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Selective carbon credits: Market preferences and ecosystem restoration in Senegal

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A B S T R A C T

The voluntary carbon market is presented as a solution to fund land and ecosystem restoration in developing economies. While the empirical literature has focused on assessing its ecological effectiveness, limited attention has been given to how this market interacts with other funding streams within national contexts. Delineating the types of projects that the voluntary carbon market can effectively fund is essential for designing a coherent and integrated funding strategy at the national level. This paper investigates the contribution of the voluntary carbon market to ecological restoration projects in Senegal. Grounded in transaction costs and organizational economics and drawing on a novel dataset of restoration projects from 2007 to 2023, we identify a pattern in which the voluntary carbon market focuses on significantly less context-specific and more certain restoration protocols. The uncertainty of ecological outcomes and the specificity of natural capital explain the recourse to the market, and the market shapes specificity by attempting to standardize assets and facilitate transactions. This impacts restoration protocols, ecosystem targeted and local benefits. Our analysis offers a detailed understanding of how market preferences influence funding allocation and project implementation. Our findings underscore the need to integrate market-based funding with other mechanisms to address land degradation.

1. Introduction

Ecosystem restoration is listed as one of the top global priorities for addressing climate change and biodiversity loss, yet it is hindered by a lack of financial resources (Brancalion et al., 2019; Deutz et al., 2020; Barbier, 2022). Numerous pledges have been agreed upon to initiate or accelerate the recovery of ecosystems globally (the Bonn Challenge, The United Nations Decade for Ecosystem Restoration). The Global Biodiversity Framework established by the Convention on Biological Diversity in 2022 includes a goal of at least 30 % of degraded terrestrial, inland water, and coastal and marine ecosystems effectively restored by 2030 (Target 2). The financing gap for restoration is estimated to be between $300 billion and $ 900 billion globally (Ding et al., 2017; Barbier, 2022; Mirzabaev and Wuepper, 2023).

Most-used methodologies in the emerging field of economics of ecosystem restoration (Mirzabaev and Wuepper, 2023) focus on evaluating the economic implications of ecosystem restoration through the costs of land degradation and the associated benefits of restoration (Aronson et al., 2010; Groot et al., 2013; Nkonya et al., 2016) and the costs of restoration (Iftekhar et al., 2017; Brancalion et al., 2019; Bodin et al., 2022) concerning different lands, technologies and success rates (Chazdon, 2008; Tong et al., 2017; Boerema et al., 2018). Cost-benefit and cost-effectiveness analyses aim to inform investment decisions and optimal landscape planning (Birch et al., 2010; A. Mirzabaev et al., 2022; Silva et al., 2023). However, the funding gap cannot be solely attributed to the lack of awareness about total costs and benefits (Mirzabaev and Wuepper, 2023). Further research is needed to establish effective mechanisms for channeling funds, which take into account the perceptions of each stakeholder and their expectations in terms of costs, revenues, risk and uncertainty (Nedopil, 2023).

The use of “innovative” economic and financial instruments for biodiversity has received increasing attention in both the academic and political spheres (Vatn, 2018; Barbier, 2022; Karolyi and La Puente, 2023). The funding landscape for biodiversity conservation and

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restoration is expected by many to shift, or at least expand, from a donor-funding model to an investor-driven approach (Crédit Suisse et al., 2014). In this context, carbon offsetting is perceived to be a solution, as carbon is the only "currency" that directly finances restoration, besides donations (Löfqvist et al., 2022). The voluntary carbon market is seen as providing a means for developing countries with limited financing access to raise significant private capital to support biodiversity conservation.

Empirical research has primarily focused on assessing the effectiveness of these funding mechanisms independently, such as payments under the REDD framework (Groom and Palmer, 2012; Simonet et al., 2019; Sunderlin et al., 2024). However, to inform resource mobilization strategies at the national level, it is critical to identify which types of ecological restoration projects are likely to be effectively funded through market-based instruments and which are not. From a recipient country's perspective, assessing the types of projects the carbon market is most inclined to fund enables the design of an effective policy mix that combines market-based instruments with other funding streams (Ring and Barton, 2015). This first requires delineating which projects are best suited for funding through the voluntary carbon market rather than other funding channels.

This study questions whether the voluntary carbon market prioritizes certain types of land restoration and why. We draw on organizational economics and transaction costs (TC) analysis as a relevant theoretical framework for understanding the conditions under which an ecological restoration project suits market-based mechanisms, and when alternative funding approaches may be necessary. Extensive literature demonstrates that TC minimization can help explain governance structure and decision-making by economic agents in market transactions (Williamson, 1981; Williamson, 1985; Leffler and Rucker, 1991; Lyons, 1994; Moss et al., 2001). TC determine the problems that each institution or organization intends to solve (Marshall, 2013) and thus may inform coordination among them.

Previous studies demonstrate that TC hinder the capacity of restoration projects to meet market preferences (Kedward et al., 2022). Indeed, ecological restoration is inherently uncertain (Folke et al., 2004; Scemama and Levrel, 2019) and involves specific TC linked to the heterogeneity of social and ecological systems and the diversity of objectives across development projects (Norgaard, 1994). From an investor perspective, high costs of monitoring, due diligence, and the inherent complexity of ecological restoration protocols further contribute to these challenges (Phan et al., 2017a; Bodin et al., 2022; Kedward et al., 2022). The varying levels of uncertainty across ecological restoration protocols and sites are likely to influence investment decisions, directing the preferences of market mechanisms.

Our study proposes to perform a detailed empirical analysis of TC at the project level to explain the choice of certain geographical locations and protocols for projects funded by the voluntary carbon market compared to other funding streams. We build specifically on Scemama and Levrel (2019)'s work on the connection between biophysical specificity and uncertainty of restoration projects and their organizational structure.

We selected Senegal as a case study to examine how the voluntary carbon market supported land restoration efforts and its interaction with other potentially overlapping sources and mechanisms such as development aid, philanthropy, and public sector funding during the same period. The need to address land degradation and desertification in West Africa and in the Sahelian zone is highlighted in international restoration perspectives (FAO and AUDA-NEPAD, 2021). Regarding coastal ecosystems, West Africa contains 14 % of the world's mangrove area, is internationally recognized as a carbon sink (Pendleton et al., 2012), and has lost on average 25 % of coverage between 1980 and 2006 (Bryan et al., 2020), for both anthropic and climatic reasons. Senegal is committed to Land degradation neutrality objective (UNCCD on desertification). Senegal has a long history of restoration and reforestation policies, starting from colonial policies (Bernard, 1993) to large-scale national campaigns in the 1980s and 1990s, continuing up to the present day (Dieng et al., 2023). Implementing such policies might be understood within a long history of rural development (Mazzero et al., 2021; Ka et al., 2021). Today, numerous restoration programs led by public and private actors are implemented, primarily focused on two types of action: mangrove restoration in coastal areas and dryland reforestation as a part of the Great Green Wall project.[1] Carbon finance is already a significant funding source in Senegal, with the implementation of large-scale mangrove restoration projects since 2009 and the establishment of a carbon bank for the Great Green Wall project in 2015 (Pan African Agency of the great green Wall, 2023). 2 241 730 credits have been issued in Senegal, 510 296 for Forestry and Land use (Ivy et al., 2023). The restoration projects implemented in diverse biomes, including semi-arid zones and wetlands, present an opportunity to explore how different funding mechanisms are allocated based on their capacity to address a wide range of ecological needs and conditions.

Conducting a comprehensive analysis of TC associated with ecological restoration in Senegal requires a deep understanding of the national context. This work stems from and requires an ambitious partnership between French and Senegalese research institutions in economics, ecology, and agronomy. It requires extensive fieldwork and data collection, allowing for a detailed examination of how funding mechanisms are implemented. Our data collection covered national, international, public, private, and hybrid initiatives. To our knowledge, no prior study has undertaken such an extensive analysis of ecological restoration efforts at a national scale.

We conclude that projects funded by the voluntary carbon market are distinct from other restoration initiatives. This difference is only partially attributable to profitability within the carbon market. An analysis of TC across various projects indicates that, on average, carbon market projects focus on some ecosystems, implement less uncertain and more standardized protocols, and reduce the specificity and complexity of their design compared to non-carbon market projects. This distinction provides a compelling explanation for the selective support of restoration efforts observed in this case study. However, the pursuit of lower transaction costs—related to the organizations involved and ecological protocols—can undermine local benefits.

By characterizing the voluntary carbon market's selective support for certain restoration projects over others and its contribution to national restoration efforts, this paper contributes to three literatures.

First, we contribute to the call for research into financing nature (Karolyi and La Puente, 2023) by focusing on implementation. Our analysis of the contribution of the voluntary carbon market at a national level helps identify the range of projects that can benefit from this specific funding channel. The tangible ecological and organizational considerations for implementation that we focus on complement the increasing number of studies focusing on the investor side of rising biodiversity finance (Löfqvist et al., 2022; Flammer et al., 2023).

Second, we contribute to the aforementioned field of ecosystem restoration economics (Mirzabaev and Wuepper, 2023). By studying the interaction of funding mechanisms in Senegal, we question the appropriate scale and parameters for assessing the effectiveness of each instrument, not only at the project level but also regarding nationally determined ecological needs. Our results highlight the distinct capacities of various funding mechanisms in effectively addressing local ecological restoration needs. This limited substitutability argues for the consideration of diverse funding mechanisms in cost-effectiveness and landscape planning analyses.

[1] The African Union's Great Green Wall program aims to combat desertification and land degradation in the Sahel region by planting trees and other vegetation on 100 million hectares (Goffner et al., 2019).

Third, our application of the TC framework to the carbon funding of land restoration in Senegal contributes to different fields of TC studies. TC analyses of the voluntary carbon market have concentrated on the content of contracts and deals rather than their implementation (Pearson et al., 2014). To address the implementation challenges, we draw from the broader TC literature on resource management and environmental policy design (Coggan et al., 2010). Most empirical research in this field has focused on Western contexts. In contrast, literature on TC that addresses cross-border markets, development assistance, and foreign direct investment in developing countries (Sara and Benjamin Newhouse, 1995; Acharya et al., 2006) is less abundant, yet crucial for understanding coordination challenges in globally defined, market-based mechanisms that fund environmental action. More specifically, our study innovates on three key methodological aspects: 1) We extend the scope to include TC related to ecological engineering, alongside traditional organizational parameters, following Scemama and Levrel, 2019; 2) We conduct a country-level analysis in a developing country to understand how TC influences the contribution of a globalized market across different projects compared to other funding models; 3) our study addresses the ecological and social consequences of minimizing TC within market mechanisms through extensive fieldwork and interviews.

This paper is organised as follows: Section 2 outlines the three key steps of our methodology, including the data collection process and the procedures for assessing costs and TC factors for each land restoration project implemented in Senegal since 2007. Section 3 presents our results, highlighting the distinct features of the two groups, "carbon market projects" and "non-carbon market projects". Finally, Section 4 discusses the implications of our findings, emphasizing the contributions to the existing literature. Section 5 concludes.

2. Materials and methods

Our method follows three key steps. First, the data collection phase involves systematically identifying restoration projects in Senegal and their key characteristics, conducting site visits and carrying out 35 semi-structured interviews. Second, we outline a set of factors theoretically aligned with market preferences, such as profitability and low TC, and adapt these factors to our case study drawing on fieldwork, interviews, and relevant literature. Finally, we assess the level of TC factors for each restoration project implemented in Senegal between 2007 and 2023.

These three steps determine whether, in Senegal, the carbon market prioritizes certain types of land restoration and, if so, whether the TC approach provides an explanation for the allocation of these funds in relation to other land restoration projects and needs.

2.1. Data collection

2.1.1. A comprehensive database of restoration projects

To be considered in our analysis, projects have to be implemented in Senegal from 2007, coinciding with the launch of the Great Green Wall Project and the introduction of a nationally designated authority for the Clean Development Mechanism in Senegal until 2023. We identify the first set of 277 environmental and biodiversity projects through 11 publicly available sources, encompassing national, international, public, private, and hybrid initiatives (Appendix A1). Then, we filter restoration projects based on the keywords used in the project descriptions. To be included, project documents must contain one of the following terms: "restoration", "reforestation", "desertification", "erosion[2]", or their equivalents in other languages. With this protocol, we can expect our list of projects associated with the restoration of land and ecosystems over the period to be exhaustive. For each project, we collect data on the stakeholders involved, the restoration practices that are implemented and the geographic coordinates of each plot[3] (Table 1). Hereafter, "carbon market projects" refer to the nine projects certified on the voluntary market or in the certification process, while "non-carbon market projects" refer to the other projects in our dataset that are not intended for certification.

The category of each project (Table 1) differentiates between agriculture, mangrove and forestry projects. Agriculture refers to the implementation of sustainable agricultural practices for soil restoration, including agro-ecology, agroforestry, sustainable agriculture, measures to avoid soil salinization, and natural regeneration projects when integrated with farming. The "agricultural projects" category also include livestock management. Mangrove projects refer to reforestation or afforestation of mangrove trees in coastal areas and deltas. Forestry projects focus on reforestation, afforestation, and forest conservation. The "Agriculture" and "forestry" categories are then refined with a list of restoration practices implemented by the project (Appendix B).

Eight projects were related to other restoration practices including pollution mitigation and waste management, reclamation of mining sites, sustainable management of fishery, and trans-boundary cooperation or long-term policy support without a clear restoration protocol mentioned. Since these projects fall outside the potential scope of intervention of the voluntary carbon market, they were not included in the subsequent steps of our analysis.

2.1.2. Site visits and semi-structured interviews

We conducted semi-structured interviews with key stakeholders identified during the data collection process and undertook site visits between February and June of 2023. We visited restoration projects across four bioclimatic regions in Senegal (Niayes, Sylvopastoral zone, Casamance, Groundnut Bassin) including in the localities on the Great Green Wall (Widou, Téssékéré, Ranérou, Labgar, Yonoufféré, Velingara Ferlo, Lingu'ere, Dahra, Matam, Louga) and the mangrove plantations in the Saloum delta (Joal Fadiouth, Palmarin, Toubakouta, Somone) and in Casamance (Ziguinchor, Kafountine, Adeane, Niassya). We conducted 35 semi-structured interviews with restoration stakeholders, including those from public administration, non-governmental organizations (NGOs), private-for-profit organizations, and development banks (Appendix C1). Semi-structured interviews allow us to explore participants' experiences while maintaining a structured approach to gather comparable data across different interviews (Andalib, 2024). Our interview guide includes questions about organizational structure, funding sources, implementation costs, roles and responsibilities, project implementation strategies, and specific challenges encountered in operations (Appendix C2). The interviews and site visits provide a comprehensive understanding of the diverse restoration protocols and stakeholders involved in ecological restoration in Senegal.

2.2. Data treatment

2.2.1. Comparative analysis

A preliminary descriptive statistical analysis determines if "carbon market projects" and "non-carbon market projects" groups differ based on their ecological and organizational features. The output of a Multiple correspondence analysis (MCA) followed by Hierarchical Clustering on Principal Components (HCPC) using the FactoMineR package (Husson et al., 2024) indicates whether the groups proposed by these classification methods distinguish projects according to whether or not they belong to the carbon market. The list of variables is adapted from the work of Coppus et al., 2019 on restoration projects in Latin America and the Caribbean. Variables reflect the socio-economic, biophysical, organizational, technical, and financial aspects of each project. We supplement these variables with more granular information on restoration

[2] Artificial infrastructures designed to prevent coastal erosion have not been considered as ecological restoration in our selection.

[3] A project usually has several intervention zones, hereafter"plots".

Table 1
Summary of data collected for each project.

General Project Information	
Project	Full project name, Affiliated program
Dates	Project start and end dates
Finances	Total project amount in euros
Size	Intervention area in hectares
Certification	Carbon certification status and standards (MDP, Verra, etc.)
Category	Mangroves, Forest, Agriculture
Indicators	Quantitative indicators (ha, trees, teqCO2, etc.)
Stakeholder Information	
Status	Various statuses (Association, NGO, Government agency, etc.)
Establishment	Year of establishment
Location	Headquarters' coordinates
Finance	Annual revenue
Role	Role in the project (Funding, Design, etc.)
Localities of Intervention	
Localities	Localities' names and coordinates of plots
Region	Agroecological region of each locality (Casamance, Sylvopastoral zone, Groundnut Bassin, Niayes, Eastern Senegal, Senegal River Valley)
On-Ground Practices	
Reforestation	Reforestation, afforestation, agroforestry, natural regeneration, re-vegetation of rangelands and pasturelands
Other Practices	Other funded practices (Energy production, Sociocultural valuation, etc.)

practices (Appendix B & D).

2.2.2. Cost analysis

To define the range of projects that could be theoretically supported by the voluntary carbon market in Senegal, we assess costs, which include both establishment and maintenance expenses (1) and a broader assessment of TC (2). Our research assesses costs from the perspective of actors in the voluntary carbon market, a globalized market driven by carbon offsetting and market efficiency. Other restoration stakeholders may prioritize different benefits and outcomes.

2.2.2.1. Expected profitability of each project on the voluntary carbon market. The voluntary carbon market should prioritize projects where the establishment and maintenance costs can be effectively covered by revenue from carbon credit sales, as the carbon market framework hinges on the ROI tied to carbon sequestration (Löfqvist et al., 2022). For each restoration project, we first compute the expected gross profitability on the voluntary carbon market.

$$\pi = \frac{\mathrm{SR} \times \mathrm{P} \times 30}{C_e + 30C_m}$$

where SR is the expected sequestration rate (in tons of CO_2 equivalent per hectare), P is the carbon credit price (USD per ton), C_e is the Establishment cost (USD per hectare), C_m is the Annual maintenance cost (USD per hectare), 30 is the project duration (years).

Establishment costs (C_e) refer to upfront capital investments, including engineering works, planting or seeding, and fencing. Maintenance costs (C_m) include ongoing management and monitoring direct expenses necessary to sustain projects (Iftekhar et al., 2017). To estimate these costs, we define the main costs based on the stakeholder interviews (Table C1), project documents, and the academic and grey literature (Mirzabaev et al., 2022; Sow et al., 2016; Nkonya et al., 2016; 2021, Giger et al., 2018). We focus on literature and data relevant to Senegal, West Africa, and sub-Saharan Africa. West Africa is often underrepresented in global cost analyses, particularly in the context of mangrove restoration (Bryan et al., 2020; Su et al., 2021). This geographic focus is essential, as the literature suggests that restoration costs are considerably lower in developing countries compared to developed ones, primarily due to lower labor costs (Bayraktarov et al., 2016).

The 30-year crediting period corresponds to the standard duration of carbon credit issuance.

The expected sequestration rate of the project (SR) is not systematically available in project documents. We complement projects documents of already certified projects in Senegal with the IPCC 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[4]. We estimate potential returns by hectare using the international carbon price (P) for forestry and land use on the voluntary carbon market (Donofrio et al., 2023) (5.40 US$ per ton in 2020). It is worth noting that the price of carbon used to calculate benefit may be lower than the actual selling price of a ton of carbon equivalent, according to interviews (up to 20 US$ per ton). Given the volatility and opacity of carbon prices, which have fluctuated throughout the study period, we applied a consistent price across all ecosystem types. This approach focuses on comparing sequestration capacity rather than reflecting real commercial benefits. We defined expected returns for six restoration protocols: Agroforestry in moist land, Agroforestry in dry land, Cropland in dry land, forest in dry land, Grassland, and Mangroves.

2.2.2.2. Assessing uncertainty and specificity levels. Building on Williamson (1981), we analyze uncertainty and asset specificity to draw boundaries between funding models and organizational structures in ecological restoration projects. Markets minimize TC when investments are non-specific and uncertainty is low, a principle applicable to natural assets (Scemama and Levrel, 2019).

Asset specificity refers to"specialized investments that cannot be redeployed to alternative uses or by alternative users without a loss in productive value" (Williamson, 1981, 1998). This concept can relate to site specificity, physical specificity, and human asset specificity (Williamson, 1981). A low site specificity reduces inventory and transportation costs due to the positioning of successive stations. In the case of ecological restoration, the project's location shape ecological interactions and ecosystem resilience. As highlighted by Scemama and Levrel (2019), site specificity in the case of ecological restoration can be understood as a strong dependency on ecosystem dynamics. Physical specificity pertains to the equipment, machinery, and infrastructure required for production and transaction processes. In the case of ecological restoration, we consider the equipment necessary for implementing restoration protocols. Human asset specificity relates to the specialized expertise needed, here it relates to the complexity of ecological engineering, requiring advanced knowledge and technical skills (Williamson Oliver, 1985; Coggan et al., 2013; Scemama and Levrel, 2019).

[4] We select data for sub-Saharan Africa when available for the following ecosystems and practices: Agroforestry (Table TABLE 5.2); Forest dryland (TABLE 4.9 (UPDATED)), Tropical dry forest Africa (TABLE 4.4), Grassland (Table 6.7)

Table 2
Factors influencing TC in restoration projects in Senegal.

	Features	Reduces TC (−1)	Neutral (0)	Increases TC (+1)
Ecological factors of specificity	Labor knowledge	X	*	Farmer-managed natural regeneration, soil organic fertilization through compost and manure, or eradication of alien or invasive species, depollution of water sources, fishery management.
		Mangrove restoration	*	Forestry and agricultural projects
	Water management	Forestry and agriculture projects on moist land.	*	Reforestation and afforestation project in the Silvopastoral zone.
	Establishment costs and equipment	Grassland, agrofestry, moist land, cropland. Mangrove restoration	X	Forestry and agroforestry projects in overgrazed land.
	Plants availability	Restoration protocols use seeds and plants available on site.	*	Restoration practices include seedlings and tree nurseries.
	Site replicability and availability	X	*	Mangrove ecosystems restoration as a specific protocol
		X	*	Mangrove projects implemented after 2018 in localities that have already been restored.
		X	*	All the projects after 2020 in the localities that host restoration initiatives frequently.
	Standardized practices	The sum of reported restoration practices or activities is up to 3.	X	The sum of reported restoration practices or activities is greater than 3.
		The project is focused on one type of restoration only.	X	The project involves supervising simultaneously revegetation of grassland and reforestation or afforestation.
	Economies of scale	The project has more than ten plots.	The project has between 4 and 10 plots	The project has up to 3 plots.
		The project restores more than 5000 ha	The project restores between 1000 and 5000 ha	The project restores up to 1000 ha
Ecological factors of uncertainty	Maintenance	*	X	Agricultural projects and agroforestry protocols.
	Survival rate of plantations	Mangroves projects, Agricultural projects, Grassland restoration	*	Forestry projects Agroforestry projects
	Carbon seq. and expected financial returns	$\pi \geq 1$	*	$\pi < 1$
	Fences	Area enclosures mentioned in the protocol	The project is not located in overgrazed lands	The project is located on overgrazed land without enclosures.
	Measurement difficulties	X	*	Soil carbon monitoring (Mangrove and agricultural projects)
	Observability	Reforestation and afforestation practices	X	Other restoration practices (soil, depollution, water management)
		Focus on ecosystem restoration.	X	Funding of additional project components such as energy production and energy efficiency programs, income generating activities, socio-cultural valuation, governance, and institutional support at a local or national level.
	Establishment time	Agricultural projects	Natural regeneration projects in arid zone Mangroves projects	Afforestation projects
Organizational factors of specificity	Centralisation and involvement of a National authority	*	X	Involvement of a national or governmental agency.
	International partnership and communication	The project is part of an international program (ex: Great Green Wall)	X	*
	Site specificity	The different intervention zones of the project are located into the same agro-ecological region	X	The different intervention zones of the project are located in various agro-ecological regions.
	Transaction specificity		X	*
		The project starts after 2015	The project starts between 2010 and 2015.	The project starts before 2010.
		X	*	The project involve transborder cooperation.
Organizational factors of uncertainty	Monitoring and behavior of parties	One stakeholder is identified as being in charge of the monitoring.		No monitoring

(*continued on next page*)

Table 2 (*continued*)

	Features	Reduces TC (−1)	Neutral (0)	Increases TC (+1)
		Quantitative indicators for monitoring.	*	The project does not include a data collection process for quantitative indicators.
	Observability	*	X	Impact measurement and performance indicators concern local communities and social impact.
	Local Benefits and Behavior of parties	Funding and implementation of income generated activities out of the restored perimeter.	X	*
	Recurring transactions and behavior of parties	Experienced stakeholders –involved in at least three other projects - in charge of the implementation.	X	*
	Heterogeneity of agents	The project is funded only by entities that have the same status (private or public)	*	Public and private funders for the same project.
		The project is implemented only entities that have the same status (private or public)	*	Public and private implementers for the same project.
		Maximum two stakeholders in charge of the implementation.	X	More than two stakeholders in charge of the implementation.
		One single funder for the project	X	Multiple funders of the project.

Legend : * : All other projects have this score. X : No project is concerned by this score.

Note: The factors are adapted from Coggan et al., 2010; McCann (2013); Coggan et al., 2013; and Phan et al., 2017. Additional literature sources were used to identify ecological and organizational characteristics of the projects, such as sequestration potential (IPCC 2019), survival rates (Mirzabaev et al. 2022), sustainable land management (Tschakert, Petra. 2004; Sow et al. 2016), land restoration impacts in drylands (Tucker et al. 2023), design principles for ecological engineering (Bergen et al. 2001) and transaction costs in environmental projects (Mettepenningen et al. 2009). These sources complement information gathered from interviews and site visits. Further justification, details, and references for this table are provided in Appendix D.

Uncertainty arises from organizational factors, such as unclear procedures or unpredictable behavior of contracted parties. In environmental projects, time lags, variability in space and time, biological diversity, unpredictable environmental outcomes, and future ecosystem conditions increase uncertainty (Coggan et al., 2010, McCann, 2013, Phan et al., 2017, Scemama and Levrel, 2019).

Through a comprehensive literature review on TC in environmental policies (McCann et al., 2005; Coggan et al., 2010; McCann, 2013) and previous TC studies on the voluntary carbon market (Phan et al., 2017), we identified 36 drivers of uncertainty (18) and specificity (18) that influence TC, as summarized in Table 2.

We distinguish the elements of specificity and uncertainty arising from biome characteristics and ecological practices (21) from those linked to a project's organizational structure (15), including contract terms, governance, and stakeholder behavior. This distinction is essential for identifying TC drivers that are "amenable to change" (McCann, 2013) i.e. those shaped by project leaders' choices, versus the ecological conditions of restoration. Our analysis aims to determine whether carbon market projects minimize TC primarily through organizational design or by selecting restoration protocols and actions suited to less uncertain biomes or ecosystems requiring less specific restoration practices (Table 2, Appendix D).

We do not include TC factors specific to the carbon certification process or the voluntary carbon market itself. Our goal is to compare project diversity to identify those that meet market requirements. TC associated with the carbon market will apply uniformly across all projects and are therefore excluded from this analysis. For instance, projects within this market require 30 years of monitoring, leading to significant TC. While the duration of monitoring itself is not taken into account, we consider six specific project features related to monitoring factors. This approach enables us to capture variations in monitoring complexity across projects, based on ecological and organizational attributes.

The influence of each project feature on TC is evaluated, with a score of −1, 0, or 1 assigned based on the criteria outlined in Table 2 (Appendix D). These scores are then aggregated by category—first into ecological uncertainty, ecological specificity, organizational uncertainty, and organizational specificity; then into broader dimensions of ecological, organizational, uncertainty, or specificity; and finally, into an overall TC score using the arithmetic mean. Each feature's scores are aggregated and normalized, yielding a final value ranging from −1 to 1.

To assess differences in TC levels between carbon market and non-carbon market projects, we conduct a Mann-Whitney *U* test, which is well-suited for comparing distributions between two independent groups without assuming normality. This test allows us to determine whether the differences in TC scores between carbon market and non carbon market projects are statistically significant.

3. Results

Our results show that the voluntary carbon market funds projects that are distinct from other restoration initiatives (Section 3.1). This difference is only partially explained by the variation in the expected profitability of projects on the carbon market (Section 3.2). Analysis of TC across projects reveals that, on average, carbon market projects are significantly less uncertain and less specific than non-carbon market projects on both organizational and ecological features (Section 3.3). This provides a compelling explanation for the selective market's support of restoration efforts in this case study. The pursuit of low TC, however, can come at the expense of local benefits (Section 3.4).

3.1. Distinct features of carbon market and non carbon market projects

Our final dataset includes 76 restoration projects that intervene in 769 plots in 273 localities in Senegal. Localities, restoration protocols, and project organization vary between the "carbon market projects" group and the "non-carbon market projects" group. The nine carbon

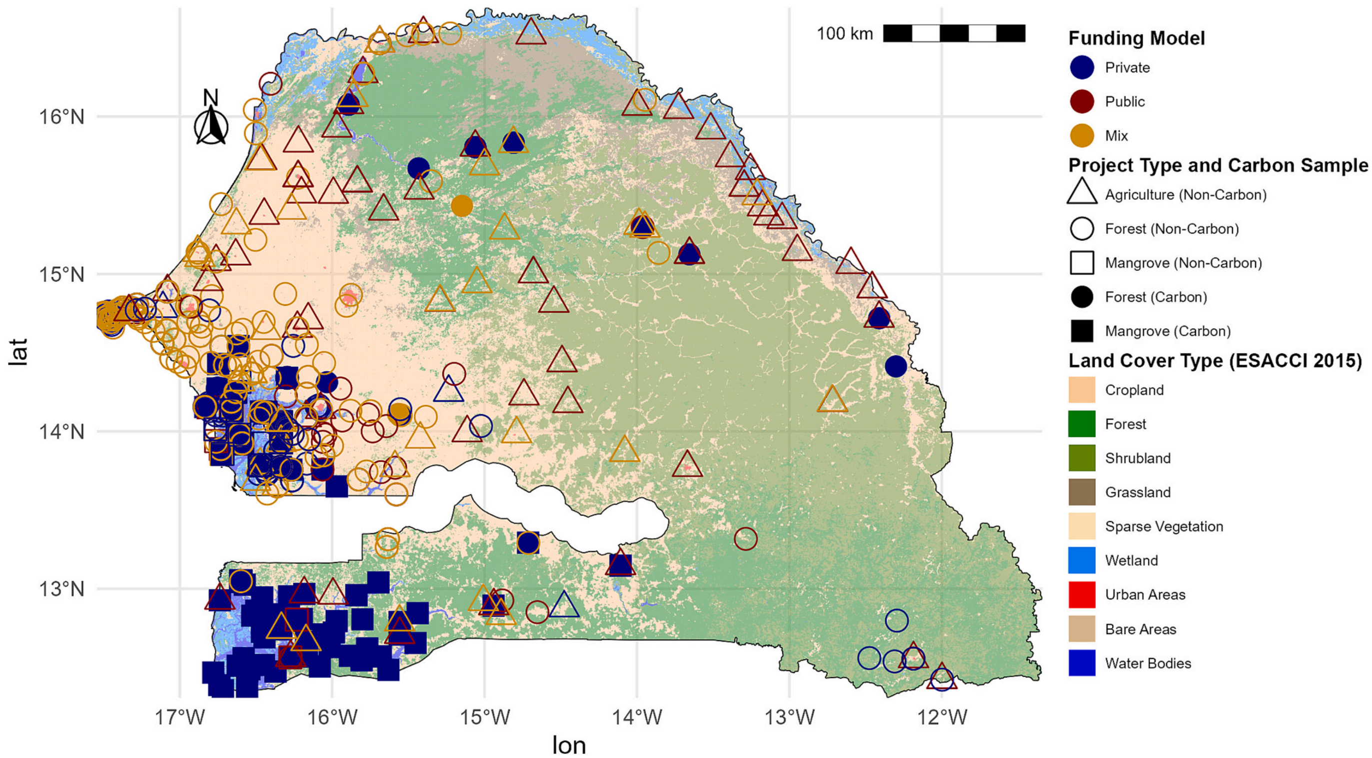

Fig. 1. Spatial distribution of carbon and non-carbon funded restoration projects in Senegal (2007–2023).
Note: Land cover types are based on ESA CCI Land Cover data (2015). Casamance region (12°N to 13.5°N latitude; 15.5°W to 17°W longitude); the main path of the Great Green Wall initiative (16°N to 14°N latitude; 16°W to 12°W longitude); the Niayes region (14.5°N to 16°N latitude; 16°W to 17°W longitude).

market projects form a unique and distinct cluster (Appendix Figs. E1 & E2), confirming our initial hypothesis that the carbon market funds a distinct range of projects.

3.1.1. Project localities

Carbon market projects are concentrated in Casamance, a subtropical region in southern Senegal, and a few more recent initiatives (2020) are along the Great Green Wall (Fig. 1). Carbon market projects intervene on average in more localities than non-carbon market projects (Table 3). The localities involved differ between the two groups: there are seventy-nine localities participating in a carbon market project, thirty-seven of which do not take part in any non-carbon market restoration initiatives, particularly in the Casamance region. The same localities are targeted by several mangrove projects. The commune of Fimela hosts 30 plots of restoration projects from 2007 to 2023, Djilor 10, and both Djilass and Toubacouta hosting 9 plots each. Projects in the Niayes region are primarily public initiatives (Fig. 1). This region is known for agricultural activities and susceptibility to coastal erosion. Finally, carbon market projects are rolled out nationally whereas non-carbon market projects include local and small projects, national projects, and regional projects shared between several countries.

3.1.2. Restoration protocols

There is no agricultural project that gets funded through carbon credits as carbon market projects primarily include mangrove and forestry initiatives. For the whole dataset, agriculture appears to be the main activity (46.05 %), followed by reforestation (28.95 %) and mangrove restoration (25.00 %). Restoration projects in our dataset include various ecological and social targets, such as food security and food systems' resilience, biodiversity conservation, carbon

Table 3
Summary statistics of ecological restoration projects in Senegal (2007–2023).

Metric	Non-Carbon market	Carbon market	Whole Dataset
Total Projects	67	9	76
Avg Duration (SD)	3.85 (3.69)	4.67 (3.00)	3.95 (3.61)
Avg Size (SD)	592,015.90 (2,025,514.87)	6,299.56 (7,807.77)	453,293.61 (1,780,014.33)
Median Size	3,000.00	2,120.00	2,560.00
Avg Year Start	2015.64	2014.89	2015.55
Avg Num Plots (SD)	9.36 (12.75)	15.33 (16.49)	10.07 (13.26)
Avg Num Stakeholders (SD)	6.06 (4.50)	2.89 (1.05)	5.68 (4.36)
Avg Num Localities (SD)	8.31 (11.03)	10.33 (13.15)	8.55 (11.22)
Private Funding	23.88 %	88.89 %	31.58 %
Public Funding	34.33 %	0 %	30.26 %
Blended Funding	41.79 %	11.11 %	38.16 %
National Funding involved	25.37 %	0 %	22.37 %
Agriculture Projects	52.24 %	0 %	46.05 %
Mangrove Projects	20.9 %	55.56 %	25.00 %
Forest Projects	26.87 %	44.44 %	28.95 %
Governance Support	58.21 %	11.11 %	52.63 %

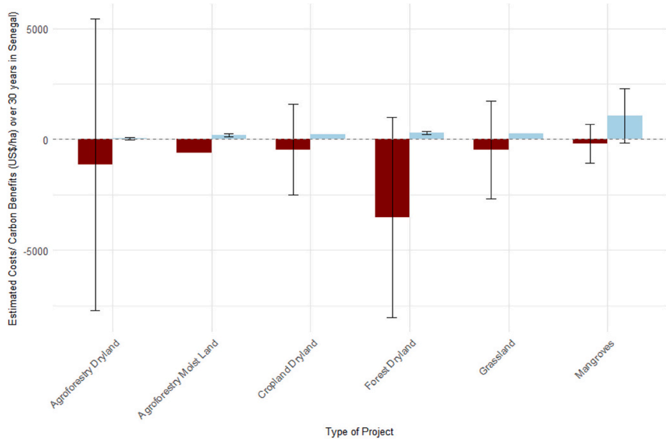

Fig. 2. Estimated costs/carbon benefits (US$/ha) over 30 years by ecosystem in Senegal.
Note: Red bars represent costs per hectare, blue bars represent carbon benefits, i.e. sequestration rate per hectare multiplied by a representative price of carbon over the period (Donofrio et al., 2023).

sequestration, energy use, and ecotourism. Ecological restoration is often (82,89 %) not the sole dimension of a project but rather one aspect among others within integrated development projects (interviews n°1,9,20, Table C1). Over half of the non-carbon market projects (58.21 %) include governance support (Table 3). In contrast, carbon market projects indicate considerably fewer diverse activities in the projects' documents.

3.1.3. Stakeholders involved

Ecological restoration projects in Senegal, both carbon and non-carbon, rely on an international effort connected to the global emphasis on restoration funding and environmental offsetting (interviews n°13,15 Table C1). The restoration projects involve a total of 342 stakeholders, including 91 NGOs, 64 government agencies or public administrations, 30 private for-profit, 9 development banks, and 6 philanthropic foundations. The carbon market projects are funded only by European stakeholders, while the funding landscape is more diverse for non-carbon market projects (Appendix G.1).

Carbon market projects involve fewer stakeholders than non-carbon market projects, with an average of 2.89 and 6.06 stakeholders per project, respectively (Table 3). The number of stakeholders ranges from 1 to 19 for a single project. We identified 21 projects implemented by the five main stakeholders, including 3 carbon market projects.

3.2. Market selectivity partially explained by expected profitability on the carbon market

Lower costs and a higher carbon sequestration rate are comparative advantages for mangroves (Fig. 2), partially explaining the voluntary carbon market's emphasis on this type of restoration (Fig. 1). Forestry projects in dryland are less profitable due to the need for expensive fences in overgrazing areas and lower carbon sequestration rate. However, these findings do not account for the implementation of carbon market projects in the Great Green Wall region (Fig. 1), as forestry initiatives in drylands appear to carry a higher risk of non-profitability (Fig. 2). This points out the need for further investigation into the transaction costs associated with these projects. However, our results indicate significant variability and a lack of reliable data on the establishment and maintenance costs for various restoration projects. Variations in the price of carbon credits are an additional factor of uncertainty for project developers, which is not reflected here as we consider an average price.

The result of our interviews indicates that the main costs are the functional costs of the full-time equivalent workers responsible for the project (Interviews N°5,6, 18, 28,33 Table C1) and the fences in overgrazed dry land areas, which are expensive. Coordination, the time required for implementation, and the success rate are important factors to consider from a project leader's perspective. This highlights the necessity for a comprehensive cost analysis that includes TC to better understand the contribution of the voluntary carbon market to land restoration. It is important to note that restoration provides other benefits that are not reflected in Fig. 2, such as improved water quality, agricultural productivity, and livelihoods.

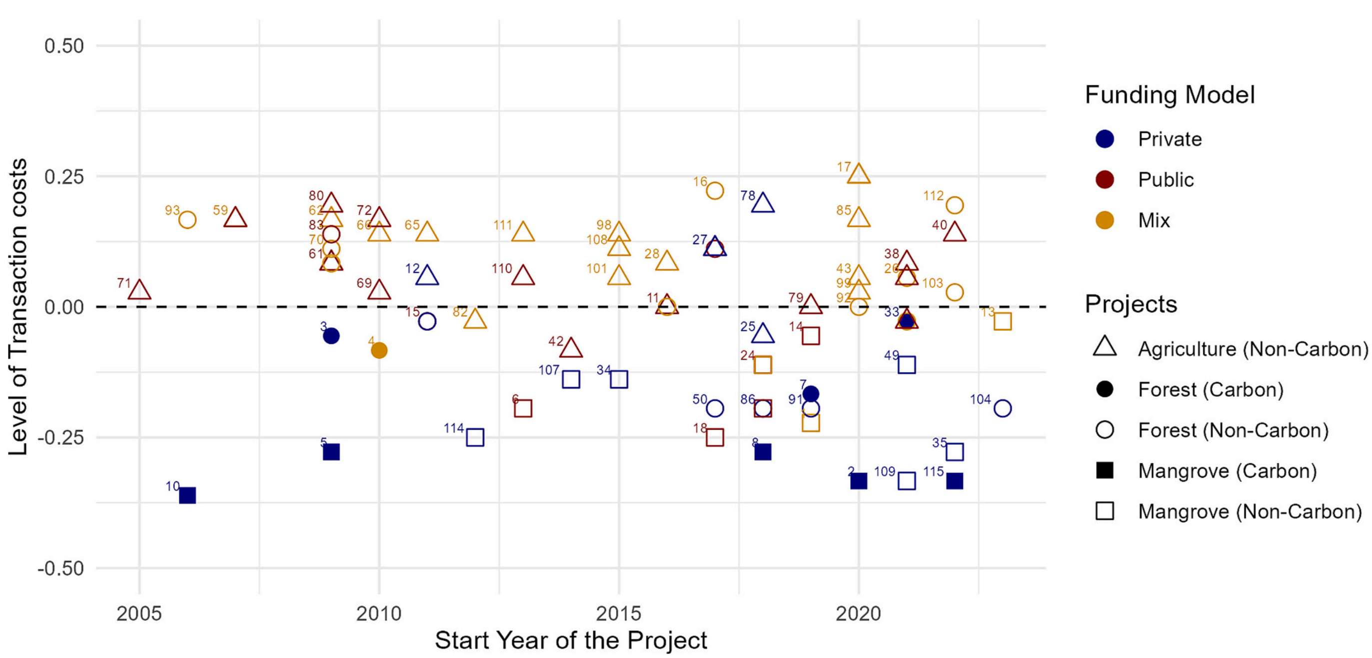

Fig. 3. TC level of each restoration project by starting year of the project.
Note: Temporal variation in TC for ecological restoration projects in Senegal (2005- 2023). The horizontal dashed line at zero indicates the baseline for comparison. Colors represent different funding models, and shapes indicate categories of projects. Carbon market projects are indicated by plain dots.

3.3. Low uncertainty and specificity of carbon market projects

Non-carbon market projects have a significantly higher average normalized transaction cost (0.0162) compared to carbon market projects (−0.213) (Appendix F). The category (agriculture, mangrove, forest) gives a first explanation for the variations in TC levels (Fig. 3). However, carbon market mangrove and forestry projects exhibit significantly lower average transaction cost scores compared to non carbon market projects of the same category (Fig. 3, Appendix G.2). Carbon-funded mangrove projects have an average normalized TC score of −0.4270, compared to −0.2973 for non-carbon mangrove projects. Carbon-funded forestry projects show an average TC score of −0.1892, while non-carbon forestry projects average − 0.0991. Within carbon-funded projects, forestry projects have significantly higher TC scores than mangrove projects. Agriculture projects have the highest average TC score 0.05170.

The average level of TC is higher for public and mixed funding models (−0.0169 and 0.0776) compared to private funding −0.144, and especially carbon funding −0.213. Private non-carbon market projects that show high TC (Fig. 3) are philanthropic projects that support pastoralism and cattle management (Projects 25, 27, 77 Fig. 3). Blended finance (Mix) incurs even larger TC (Figs. 3 & 4). These differences across funding models remain consistent throughout the period studied (Fig. 3) (Appendix H).

Each project's ecological and organizational features influence transaction uncertainty and asset specificity. Carbon market projects exhibit, on average, significantly lower levels of uncertainty (−0,222) and specificity (−0,204) compared to non-carbon market projects (Uncertainty: 0,142 and Specificity: −0.109) (Fig. 4–4, Appendix F).

The distinction between ecological and organizational features shows that carbon market projects have reduced uncertainty and specificity in both the organizational choices made by project leaders (Fig. 4–2) and the selection of ecosystems and ecological protocols implemented (Fig. 4–3). Carbon market projects display on average significantly lower TC regarding their ecological (−0.164) and organizational (−0.281) features than non-carbon market projects (Ecology: 0,0682; Organization: −0.0567) (Fig. 4 Appendix F).

The carbon-forestry projects that show positive ecological uncertainty scores (Fig. 4–2) are Great Green wall projects in drylands. These findings align with interview insights, highlighting the challenges and low success rates that threaten the viability of these projects (Fig. 2). For these projects, the uncertainty is mitigated by low ecological specificity i.e. standardized restoration protocols. The plots of land are larger, there are no tree nurseries, and water management is limited. There is no involvement in agricultural projects aside from reforestation. Fig. 4 shows lower organizational TC compared to other projects in the Great Green Wall area.

However, local projects can display a coordination advantage that is difficult to achieve in carbon market projects and large-scale international initiatives. Three non-carbon forest projects have the lowest organizational-related scores (Fig. 4–2). Evidence from interviews and data indicates that these projects are integrated into a systematic, long-term tree-planting program conducted annually by a Senegalese NGO over a decade, which contributes to exceptionally low TC.

3.4. Trade-offs between TC reduction and local benefits

The results of our interviews highlight trade-offs between answering local needs and mitigating project uncertainty and specificity. In arid zones, using fences is necessary to mitigate ecological uncertainty caused by overgrazing and wildlife. This has led to local conflicts, diminished local support (Ka et al., 2021), and local benefits (Cesaro et al., 2023). Another specific characteristic of carbon market projects is the size of plots, highlighted in the literature as a way to reduce costs and improve feasibility (Cacho et al., 2013). Large plots allow for economies of scale and enhance international communication about the project, as the number of hectares is a common performance indicator. On the Great Green Wall, the choice has been to close perimeters of more than 500 or even 1,000 ha as one unit. However, large plots negatively impact local engagement and social dynamics and have hindered pastoral mobility (Wade et al., 2018; Ka et al., 2021; Cesaro et al., 2023).

The need for mangrove restoration has decreased due to the implementation of numerous projects and the natural regeneration capacity of mangrove ecosystems, as demonstrated by remote sensing studies in Senegal (Andrieu, 2018). Several donors, public authorities, and project leaders mentioned in interviews (Table C1) that the proliferation of carbon-certified initiatives to preserve mangroves has led to significant competition between projects to secure target areas with an increasing risk of land-grabbing (Cormier-Salem and Panfili, 2016). Concurrently, certain severe forms of soil degradation, such as the salinization of soils in Casamance, remain inadequately addressed by large-scale international initiatives due to their highly specific nature and despite their significant impact on local agricultural productivity. The phenomenon of *over-restoration* of mangroves raises questions about the efficient allocation of financial resources in addressing local priorities. Our interview findings suggest a potential misalignment between the preference for less idiosyncratic projects and the need to adequately respond to context-specific territorial challenges, emphasizing the need to balance social, ecological, and market viability.

4. Discussion

This research builds on previous studies that examined the relationship between environmental specificity and uncertainty and their influence on the organizational form of restoration projects (Scemama and Levrel, 2019). Our contribution empirically studies the implementation of a globalized market, the voluntary carbon market, that has emerged due to an institutional environment promoting carbon offsetting and nature-based solutions as economic activities at a global scale. We focus on the case of Senegal to explore how the voluntary carbon market interacts with on-the-ground restoration needs and other financial mechanisms, such as traditional development aid, private non-carbon and public sector-led projects.

Our findings indicate that the carbon market has incentivized some particular reforestation activities, reflecting a tree-centered approach commonly emphasized in the literature on carbon market projects (Seddon et al., 2021). In particular, mangrove restoration has gained prominence. Contributions to other forms of land restoration, such as agroforestry, mitigating desertification, or restoring salt-affected soils, have remained at best marginal. This knowledge can inform better coordination of funds at the national level and avoid crowding out. While the observed prioritization of mangrove restoration aligns with efficient carbon sequestration outcomes, extending carbon market mechanisms to support arid afforestation may not be equally effective. Projects targeting afforestation in arid zones or addressing broader ecological concerns, such as soil erosion, may be better suited for alternative funding sources, given their complexity and potentially slower carbon sequestration outcomes. The private sector's preference for projects with quicker, more quantifiable outcomes highlights the need to align funding mechanisms with ecological objectives they can adequately address.

Furthermore, the implementation of market-based mechanisms is not neutral on a project's features and design. The uncertainty of ecological outcomes and the specificity of natural capital (Scemama and Levrel, 2019) is an element that explains the greater or lesser recourse to the market, but the market itself shapes specificity by attempting to standardize assets and facilitate transactions. These market-driven strategies have tangible effects on the ground, potentially limiting local and ecological benefits.

Questions about the comprehensiveness of our dataset remain. Project selection through project documents might prioritize communication channels favored by NGOs and international organizations,

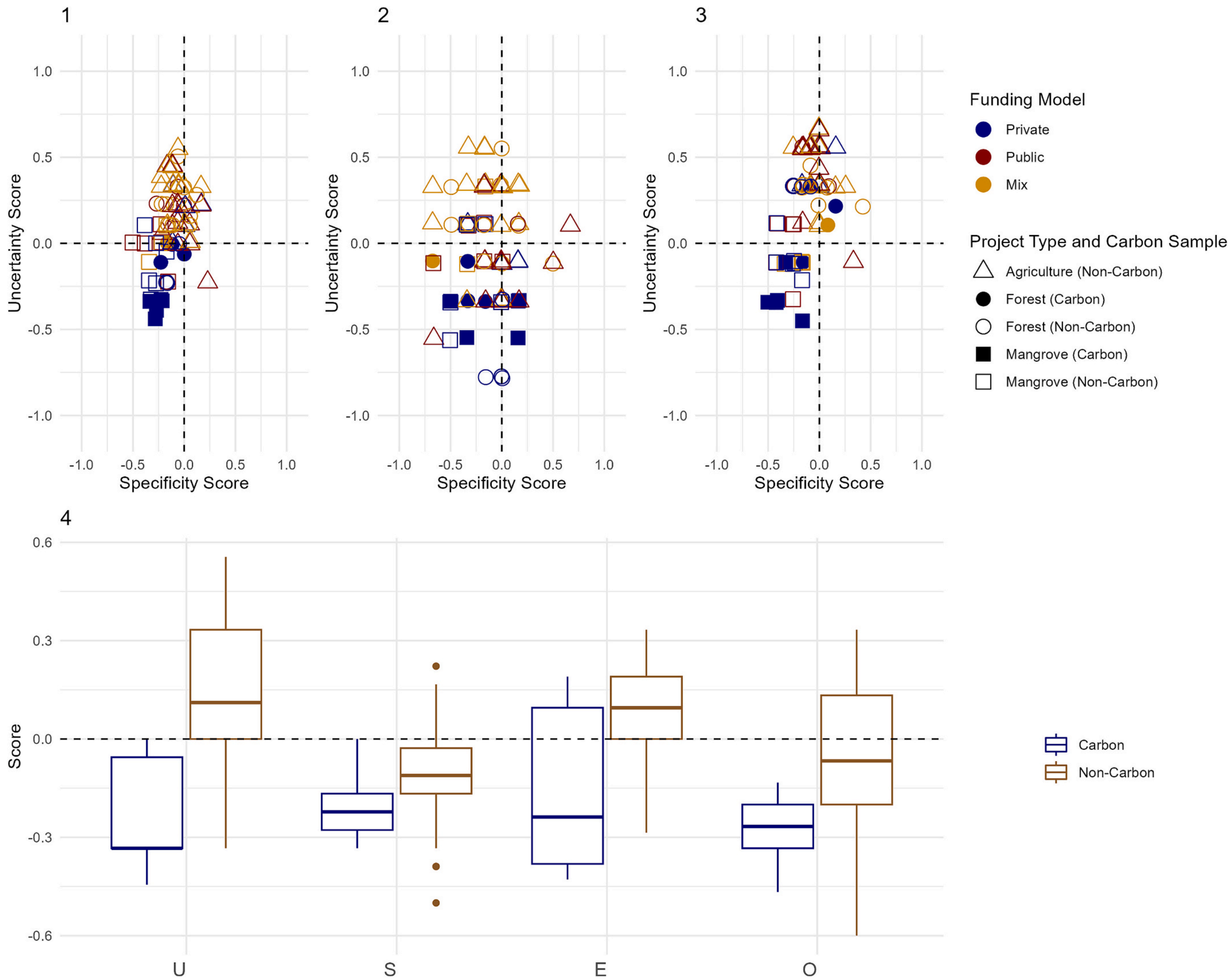

Fig. 4. Uncertainty vs. specificity analysis of restoration projects (2007–2023) – (1) Uncertainty and specificity scores; (2) organization-related scores; (3) Ecologically related scores; (4) Ecological (E), organizational (O), uncertainty (U), and specificity (S) scores of the carbon market and the non-carbon market projects.

potentially overlooking local initiatives and projects implemented by local governments or the Senegalese government. The availability of data on project features and restoration protocols—particularly for non-certified projects—and the constraints faced during information collection in interviews may impede the comparability of projects. Nonetheless, based on external validation and cross-checking of sources, the list of certified carbon market projects identified here is exhaustive.

This result synthesizes studies with an ecological approach that describe sequestration rates, highlighting higher and less variable success rates for restoration practices in sub-Saharan ecosystems (Andrieu, 2018; Mirzabaev et al., 2022; Tucker et al., 2023), as well as studies that describe favorable organizational features for carbon market projects (Pearson et al., 2014; Phan et al., 2017). We show that both aspects are influenced by TC minimization.

The carbon market's contribution to land restoration in Senegal can be understood through the TC analytical framework, which explains the focus on activities with lower uncertainty and specificity. Consistent with Williamson (1981), our analysis is not normative about the governance structure one should adopt. Our study uses the framework of organizational economics and the identification of TC to provide an explanation for the diversity of funding models and their distribution across projects. Our application of the TC framework could still be expanded with additional factors and project features. It is likely that our analysis misses some factors to explain the geographical distribution of funding models, such as the distance from the cities and road connections. Moreover, the various features and factors in this analysis are not weighted. Trade-offs among, for instance, frequency and prospection costs or economies of scale and monitoring challenges, are not explicitly addressed, as all 37 criteria are treated equally. Engaging further with stakeholders could facilitate the prioritization or ranking of these factors, enhancing the relevance and accuracy of the TC framework in this case study.

The coexistence over time of carbon market projects and other restoration projects that do not have the same protocols, practices and stakeholders involved (Fig. 3) and the spatial distribution of carbon market projects from non-carbon market projects (Fig. 1) leads us to believe that ecological restoration in Senegal is characterized by a dual or segmented market structure. However, our limited timeframe prevents us from determining whether the carbon market has replaced a public activity or whether it has opened up a new form of restoration, for instance, in the case of mangroves. Also, we do not consider the evolution of the demand from credit buyers, which can be influenced by the evolution of the trust in the offset market, trends and international requirements, impacting the types of projects funded by the market (Delacote et al., 2024).

While our study does not allow us to predict the market's future contribution, it points to several obstacles that may arise as the market scales up. The results regarding ecological factors of TC (Fig. 4–1) likely indicate limited substitutability between non-carbon and carbon funding models for restoration projects. TC factors can evolve; for instance, advancements in precision remote sensing techniques (Tucker et al., 2023) can reduce costs associated with monitoring. However, biological requirements are examples of factors that are not amenable to change (McCann, 2013) and can only be influenced to a very limited extent. Once the less uncertain and specific restoration projects have been addressed, the remaining restoration needs may require a different approach. Identifying suitable mechanisms for fulfilling these residual needs becomes essential for achieving comprehensive restoration.

Using the TC framework, we move beyond an *ecosystem merit order perspective*, which, after analyzing the return on investment, might suggest that increasing the price of carbon credits is necessary to finance currently unprofitable restoration projects. Instead, our findings illustrate the limited potential of relying solely on a price increase to remove numerous barriers to scaling up financial mechanisms for restoration. Beyond the high variability of restoration costs (Brancalion et al., 2016; Waldron et al., 2020), the specific local characteristics of projects and ecological uncertainty are crucial for understanding and planning market interventions. We extend Cacho et al., 2013 concept of the "Project Feasibility Frontier" for the carbon market, which indicates the minimum project size required for feasibility at various carbon prices by incorporating other factors. The question remains open if, with a significantly higher carbon price and with the ongoing institutional capacity building in the country, the projects in arid zones are more likely to be financed or if, given the global nature of the carbon market, investors may prefer less uncertain assets in other countries over higher-risk ecological conditions. The tangible ecological and organizational considerations we focus on can strengthen the financial and policy frameworks suggested by other studies to address barriers to scaling up biodiversity finance (Löfqvist et al., 2022; Flammer et al., 2023; Delacote et al., 2024).

However, these mechanisms can only be scaled up if the trade-offs between the imperative of TC reduction from a project developer's perspective and the suitability to local needs are addressed. We contribute to current debates on social-ecological synergies and trade-offs in international Biodiversity action (Jindal et al., 2008; Miller, 2014). Despite the promise of delivering positive outcomes for both people and nature, the results of these efforts have been decidedly mixed (Brooks et al., 2012; Tedesco et al., 2023). Market-based mechanisms have faced heavy criticisms for their tendency to reinforce North-South power imbalances (Chausson et al., 2023) if not integrated into coherent and sustained global development aid policies (Karsenty, 2004; Treyer et al., 2023), and financial reforms (Dempsey et al., 2022).

5. Conclusion

The case study of Senegal highlights the role of the voluntary carbon market in supporting ecological restoration projects, particularly mangrove restoration. However, our findings also reveal limitations and challenges associated with this funding mechanism. The market's preference for projects with predictable outcomes and lower risks results in a geographical concentration of carbon market projects and excludes more complex and uncertain restoration initiatives from this kind of funding. This underscores the need for a more diversified approach to address the broader ecological restoration needs. Integrating ecological features into the TC framework provides valuable insights into how biophysical conditions influence the funding source. Our research suggests that simply increasing the price of carbon may not be sufficient to address the challenges associated with more complex and uncertain restoration projects. Beyond funding gap, our research is a call to explicitly address financial coordination gaps and potential solutions as blended models and temporal sequencing.

CRediT authorship contribution statement

Morgane Gonon: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rémi Prudhomme:** Writing – original draft, Supervision, Project administration, Investigation. **Marieme Ba:** Project administration, Resources, Writing – review & editing. **Penda Diop:** Data curation, Writing – review & editing. **Tamsir Mbaye:** Conceptualization, Project administration, Resources, Writing – review & editing. **Harold Levrel:** Supervision, Project administration, Methodology. **Adrien Comte:** Writing – original draft, Validation, Supervision, Methodology, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Morgane Gonon reports financial support was provided by the French Development Agency and the Chaire Comptabilité écologique (CIRED). If there are other authors, they 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. Supplementary data

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