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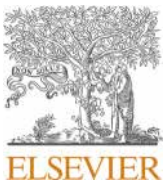

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The impact of scientific controversies on standards and methodologies in the voluntary blue carbon market

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ABSTRACT

With the proliferation of scientific studies on blue carbon in recent years, numerous controversies have emerged in the academic literature. Simultaneously, the voluntary carbon market has expanded significantly, initially at the terrestrial level and, over the past decade, also in the marine realm. While some studies have the emergence of a specialized literature on the blue carbon market, none have examined the connections and relationships between scientists and the voluntary carbon market (VCM). This article maps the scientific controversies surrounding the methodologies developed by standards for the blue carbon market in order to clarify how these controversies are considered in the methodology update process. A quantitative analysis of articles highlighting controversies was conducted, accompanied by a qualitative analysis of methodologies used in the VCM. Interviews with key stakeholders further provided depth to the analysis. An acceleration in updates to certification methodologies developed by standards is observed, correlated with the increasing number of articles highlighting controversies. However, the relationship between research and certification methodologies appears challenging as few scientific articles are cited in most methods, and reciprocally. Mapping the actors reveals that the links and interactions are diverse and occur through various communication channels.

1. Introduction

To limit the global temperature increase to less than 1.5–2°C above pre-industrial levels as agreed to by parties of the United Nations Framework Convention on Climate Change (UNFCCC) in the Paris Agreement, it is imperative to address increasing emissions through mitigation strategies, including emission prevention, reduction, and restoration of carbon-absorbing ecosystems (Gao et al., 2018; Hermwille and Kreibich, 2021; Schindler Murray and Milligan, 2023). International policies have been put in place to tackle this issue. The Kyoto Protocol of the UNFCCC set up, among other things, the creation and deployment of so-called "flexibility mechanisms" that enabled the development of carbon markets to assist countries in achieving their goals.

Besides the Kyoto Protocol and more recently the Article 6 of the Paris Agreement, a market for voluntary carbon offsetting has emerged. This market allows entities not subject to regulatory markets but concerned about their carbon footprint and/or reputation to acquire verified emission reduction credits (Robert-Demontrond and Joyeau, 2012) based on natural or technological climate solutions. These credits are awarded by various compensation structures, whether private for-profit companies or non-profit associations and foundations. Projects that generate carbon credits are of two types. First, carbon dioxide (CO2) emission reduction projects aim to directly decrease CO2 emissions through various measures such as energy efficiency improvements. Second, compensation projects seek to offset unavoidable CO2 emissions by removing an equivalent amount of carbon dioxide from the atmosphere or preventing future emissions. (Calel, 2013; Burke and Gambhir, 2022).

Natural climate solutions, involving various management actions (Roe et al., 2021) aimed at increasing carbon sequestration by vegetation growth, are crucial complements to decarbonization efforts, especially for countries and businesses aiming for net-zero emissions (Friess et al., 2022a) with benefits on human well-being and biodiversity (Roe et al., 2021). These solutions have the potential to sequester 23.8 petagrams of CO2 equivalent (CO2e) per year, which accounts for 37 % of the cost-effective CO2 mitigation needed by 2030 for a 66 % chance of

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keeping temperature increases below 2°C (Friess et al., 2022a; Griscom et al., 2017).

Among these solutions, the protection and restoration of coastal ecosystems such as mangrove forests, seagrass meadows, and salt marshes, defined as blue carbon ecosystems (BCE), are particularly important. These ecosystems have a high capacity for carbon sequestration per surface area (Duarte et al., 2005; Wedding et al., 2021), which contribute to climate mitigation (Pendleton et al., 2012). The accumulation and long-term storage of carbon primarily occur in the sediments of blue carbon coastal ecosystems, rather than in their above-ground biomass (Williamson and Gattuso, 2022). This results in carbon accumulation in the soil over millennia, contributing to the sustained negative global warming potential of blue carbon ecosystems (BCEs) (Wedding et al., 2021) compared to land-based solutions (Friess et al., 2022b). For the restoration of coastal blue carbon ecosystems to constitute a valid contribution to national climate strategies or carbon trading, it is crucial to ensure that the management actions undertaken clearly result in additional carbon absorption and storage (Hilmi et al., 2021). For this reason, there are calls for the establishment of internationally recognized standards to reliably estimate and verify these climate benefits, as well as long-term monitoring to ensure secure carbon storage (Williamson and Gattuso, 2022). The quality of carbon credits, for terrestrial and blue carbon, remains a significant issue, highlighting the need for rigorous accreditation and verification. Critics of the carbon market raise several concerns, including its credibility and usefulness. In January 2023, *The Guardian* and *Die Zeit* analyzed scientific studies of Verra's[1] programs concerning tropical forests. The investigation revealed that over 90 % of their compensation credits for tropical forests are likely to be "ghost credits" (Greenfield, 2023) and do not represent genuine carbon reductions. A study conducted by researchers at the University of Cambridge in 2022 on 40 Verra projects showed that, even though some had halted deforestation, the affected areas were extremely small (Guizar-Coutiño et al., 2022) compared to the areas covered by the projects. In 2023, West et al., also examined the effects of 26 such project sites in six countries on three continents but found that most projects have not significantly reduced deforestation, with reductions lower than claimed (West et al., 2023).

Since the early 2000s, with the pioneering work of the Plan Vivo Foundation in Mexico, standards have been established to certify restoration and conservation projects within the voluntary carbon market for land-based projects. In 2014, over a decade after the emergence of the first certifications, the first blue carbon project was certified. Since the 2010s, methods and certification standards for blue carbon projects have proliferated. These standards are regularly updated.

Recently, the blue carbon market has gained momentum. This renewed interest reflects a broader shift in the carbon market, where ocean-based carbon sequestration is increasingly seen as a critical complement to land-based strategies partly in response to critiques of terrestrial carbon credits. De Pryck and Boettcher (2024) trace the evolution of scientific research on blue carbon through three phases: a period of problematization and enthusiasm (1960s-1990s), a phase of experimentation and regulation (2000s-2010s), and a renewed wave of enthusiasm since 2014, marked by growing attention to blue carbon solutions. In parallel, there has been a marked increase in scientific interest in blue carbon, driven largely by the need for better quantification, prediction, and management in line with global carbon neutrality goals. Sun et al. (2024) analyze the exponential upward trend in blue carbon publications between 2003 and 2022, identifying three distinct phases: an exploration period (2003–2007), a development period (2008–2015), and an explosion period (2016–2022). Since 2016, the integration of blue carbon into national strategies has intensified research on carbon sink quantification, model prediction, and blue carbon management, in response to the global goal of carbon neutrality (Sun et al., 2024). Both the multiplication of blue carbon projects, and the increase in scientific literature on the subject have been analyzed (Sun et al., 2024), but the interactions between project development and scientific research remain unexplored.

While the carbon market faces various controversies, the emerging field of blue carbon presents its own unique challenges. Despite its growing prominence, blue carbon has been relatively understudied compared to terrestrial ecosystems, so many uncertainties and controversies remain, regarding the carbon dynamics of coastal ecosystems as well as the design of blue carbon projects and their impacts on local communities. In this article we analyze controversies specifically related to blue carbon and the associated stakeholders, focusing on the integration of scientific debates into the development of certification methodologies for restoration or protection projects within the voluntary blue carbon market.

Drawing on the literature in Science & Technology Studies (STS) on scientific and socio technical controversies, we define a controversy as a process of debate and contestation surrounding scientific, technical, social, or political issues (Jasanoff, 2019). Controversies can emerge at two levels: within scientific communities, where discussions focus on the validation of facts and the feasibility of projects, and within the social or political sphere, where the stakes partly depend on the interpretation of scientific and technical facts. The study of controversies allows for the analysis of how social actors challenge established knowledge and attempt to influence decisions by exploring and resolving the uncertainties inherent in these debates. In this article, we analyse whether and how controversies regarding blue carbon in the scientific literature and in the project and standard communities relate.

To do so, we will review the debates surrounding the standards and methodologies of blue carbon around the five key controversies identified (Table 1.).

This article aims to bridge the gap in the existing literature on the relation between methodologies and the academic literature on blue carbon market and provide a detailed overview of the relationship between scientific articles addressing the issues, referred to as controversies, of the blue carbon market and the drafting of certification methodologies for carbon sequestration projects targeting blue carbon ecosystems, developed by voluntary standards. By analyzing these interactions, we aim to better understand how the concerns raised by researchers influence the development of certification standards and the extent to which these standards address the critical issues of the blue carbon market.

2. Material and methods

Our research methodology integrates both quantitative and qualitative approaches to investigate the controversies surrounding the blue carbon market. The five key areas of controversy (Table 1.) were defined based on a primary corpus of articles that we identified through an extensive literature review. Initially, a broader set of controversies was recognized; however, through a process of refinement, some categories were consolidated. For instance, the issues of monitoring and transparency were initially treated separately, but were later grouped under the broader category of 'environmental integrity' due to their close conceptual overlap. This approach allowed us to streamline the analysis and focus on the most significant and recurring points of contention within the literature.

Then, we began with a quantitative analysis of the scientific literature, using the *Web of Science* database to systematically collect a corpus on blue carbon market controversies. The *Web of Science* database includes scientific articles exclusively in English, selected by the database editors. This analysis focused on mapping the evolution of controversies within the literature, using queries addressing blue carbon, market dynamics, and associated standards and controversies (Table with queries in the supplementary materials). The queries yielded 340 results. A

[1] 1 Verra is a standard developing carbon sequestration methodology.

Table 1
Definition of controversies associated with the blue carbon market.

Topic of controversy	Details of the controversy
Additionality	Additionality refers to the requirement for carbon offset projects to result in verifiable reductions or removals of emissions that would not have occurred without the project, considering prevailing market conditions, regulatory demands, and business-as-usual scenarios. This ensures that claimed emission reductions are authentic and lead to a net decrease in greenhouse gas emissions beyond what would occur naturally. A second aspect is financial additionality, emphasizing that carbon market funds should support restoration projects that would not occur without this funding. This underscores the necessity of ensuring that funds allocated to carbon offset projects genuinely contribute to reducing greenhouse gas emissions by financing initiatives that surpass what would not be funded otherwise (Bento et al., 2012; Richards and Huebner, 2012).
Carbon Leakage	How a compensation action in one area can potentially shift pressures to other areas, thus invalidating the initial environmental benefits.
Accounting	How to accurately measure and quantify net carbon emission reductions, as well as the validity of methods used to estimate carbon stocks in marine ecosystems without double counting.
Social Justice	How a project must be designed and implemented to ensure equitable distribution of costs and benefits, as well as respect for the rights of local communities and indigenous peoples
Environmental Integrity	How to ensure that restoration or protection projects do not result in additional ecological damage or undesirable disruptions to marine ecosystems. Although the term "environmental integrity" is mentioned in various UNFCCC decisions and the Paris Agreement, without a defined definition (Schneider and La Hoz Theuer, 2018), this concept refers to real, measurable, and long-term mitigation benefits, as well as verified emission reductions by designated entities. Through a review of submissions and literature, Schneider and La Hoz Theuer (2018) provide three potential definitions for environmental integrity: (1) Aggregate achievement of mitigation targets, ensuring that international transfers do not result in actual emissions exceeding the aggregated target level. (2) No increase in global aggregate emissions, ensuring that international transfers lead to global greenhouse gas emissions no higher than if the transfers did not occur. (3) Decrease of global emissions, ensuring that international transfers result in reduced global greenhouse gas emissions compared to a scenario without transfers. In this paper, we will choose definition number two because this definition is more appropriate in the context of a voluntary carbon market, as it does not set a specific carbon mitigation target.

selection of articles was made by screening the titles and abstracts. Articles that did not focus on market-based approach, discussion of controversies, and focus on marine ecosystems, were discarded. After removing duplicates and screening titles and abstracts, 43 articles were kept for the analysis. The set of 43 articles was then supplemented with 8 additional articles provided by experts from the field (interviewees, see next section) or identified through snowball effect (references in the articles previously found), resulting in a total corpus of 51 articles (Supp Mat list of articles).

The corpus was analyzed quantitatively through assessments of ecosystems, geographical areas, publication dates, and authors, as well as qualitatively, focusing on the controversies highlighted. We also collected a set of methodologies which we analyzed qualitatively by examining the updates made between each version. In addition, we conducted 12 semi structured interviews (six from academia, two from carbon market standards, one from multipartite coalition (a multi-stakeholder coalition refers to the grouping of actors from different stakeholders in the blue carbon market (NGOs, researchers, international agencies, companies, etc.) who come together to work on a common issue), one from NGO, one project developer and one consultant for carbon market standards) to complement our understanding of market dynamics (see Supp Mat list of interviewees). Interviewees were selected based on their roles in article publications, guideline development, or project implementation within the blue carbon market. Given the limited number of interviews, they were not intended to be fully representative of all stakeholders within the blue carbon market but were used to reach a more detailed understanding of market functioning, actor relationships, and perspectives on controversies. They enabled us to identify salient issues and to contextualize the literature through an analytical framework encompassing the proliferation of methods, the drafting of methodologies, and the five identified controversies.

3. Findings

3.1. The multiplication of methods

Since the 2010s, there has been a proliferation of methods and certification standards for carbon sequestration projects (Fig. 1). Notable developments include the publication on a global scale of the Plan Vivo standard and Verra VCS's VM007 REDD+ methodology. However, if the fourth version of Plan Vivo was adapted to include mangrove ecosystems, it's only from the 2020 s that methodologies have developed specific categories within their frameworks for blue ecosystems. Subsequently, the Climate Action Reserve introduced the Mexico Forest Plan such as Verra VCS introduced the VM0033 methodology. Since the 2010s, with the American Carbon Registry and the Yokohama BC Credit, we have also seen the development of local and national methodologies. In 2021, Japan developed its own methodology, J-Blue Credit, for macroalgal beds. In France, it was in 2023 that the Ministry of Ecological Transition published the first specialized methodology for seagrass meadows. Methods initially designed for the terrestrial carbon market are now diversifying to include specific components for marine ecosystems, and specialized standards are emerging to address this new direction.

There are 10 methods pertaining to seven standards of the carbon market that address blue carbon ecosystems in 2024. Except for the *Label Bas Carbone Herbier Marin* and *JBlue Credit*, all methods apply to mangroves and wetlands. However, seagrasses are not consistently included, as seen in the *American Carbon Registry*. Among the methods, those encompassing the widest range of ecosystems are the VERRA and Plan Vivo methodologies.

Carbon certification methods are regularly updated. The provided figure details the timeline of updates of methodologies from 2001 to 2024. Plan Vivo shows its progression from V1 (2002) to V5 (2024), with blue carbon consideration starting from V4 (2013). The Climate Action Reserve Mexican Forest Plan moves from V1.0 (2011) to V3.0 (2022), incorporating blue carbon from V3.0. In this version, the methodology incorporated various mechanisms to fulfill permanence obligations, including the Project Implementation Agreement. Verra VCS VM0033 Methodology for Tidal Wetland and Seagrass Restoration begins with V1.0 (2015) and evolves to V3.0 (2024), with blue carbon ecosystems considered from V1.0 (2015). In V2.0 we observe a reassessment of standardized methods for determining additionality and in V3.0, Verra added the use of the "Non-Permanence Risk Tool". VM007 REDD+ Methodology Framework starts at V1.0 (2011) and advances to V1.8 (2024), including blue carbon ecosystems from V1.6 (2021). The American Carbon Registry shows updates from V1.0 (2014) to V1.1 (2022), with blue carbon consideration beginning at V1.1. J-Blue Credit appears at V1.0 (2023), with no prior versions shown, and specializes in microalgae. Label Bas Carbone Mangroves and Label Bas Carbone Herbiers Marins were both introduced at V1.0 (2023), including blue carbon ecosystems from the start and specializing in only one specific blue carbon ecosystem, while the other methods do not target specific blue carbon ecosystems.

The Verified Carbon Standard (VCS) VM0033 method has been updated twice between 2022 and 2024 (Fig. 1). The CAR MFP method

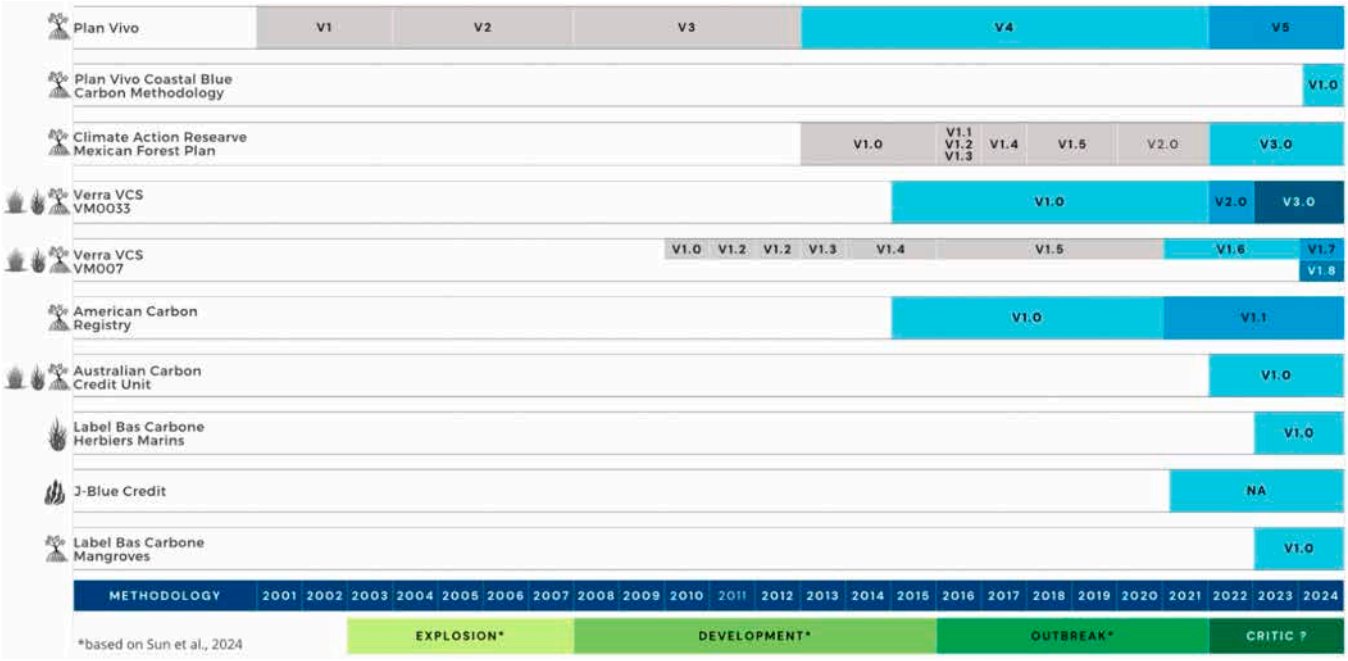

Fig. 1. Timeline of the updates to blue carbon project certification methods. Grey represents previous versions without consideration of blue carbon ecosystems, shades of blue represent versions accounting for blue carbon ecosystems. Shades of green represent the periods of evolution in blue carbon literature proposed by Sun et al. *Only the versions that take blue carbon ecosystems into account have been highlighted in shades of blue. Previous versions were solely for terrestrial ecosystems.*

has had seven new versions since 2016, with three updates in 2016 alone. Additionally, the VM0007 method has been revised seven times over the past fourteen years, and three times since they included blue carbon ecosystems.

A common theme among these methodological updates is the clarification of definitions and applicability conditions. For example, the CAR MFP has clarified project areas and activities for different types of land, allowing better adaptation to project specifics. Moreover, in its V3.0, the standard improved its methodology on additionality and permanence questions. Similarly, VM007 REDD+ and VM0033 have adjusted terms and conditions to incorporate new scientific knowledge and meet the changing needs of the market. Recent versions of methodologies, such as VM0033 V2.0, have included various activities like coastal ecosystem restoration, emphasizing the growing importance of blue carbon ecosystems. improving additionality and permanence issues in its V3.0. Subsequent versions (V1.3 to V1.7) expanded the scope of the REDD+ method to include a wider range of activities and ecosystems, including peatlands, tidal wetlands, as well as forest and coastal ecosystem restoration activities. In the V1.7, VM007 tries to tackle accounting issues by adjusting the estimation of uncertainty.

The methodologies have also strengthened environmental safeguards. Requirements for maintaining natural vegetation cover, as seen in CAR MFP V1.4, and tools for assessing climate risks, such as the VCS AFOLU non-permanence risk tool in VM0033, have been incorporated. Finally, improving transparency and accounting is a common feature. The methodologies have refined their verification protocols and integrated specific guidelines for new activities. For example, the reevaluation of additionality methods in VM0033 V2.0. V3.0 of VM0033 also corrects a provision allowing project areas to change during the project crediting period to accommodate land migration due to sea-level rise. This demonstrates a recognition of the impacts of climate change on coastal ecosystems and an adaptation of projects to address these challenges.

3.2. The emergence of scientific controversies

Based on our initial corpus of scientific articles, we find that 51 articles focus on blue carbon controversies. The five controversies identified in our corpus were also discussed during interviews. These themes represent some of the primary scientific controversies surrounding the carbon market (Table 1) and have tripled between 2016 and 2022, reflecting heightened awareness and deeper inquiry into the impacts and effectiveness of these markets.

The first scientific publications identified date back to 2009, marking the beginning of a critical examination of this sector. Since 2016, there has been a steady and significant increase in the number of critical papers on the subject (Fig. 2). This trend continues unabated to this day, demonstrating an increasingly engaged academic community in the assessment of environmental policies. Since the beginning of 2024, eight new articles have already been published, each highlighting different controversies and challenges associated with the blue carbon market. These recent publications underscore various concerns, ranging from issues of environmental integrity (Orford, 2024) and the effectiveness of emission reduction measures (Miller and Taylor, 2024) to the protection of marine ecosystems (Sapkota and White, 2020) and the socio-economic implications for local communities (Cormier-Salem and Panfili, 2016)

According to Sun et al., 427 articles on blue carbon were published in 2020, 482 in 2021, and 634 in 2022. By taking our corpus, 0.23 % of the papers in 2020 focused on controversies, 0.6 % in 2021, and 2 % in 2022, representing an increase of 67 % from 2020 to 2021 and 77 % from 2021 to 2022. This increase outpaces the overall rise in blue carbon papers, which saw an 11.4 % increase between 2020 and 2021 and a 24 % increase from 2021 to 2022. Although the number of papers focusing on controversies remains very low, scientific interest in these issues is noticeably rising.

Since 2009, there has been a general increase in the number of publications for all analyzed controversies, with a sharp acceleration starting in 2021 (Fig. 2). Environmental Integrity and accounting are at the forefront, closely followed by additionality. Social justice and carbon leakage are also experiencing growth, although somewhat less pronounced compared to the other categories (Fig. 2).

Among the 51 articles reviewed, 61 % focus on environmental integrity, 39 % address accounting issues, 35 % mention additionality

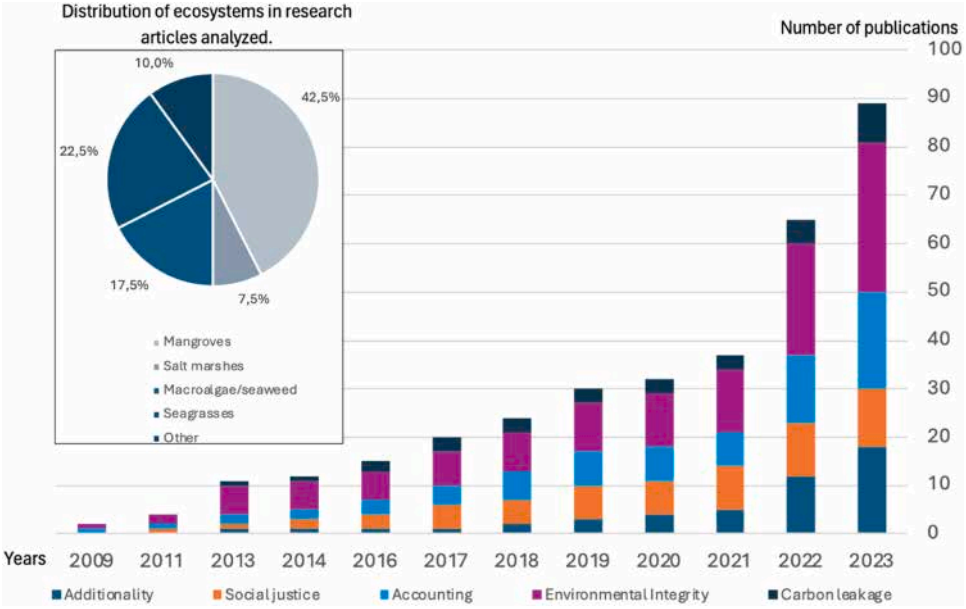

Fig. 2. Cumulative number of publications by controversies. *A single paper can address multiple controversies.*

issues, 24 % deal with social justice, and only 16 % mention carbon leakage. These percentages indicate the relative proportions of articles addressing each type of issue, thus showing the most frequently debated topics in the context of climate and environmental policy controversies since 2009.

There is a notable correlation between the geographic repartition of the number of blue carbon projects and the number of articles discussing controversies (Fig. 3a & 3b). Generally, countries with more blue carbon projects tend to have more scientific articles addressing related controversies. However, notable exceptions exist, such as the United States, which has a significant number of articles, but relatively fewer projects compared to its counterparts. This discrepancy suggests that while the U.S. may have a robust academic and research interest in blue carbon issues, the implementation of projects is not as extensive. In contrast, developing countries like India and Indonesia, which have emerging blue carbon projects, are beginning to see a rise in scientific publications addressing blue carbon controversies. This recent trend may indicate a growing recognition of the need to scrutinize and address potential issues within blue carbon initiatives in these regions.

3.3. Controversy about certification methods within the scientific community and knowledge gaps

The recent trend in scientific publications indicates a growing recognition of the need to scrutinize and address potential issues within blue carbon initiatives in these regions, highlighting an increasing global awareness and academic engagement with the complexities and challenges associated with blue carbon markets. This trend however does not imply a closing of these controversies.

Interviews reveal a controversy among scientists on the effectiveness of the carbon certification methods. Some of our interviewees find that they use “very good measurement systems” (#interview 3), while others highlight that there are “measurement problems with the methodology” (#interview 5). This reflects a diversity of opinions and approaches in this field. We can observe divisions in the academic world, as two interviewees shared: “In the academic world, some colleagues and some extremely close collaborators I have worked with were very irritated by this article” (#interview 2), “we published that, and then that upset some of the blue carbon practitioners […] Some people got angry” (#interview 5). Not all scientists agree on the rates of sequestration and storage related in different blue carbon ecosystems, primarily because “there are huge uncertainties in measuring the amount of CO2 that has been stored” (#interview 2).

Not all blue carbon ecosystems have received the same amount of scientific expertise. For example, the number of articles on mangroves has been relatively consistent over the years, with a notable peak in 2022 (five articles) and a total of 17 articles focusing on mangroves. Interest in macroalgae/seaweed has grown recently, also peaking in 2022 with three articles. The number of articles on seagrasses has become more recurrent, with at least one article each year since 2021, matching the peak interest in macroalgae/seaweed in 2022 (three articles) (Fig. 2). In contrast, only three articles discuss salt marshes, highlighting a lack of information on this ecosystem despite its inclusion in certification methods. The ’General’ category, which encompasses articles not specifically focused on one blue carbon ecosystem but on blue carbon more broadly, has seen a notable increase since 2020, with the highest number of articles (seven) in 2022 and a total of 22 general articles. The most studied ecosystem is mangroves, followed by seagrasses and saltmarshes. A new area of interest is emerging around algae, while marshes are the least studied. Most articles do not mention specific ecosystems (Supp Mat trend in the number of papers by ecosystem). Yet, all of these types of ecosystems are taken into account in methodologies, even though for some of them, like marshes, there is relatively little data available in the literature.

Are these diverging views among scientists reflected in the development and refinement of standards methodologies? In fact, we find that few scientific publications are cited in the current methodologies developed by the standards for the blue carbon market. The integration of these publications into methodologies seems relatively recent. For example, the first version of the VCS VM0033 methodology, published in 2015, contained only 23 references for 95 pages. In its second version, although the number of pages increased to 113, only 28 references are cited. Similarly, for the VCS VM0007 methodology, the reference section appears only from version 1.5 onwards, with only two IPCC good practice guides cited. These two references remain the only ones for the 56 pages of version 1.7 of VM0007. Regarding the Mexican Forest Plan by Climate Action Reserve, there were only 20 references from version 1 to version 1.5, despite an increase in the number of pages from 49 to 56. The American Carbon Registry does not cite any scientific reference in 129 pages. Only the Label Bas Carbone methodology on the protection of *Posidonia seagrass meadows* lists 48 bibliographic references for 33 pages. While there is a correlation between the increase in scientific

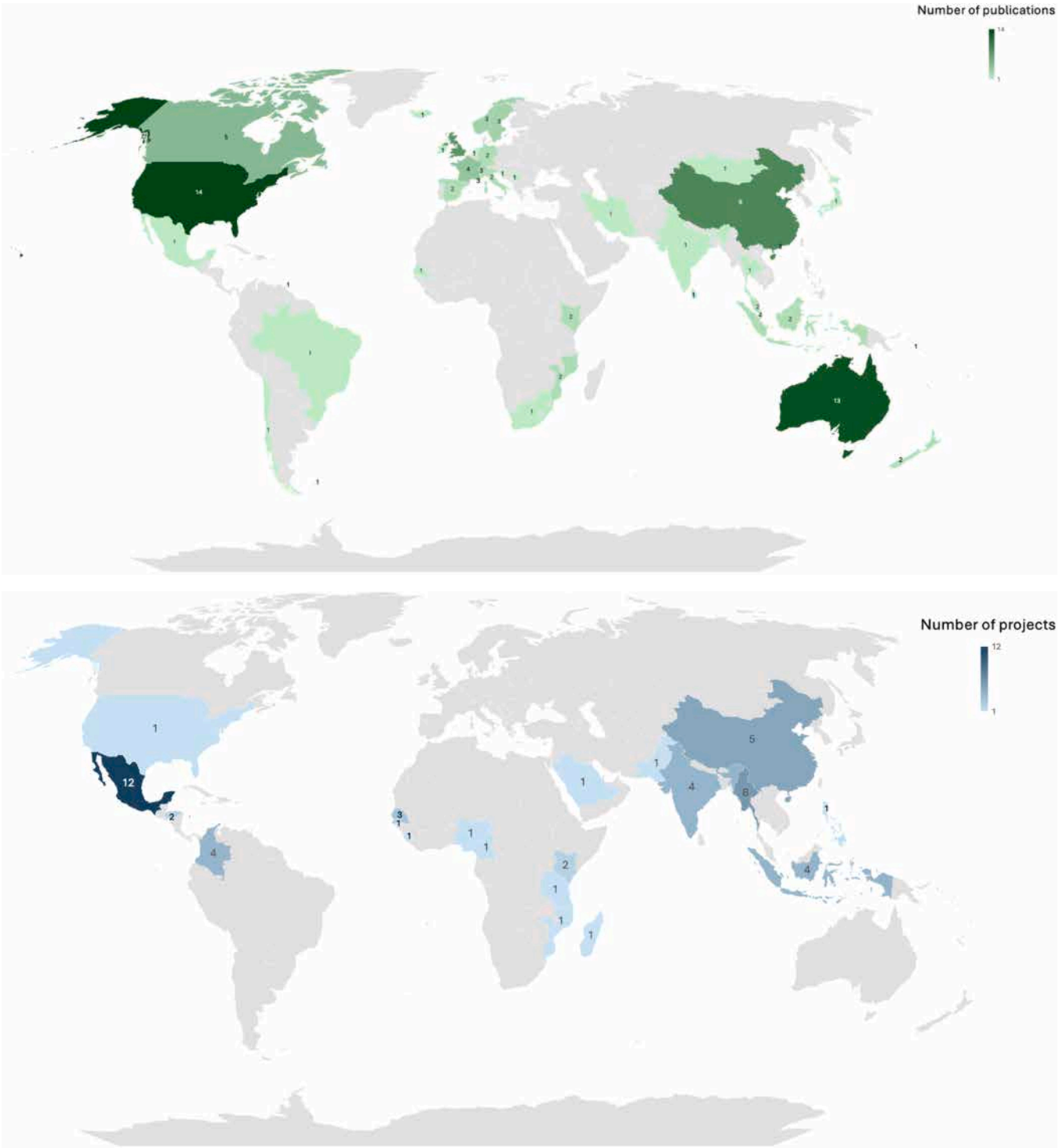

Fig. 3. A: Number of publications since 2009 for each country on blue carbon market controversies. A publication is attributed to a country according to the affiliation of the first author. Fig. 3B: Accredited, undergoing validation and under development blue carbon project in 2023. Data source: FairCarbon.

publications and the updating of methods, this does not necessarily imply a direct causal relationship. Other more complicated links may be at play, for instance through media attention.

4. Discussion

4.1. Does the multiplication of methodologies threaten the credibility of the carbon market?

While the diversity of methods can offer advantages, it also presents significant risks. Voluntary standards constitute a form of political regulation through the embedding of product and service markets (Fouilleux and Loconto, 2017). The proliferation of standards and

methods for carbon sequestration and accounting can threaten the credibility of the carbon market. According to Delacote et al. (2024), the credibility of carbon credits relies on transparent and verifiable methods. Moreover, research has shown that the proliferation of carbon sequestration methodologies can lead to confusion and a lack of coherence, making the market unstable (Arjaliès et al., 2013) and making it difficult to evaluate and compare projects (Crifo et al., 2020). In the interviews, the project developer expressed the need for more transparency from labels, investors, and developers to facilitate the exchange of information (#interview 11). Moreover, the absence of harmonized standards complicates the verification and certification of carbon credits, which can result in inconsistent outcomes or significant differences in the estimation of sequestered carbon, undermining investor confidence (Crifo et al., 2020). Thus, the diversity of approaches can compromise the trust necessary for market stability. During interviews, 4 scientists expressed concerns about the proliferation of standards and methods: "What can be feared about having many standards is that, although the advantage is that it reflects market diversity and the range of possible approaches, there are two pitfalls. The first is the potential disparity in credit quality, and the second is the difficulty for credit buyers to distinguish between different certificates" (#interview 4), with some even suggesting a single methodology: "We shouldn't have more than one scientific methodology so that everyone measures carbon burial the same way" (#interview 5).

These standards aim to reduce information asymmetry between consumers and producers of certification to build trust (Crifo et al., 2020) and play a similar role of a law in the absence of a central authority regulating the market (Reinecke et al., 2012). As explained by Crifo et al. (2020), the increase in knowledge production leads to an increase in demand and thus the multiplication of standards. As knowledge about blue ecosystems expands, we increasingly realize their potential for carbon sequestration. Consequently, the demand for the use and development of blue carbon projects is growing significantly. As a result, more and more standards are being developed to regulate this emerging market. While the exact cause-and-effect relationship might not be explicit, we can observe a strong correlation between the observation of Sun et al. (2024) on the growing number of publications on the blue carbon market and the increase, since the 2010s, in the number of methods and standards targeting blue carbon ecosystems. The proliferation of methodologies is closely correlated with the notable increase in scientific publications on the subject (Fig. 2; Fig. 3). The significant increase in the number of scientific publications and the development of new methods are indicators of an expanding research dynamic (De Pryck and Boettcher, 2024; Sun et al., 2024).

On the other hand, the diversity of methods allows for better adaptation to ecological and geographical specificities. The most recently developed methods are ecosystem-specific (Fig. 1). For instance, J-Blue Credit, whose first version was published in 2021, focuses on microalgae. Similarly, the two Low Carbon Label methodologies released in 2023 are specifically tailored to seagrass meadows and mangroves. This flexibility can maximize the potential for carbon sequestration while minimizing negative impacts for example, some are dedicated to specific seagrasses that are only found in the Mediterranean (LBC Herbiers Marins), while others are dedicated to wetlands everywhere (Verra VCS VM0033). Customizing methods based on local specifics can lead to more effective practices (#interview 3). There are emerging requests from various stakeholders for the development of new methodologies. For instance, investment funds and Anglo-Saxon organizations such as the Ofwat Innovation Fund have advocated for the development of a UK seagrass Carbon Code, which would serve as a voluntary standard for the UK (Ward et al., 2023).

4.2. Does the specification of methods improve their credibility?

The interactions between actors from techno-economic networks (Callon, 1991) that develop, produce, distribute, and disseminate methods to generate products and services in terms of standards by enrolling different actors from various networks (Fouilleux and Loconto, 2017). Additionally, a voluntary standard aims to establish an information exchange at a distance between consumers and producers regarding the intrinsic qualities of products, which are not visible to the naked eye, put on the market (Fouilleux and Loconto, 2017). Although carbon sequestration methods became more specific and incorporated more elements, certain ambiguities persist, particularly regarding verification and monitoring processes.

These ambiguities can significantly impact the credibility and reliability of carbon sequestration projects. The decision to reduce verification requirements or space out checks over time, especially for long-term certified projects, raises significant concerns (#interview 1; #interview 11). Local population, project developers, researchers, investors and standards may have distinct interests. Investors play a critical role by providing the necessary funding for projects, while also contributing to the development of standards and relying on scientific knowledge to inform their decisions. This interaction emphasizes the importance of credible and reliable scientific data in attracting and securing investment. They want assurance that the credit they purchase genuinely contribute to carbon sequestration, while project developers aim to gain access to markets and secure funding for their carbon sequestration projects through certifications to attract investors and buyers.

According to Cames et al. (2016), strict verification standards are necessary to ensure the reliability of carbon credits. When verification processes are compromised, investor and stakeholder confidence can wane, affecting carbon market stability. However, during interviews, 2 out of 5 scientists noted the necessity of simplifications in verification processes to meet practical demands: "We are aware of measurement biases, yet we must provide methods to verify and quantify stored carbon to a certifying body, necessitating reasonable compromises" (#interview 2). Additionally, "considering all uncertainties to guarantee sequestration is extremely costly and labor-intensive" (#interview 2), but compromises in verification can undermine environmental integrity (Streck and Chagas, 2007). Reduced requirements can lead to errors in sequestration estimates and lower transparency, although "overly stringent methodologies can significantly contract credit supply" (#interview 4).

These issues are not new as they have emerged in terrestrial ecosystems before (Kuik and Gerlagh, 2003; Murray and Graham, 2007; Richards and Huebner, 2012). The literature highlights that carbon offset projects face multiple challenges that undermine their credibility and effectiveness. Overcrediting and insufficient environmental impact have been frequently highlighted, raising concerns about the actual benefits of these projects (Delacote et al., 2024). Many offset initiatives fail to provide evidence of additionality, meaning they do not contribute to real emission reductions. Furthermore, the lack of reliable data presents a significant challenge in assessing the true impact of these projects (Fleming et al., 2022). Issues of permanence and leakage further complicate the situation, as there are concerns about whether emission reductions are lasting and whether emissions are simply displaced to other areas. Additionally, carbon offset projects must account for non-carbon externalities, which include both positive co-benefits, such as biodiversity conservation, and negative impacts, such as human rights violations. It is crucial to consider both environmental and social co-benefits and trade-offs in these projects. Involving local communities in project planning and implementation is also essential to ensure equitable outcomes and enhance the overall effectiveness of carbon offset initiatives (Fleming et al., (2022); Delacote et al. (2024)).

4.3. Impact of dialogue between standards bodies and scientists on methodological credibility

There is a trend among investors to financially support concepts originating from academia, even if they are still speculative, provided

they can be transformed into commercial products (Murray and Graham, 2007; #interview 7) leading to an instrumentalization of science.

Science and economics are closely intertwined, with science being a driver of economic growth (Stephan, 1996; Žažar and Roth, 2024). In recent years, there has been a shift from scientific knowledge as a public good towards the production of scientific knowledge for industries, where the production and value of scientific knowledge are determined by its instrumentality and economic desirability (Žažar and Roth, 2024) to develop blue carbon methodologies. Sun et al. (2024) categorized three periods from 2003 to 2022, spanning from the surge in research on blue carbon themes to the outbreak. This appears to substantiate Zazar's thesis. However, it is plausible that we are entering a new phase as of the early 2020 s, which we could term the "criticisms" phase (Fig. 2).

However, scientists may not necessarily know how the knowledge they produce can be used by businesses (Hellmann, 2007). To address this issue, Hellmann (2007) suggests initiating a communication process between science and businesses to "create […] this safe space where people can have these exchanges" (#interview 7)

Moreover, scientific knowledge is used to justify the development of public and private policies aimed at ensuring accounting and transparency (Kazancigil, 1998). Scientists provide critical knowledge and contributions to standards organizations. This dual relationship between scientists and standards highlights the complexity of actor interactions. Ideally, it should ensure that carbon project standards are grounded in the latest scientific research. During our interview with one of the standards, the interviewee explained an evolution in the reception of critical scientific papers. Previously, the "initial reaction was to defend the project and invalidate scientific findings. Today, the approach is to contact the researchers directly to understand their methods, data, and whether their findings can help improve projects or methodologies" (#interview 10). However, from the point of view of the research, the standards never contact them (#interview 2, #interview 4, #interview 5, #interview 8): "I emailed the lead authors of all international protocols offering to help update them, and only one responded, saying the critique was great and needed but wasn't working there anymore and then forwarded it without further follow-up" (#interview 5). Despite this, scientists expressed willingness to collaborate: "If Verra or someone asked me to work with them, I'd be happy to, but they're not asking" (#interview 5). For the project developer: "it's a bit like worlds that often ignore each other" (#interview 11).

Lack of communication and collaboration can lead to a gap between field practices and standard requirements. Goldstein et al. (2020) highlight the importance of adaptable standards to incorporate new scientific discoveries and environmental changes. It is important to be aware of the limitations of the relationship between science and society to establish mediation to bridge this gap (Eastes et al., 2011).

Through the mapping of stakeholders, we realize that scientists play a multifaceted and central role. They serve as both direct scientific resources for standards, participating in working groups organized by standard-setting bodies, and through multipartite coalitions (eg: One Planet Summit) that produce materials to improve the integrity of the carbon market. Additionally, scientists act as a source of direct criticism, publishing articles in academic literature and contributing to or being amplified by the media. This dual role highlights their influence and the critical nature of their contributions. Moreover, the boundaries between actors are porous and permeable. Stakeholders are not confined to a single role, which complicates the relationships among them. For example, one of the interviewees presented themself both as an academic and the co-funder of an advisory firm. Moreover, in three interviews, people navigating between the academic and private sectors have been highlighted. This fluidity adds complexity to the interactions and dynamics within the blue carbon market.

Collaborative networks and information exchange platforms can play a crucial role in facilitating dialogue (Bodin, 2017). This is why one of the two standards of which we interviewed representatives created working groups composed of "scientists, project developers, methodology developers, and representatives from major Non-Governmental Organizations (NGOs) like The Nature Conservancy and Wildlife Conservation Society" (#interview 10). Since the early 2000s, multipartite coalitions have emerged and positioned themselves as a representative grouping of various market actors (#interview 7) promoting the voluntary carbon market through best practice guides (Fouilleux, 2013) but also to assume the role "of watch dogs [which holds] holds everyone accountable, not just the standards, but the investors and the NGOs themselves" (#interview 7).

4.4. Uncertainty in sequestration estimates and controversies in measurement approaches

A key concern highlighted by one interviewee encapsulates a prevalent issue: "People will overestimate how much carbon can be stored, can be sequestered by blue carbon projects and they will use those incorrect inflated numbers to offset carbon emissions" (#interview 5). Accurate measurement and prediction of carbon sequestration in blue carbon ecosystems are complex and fraught with uncertainties. Variability in ecosystem types, regional differences, and evolving methodologies contribute to the difficulty in generating reliable estimates. This complexity can lead to the overestimation of sequestration capacities (see the debate between Williamson et al., 2024 and Mason et al., 2024). There is also potential conflict of interest where project developers and investors have financial incentives to present optimistic projections to attract funding and support (Delacote et al., 2024). This optimism bias can lead to inflated claims about the carbon sequestration potential of blue carbon projects. The absence of universally accepted methodologies and standards for measuring and verifying carbon sequestration in blue carbon ecosystems exacerbates the problem. Without standardized protocols, different projects may use varying assumptions and metrics (Lee et al., 2013), leading once again to overestimations.

Marine ecosystems, such as mangroves, seagrasses, and salt marshes, have unique ecological dynamics and interactions that require tailored approaches, both within the same ecosystem depending on location and between different ecosystems: "There is a factor of 20 difference in the amount of carbon stored between one mangrove and another, and significant differences even within the same mangrove" (#interview 2). Marine ecosystems play a crucial role in carbon sequestration. Their ecological dynamics are complex and influenced by factors like tides, salinity, and nutrient inputs. While mangroves are well-integrated into blue carbon projects, seagrasses and salt marshes remain under-studied and underrepresented. Seagrasses, for instance, can sequester carbon in their sediments over very long periods, but their inclusion in blue carbon projects requires adapted measurement and verification methods (Comte et al., 2024). There remains a lack of knowledge for several marine ecosystems. While mangroves are well studied, as noted in Sun et al. (2024): a cluster analysis based on keywords in the co-occurrence network highlights "mangrove carbon stock" as the only marine ecosystem emerging from this analysis.

Adapting terrestrial carbon market mechanisms to marine environments without considering ecological specifics can lead to inefficiencies. As noted by Friess et al. (2022a), the Verra VM0007 method has several limitations when applied to blue carbon projects. The addition of blue carbon modules to an existing REDD+ methodology limits their effectiveness due to the lack of adaptability to projects different from terrestrial ones, raising concerns about replicating land based issues in the ocean (#interview 2; #interview 8). The voluntary blue carbon market faces similar controversies to those seen in the voluntary terrestrial carbon market (West et al., 2023; Delacote et al., 2024). However, the challenges are more complex in the blue carbon context, largely due to limited knowledge about marine ecosystems and unresolved questions around land tenure and property rights, especially since these ecosystems are often situated on public land (Gonon et al., 2025). A tailored approach, considering each type of marine ecosystem, is essential to ensure the robustness and efficiency of blue carbon

sequestration strategies. Howard et al. (2017) highlight the need for developing specific methods for seagrasses and salt marshes to better capture their sequestration potential and ensure precise and verifiable measures, overcoming current limitations and allowing adjustments specific to marine ecosystems, thus improving the accuracy and relevance of blue carbon projects.

4.5. Beyond methodological robustness: broader social issues in sequestration controversies

Despite general guidance on developing Nationally Determined Contributions (NDCs) including the importance of community consultation (Dencer-Brown et al., 2022), one persistent criticism of the methodologies is the lack of consideration for local populations and the transparency of benefit redistribution (Cormier-Salem and Panfili, 2016). However, local populations "are very important for the success of any green project or any conservation-related projects, you need local people" (#interview 3), particularly due to their knowledge of the area.

Each region has unique characteristics, which means that conservation approaches must be adjusted to local needs and circumstances: a globalist, uniform conservation method is ineffective. Sodhi et al. (2011) highlight the failure of top-down conservation projects to integrate local socio-economic situations. They therefore propose a conservation approach that better incorporates human-nature interactions, particularly through a bottom-up approach. Local communities often have a deep understanding of their environment and can offer insights into which practices are likely to succeed.

Local populations, in collaboration with local conservation experts, can develop tailored approaches that acknowledge both the necessity of nature conservation and the need for local populations to access essential resources by designing carbon sequestration projects that do not deprive communities of their livelihoods but instead provide alternative benefits, such as employment opportunities or improved infrastructure. This will also allow local expertise to be integrated into conservation programs. Additionally, a bottom-up approach provides residents with a platform to voice their opinions and concerns. Indigenous peoples have long advocated for their knowledge to be recognized and respected as part of their right to self-determination (Nightingale and Richmond, 2022; Makondo and Thomas, 2018). Recognizing and incorporating Indigenous knowledge is particularly relevant in blue carbon ecosystems, such as mangroves and seagrasses, where traditional management practices often align with ecological preservation. Integrating this knowledge can enhance the effectiveness and cultural legitimacy of blue carbon initiatives, ensuring that conservation efforts support both carbon sequestration goals and community well-being.

5. Limitation and future research

The imperative for transparent project certifications, as stipulated by standards for the benefit of consumers and investors, is catalyzing the advent of rating agencies. Nonetheless, scholarly inquiry into their function as integral actors within the carbon market remains scant. Consequently, an empirical investigation is warranted to elucidate their influence on the standing of scientists, thereby potentially compromising their traditional role of highlighting issues or providing solutions. Of particular concern is the prospect that standards may increasingly base decisions not on scientific merit, but rather on the evaluations furnished by these agencies. Moreover our analysis does not account for cases where research was conducted in a country different from that of the authors' institutional affiliations, potentially leading to a geographic bias in the representation of research activities.

Carrying out interviews with a larger and more representative sample of stakeholders would be necessary to confirm hypotheses derived from the interviews. A larger sample would allow for capturing a greater diversity of perspectives and experiences, thereby enriching the depth and reliability of the drawn conclusions. As it stands, some key groups as standards or project developers are underrepresented. For future research, it will be crucial to include a larger number of participants to obtain a more comprehensive and nuanced understanding of the studied dynamics.

6. Conclusion

The correlation between the publication of articles that bring forth controversies and the updating of methods underscores the siloed nature of these two communities: the standards and the scientists, with limited arenas for dialogue. Despite the growing body of literature and methodological advancements, challenges persist within the blue carbon market. Scientific controversies, particularly surrounding additionality, carbon leakage, and environmental integrity, have become more prevalent, necessitating ongoing methodological refinement. The continuous updates observed in standards like VCS VM0033, and CAR MFP demonstrate efforts to enhance definitions, clarify applicability conditions, and improve verification protocols, yet ambiguities remain, especially concerning verification and monitoring processes. The proliferation of methodologies and certification standards has introduced confusion and inconsistencies, potentially undermining project credibility and effectiveness. However, this methodological diversity also allows for better adaptation to ecological and geographical specifics, maximizing carbon sequestration potential. While significant strides have been made, ongoing efforts are essential to improve methodologies, foster stakeholder collaboration, and address emerging challenges. A tailored approach, considering ecosystem-specific characteristics and integrating new scientific findings, is vital to ensure the efficacy and credibility of blue carbon sequestration initiatives.

CRediT authorship contribution statement

Delamarre Alice: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Adrien Comte:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Béatrice Cointe:** Writing – review & editing, Validation, Methodology, Conceptualization.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2025.104179.

Data availability

Data will be made available on request.

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