are exploring and implementing CPIs must develop effective legal and incentive frameworks to promote transparency, prevent greenwashing, and incentivize crediting at the jurisdictional scale. Bolstered by emerging technologies, D-MRV processes are capable of making more accurate assessments which have the potential to improve transparency and credibility of offsets being produced if the data is properly utilized.

Finally, efforts should combine existing UN REDD + avoided deforestation projects with A/R projects, low-carbon investments, and agroforestry initiatives to ensure gains in forest cover are permanent. We expect that our findings will encourage further investment from the public and private sectors in developing high-quality carbon markets in LATAM, which will provide equitable benefits to IPLCs and support climate-resilient development in the region.

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Declaration of competing interest

The authors declare that they have no potential real or perceived conflict of interest. Authors Marcela Rondon, Ewane Basil Ewane, Jorge F. Montenegro, Austin Blanton, Judith Pons, and Midhun Mohan, were employed by the company Ecoresolve Inc. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

Data will be made available on request.

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