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# Role of Informal Governance in Addressing Climate Change: A Comprehensive Review of Local and Community-Driven Solutions

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**Abstract.** The purpose of this paper is to investigate the critical but underexplored role of informal governance in addressing "dark carbon", which is unaccounted carbon emissions from microbial, geological, and anthropogenic sources that are frequently overlooked in Earth System Models and climate policies. A systematic review of 80 peer-reviewed studies is conducted to assess how decentralized, non-state, and community-based actors contribute to climate mitigation and adaptation, particularly where formal governance frameworks fall short. The review reveals that informal governance mechanisms, including indigenous practices, local NGOs, and citizen science initiatives, effectively identify and respond to hidden carbon sources. These actors exhibit adaptive capacity, deep local knowledge, and legitimacy, often surpassing formal systems in responsiveness and innovation. However, challenges such as limited scalability, resource constraints, and weak policy integration remain. Informal governance is not simply supplementary but fundamental to addressing climate governance blind spots, particularly in managing dark carbon. The study underscores the need for integrated governance models that bridge formal and informal systems and recommends incorporating dark carbon awareness into monitoring frameworks, policy design, and public discourse to enhance the inclusivity, equity, and resilience of climate action.

## 1. INTRODUCTION

Climate change is one of the most pressing challenges of the 21st century, with profound impacts on ecosystems, human societies, and economies worldwide. The accelerating effects of global warming, including rising temperatures, more frequent extreme weather events, and shifting ecosystems, underscore the urgency of comprehensive and effective climate action. As nations struggle to implement large-scale mitigation and adaptation strategies, the need for innovative and multi-dimensional governance frameworks has never been clearer. While formal governance structures, such as national policies and international agreements like the Paris Agreement, play a critical role in combating climate change, they often fall short in addressing the immediate and localized needs that arise in vulnerable communities. Moreover, these formal mechanisms tend to overlook the vital contributions of informal governance in shaping sustainable climate solutions (Verloo, 2023).

Informal governance refers to the non-official systems of decision-making and action that often operate outside the realm of formal governmental structures. These systems include grassroots movements, local knowledge, community-based initiatives, indigenous practices, and the work of non-governmental organizations (NGOs) and activist groups. While these governance mechanisms often work in parallel with formal policies, they are frequently marginalized or underestimated in the literature on climate change governance (Krawchenko & McDonald, 2023). However, informal governance has been increasingly recognized as an essential part of the global response to climate change, especially as it contributes to both mitigation and adaptation efforts at the local level. In many cases, informal governance mechanisms have been instrumental in mobilizing communities, leveraging local knowledge, and implementing context-specific solutions that formal policies often overlook (Tubridy et al., 2022).

Despite the growing acknowledgment of the importance of informal governance, there remains a significant gap in climate governance literature. The bulk of existing research focuses predominantly on formal governance mechanisms—such as national-level climate policies, international agreements, and the role of state actors in addressing climate change. This emphasis often neglects the role of non-state actors and local communities, whose actions can be just as impactful, if not more so, in promoting sustainable practices, reducing emissions, and enhancing resilience to climate impacts (Fletcher et al., 2021). The emphasis on top-down governance models has led to a limited understanding of how informal governance can contribute to, and even lead, efforts to mitigate and adapt to climate change. There is also a lack of comprehensive reviews that synthesize the various forms of informal governance, assess their effectiveness, and explore their potential to complement and strengthen formal governance frameworks (Froeling et al., 2021).

The purpose of this review is to address this gap by systematically analyzing the role of informal governance in the context of climate change. Through this exploration, the paper seeks to shed light on how local communities, activists, indigenous groups, and other non-state actors contribute to climate change mitigation and adaptation. By examining the diverse range of informal governance mechanisms at play, this review will provide insights into their effectiveness, the challenges they face, and their potential for scaling up and integrating with formal governance frameworks (Bliznetskaya, 2023). The aim is to demonstrate that informal governance is not only a complementary force but is in fact an indispensable part of the broader climate governance landscape. Moreover, the review will explore how informal governance can be integrated into formal policy-making processes to create more inclusive, effective, and resilient climate strategies (Mallick & Rahman, 2020).

The review will focus on several key areas. First, it will define and conceptualize informal governance, exploring its various forms and distinguishing it from formal governance structures. It will then analyze the role of informal governance in climate change mitigation, focusing on grassroots movements, community-led initiatives, and the integration of local knowledge into climate action (Bouman et al., 2021). Similarly, it will explore how informal governance contributes to climate change adaptation,

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particularly through community-based adaptation strategies and indigenous knowledge systems. Furthermore, the review will examine the challenges that informal governance structures face, including resource constraints, institutional barriers, and the limited scalability of local solutions. Finally, the paper will propose recommendations for integrating informal governance into formal climate policy, highlighting how collaboration between state and non-state actors can enhance the effectiveness of global climate action (Fernández-Llamazares et al., 2021).

The work aims to contribute to the growing body of literature on climate governance by highlighting the importance of informal governance in addressing climate change. By considering bottom-up approaches alongside top-down policies, the review seeks to promote a more holistic and inclusive approach to climate governance—one that recognizes the complementary roles of both formal and informal actors in the fight against climate change. The insights offered in this paper are intended not only to advance academic understanding but also to provide practical recommendations for policymakers, NGOs, and local communities seeking to strengthen their climate resilience and mitigation efforts.

In the following sections, the paper will first introduce the theoretical framework and key concepts related to climate governance, with a particular focus on the distinction between informal and formal governance. It will then provide an in-depth analysis of the role of informal governance in climate change mitigation and adaptation, supported by relevant case studies from around the world. The challenges faced by informal governance structures will be discussed, including barriers to resource mobilization, institutional integration, and social equity. The paper will then explore opportunities for integrating informal governance into formal climate policy frameworks, offering recommendations for policymakers to support and enhance these non-state actions. Finally, the paper will conclude with a summary of key insights and a call to action for strengthening the role of informal governance in global climate change strategies (Bahman et al., 2024; Bahman et al., 2025).

## 2. METHODOLOGY

This paper adopts a systematic literature review methodology following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Moher et al., 2016) to explore the role of informal governance in climate change. The review approach was chosen to ensure a transparent, reproducible, and comprehensive analysis of the existing literature, minimizing biases and ensuring the inclusion of high-quality studies. PRISMA provides a structured process that includes four main stages: identification, screening, eligibility assessment, and data extraction.

The first stage of the methodology involved identifying relevant studies through a comprehensive search of several peer-reviewed academic databases. These databases included Scopus, Web of Science, Google Scholar, JSTOR, and ScienceDirect. The search was conducted using a variety of keywords and phrases that focused on informal governance and climate change. Keywords such as "informal governance and climate change," "community-based adaptation," "local knowledge and climate action," "grassroots movements and climate mitigation," and "non-state actors in climate governance" were employed. The search was restricted to English-language publications published between 2000 and the present to ensure that the review captured the most up-to-date research relevant to the topic.

Following the identification phase, the next step was screening. After the removal of duplicates and an initial review of titles and abstracts, studies that did not directly address informal governance or climate change were excluded. Articles that focused primarily on formal governance structures, state actors, or unrelated sectors, such as health or urban planning, were also excluded. A thorough screening process resulted in the elimination of 300 studies, leaving 200 articles for full-text review. In the eligibility stage, each of the 200 remaining studies underwent full-text screening. The studies were assessed based on predefined inclusion and exclusion criteria. To be included, studies needed to focus on the role of informal governance in climate action, particularly on grassroots movements, community-based adaptation, and the contributions of indigenous knowledge. Studies that were not directly related to governance or climate change were excluded, as were non-peer-reviewed publications such as reports and opinion pieces. After the eligibility assessment, 120 articles were excluded, leaving 80 studies that met all inclusion criteria. These 80 studies formed the basis for the final analysis (Table 1).

Data extraction was conducted in a systematic manner, with key information extracted from each of the 80 included studies. The extracted data included the authors and year of publication, the geographical focus of the study, key findings related to informal governance in climate change, the methodological approach used in each study, the specific climate focus (mitigation, adaptation, resilience), and any challenges or barriers identified in the implementation of informal governance strategies. This data extraction allowed for a thematic synthesis of the findings and facilitated the identification of key themes across the studies.

To ensure the quality of the studies included in the review, a quality assessment was performed using the Critical Appraisal Skills Programme (CASP) checklist (Long et al., 2020). Each study was evaluated for its methodological rigor, with ratings of high, moderate, or low quality based on the robustness of the research design, data collection methods, and overall relevance to the review topic. Table 2 summarizes the quality appraisal of the 80 studies included in this review using the CASP framework, with the majority showing strong methodological rigor in key areas such as clarity of aims and evidence-supported findings.

The synthesis of the findings was organized around key themes, such as the role of grassroots movements, community-based adaptation strategies, indigenous knowledge systems, the involvement of non-governmental organizations, and the challenges faced by informal governance structures. This thematic analysis allowed for a deeper understanding of the strengths and weaknesses of informal governance mechanisms in addressing climate change. Finally, the review proposed recommendations for integrating informal governance into formal policy-making processes, identifying opportunities for collaboration between state and non-state actors to enhance the effectiveness of climate action.

Table 1: Inclusion and exclusion criteria for literature selection.

| Inclusion criteria | Exclusion criteria |
|---|---|
| Articles discussing informal governance in the context of climate change. | Articles not directly related to governance or climate change. |
| Studies that focus on non-state actors, local knowledge, and grassroots movements | Studies that are primarily focused on formal governance systems or state actors |
| Empirical studies, case studies, and theoretical frameworks | Grey literature, reports without peer review, and non-academic sources |
| Studies published between 2000 and present | Publications prior to 2000 |
| Articles in peer-reviewed journals and conference proceedings | Opinion pieces and editorials without substantial evidence or data |

Table 2: Summary of critical appraisal using the CASP checklist for included studies.

| Criteria | Assessment focus | % of studies meeting criteria | Comments |
|---|---|---|---|
| Clear statement of research aims | Whether the study's objective was clearly defined | 95% | Most studies clearly articulated research questions. |
| Appropriate methodology | Suitability of qualitative/quantitative/mixed methods used | 89% | Some exploratory studies lacked methodological justification. |
| Research design clarity | Adequacy of the study design in addressing the research aim | 85% | A few lacked detail on sampling or site selection. |
| Recruitment strategy appropriateness | Appropriateness of participant/sample selection methods | 78% | Studies involving informal actors sometimes lacked clarity in recruitment. |
| Data collection rigor | Clarity and transparency of how data were collected | 88% | Most used robust protocols; field-based studies more consistent. |
| Reflexivity of researchers | Consideration of researcher influence or bias | 52% | Often overlooked, especially in technical and modeling studies. |
| Ethical considerations addressed | Ethical approval, consent, and community engagement | 81% | Many field studies had ethical review, though reporting varied. |
| Data analysis appropriateness | Clarity, justification, and robustness of analysis approach | 84% | Quantitative studies tended to report this better than qualitative ones. |
| Findings supported by evidence | Extent to which results were grounded in data | 91% | High correlation between claims and evidence across studies. |
| Contribution to existing knowledge | Novelty and relevance of findings to the field | 86% | Especially strong among informal governance and emissions tracking studies. |

## 3. LITERATURE REVIEW

### 3.1. Understanding Dark Carbon

The term *dark carbon* refers to poorly quantified or unaccounted-for carbon sources and sinks that lie outside the traditionally modeled Earth System carbon budgets. This concept draws parallels to “dark matter” in astrophysics—representing an influential but poorly observed component of a larger system (Qi et al., 2023). In the context of climate science, dark carbon encompasses several hidden or underestimated processes, such as subterranean carbon mobilization, unaccounted black carbon deposition, cryptic biogenic emissions from wetlands, deep ocean sequestration variability, and carbon fluxes from permafrost or disturbed ecosystems. These components, while often fragmented across subdisciplines, collectively represent a potentially significant blind spot in climate governance and global carbon accounting (Reich et al., 2024).

Scientific interest in these “invisible” or indirect contributors to the carbon cycle has intensified in recent years due to increasing discrepancies between observed atmospheric $CO_2$ concentrations and modeled outputs. This suggests either an overestimation of sinks, underestimation of sources, or both. The relevance of dark carbon lies in its potential to exacerbate climate uncertainty, undermine emissions mitigation models, and obscure feedback mechanisms that could accelerate climate change, especially under nonlinear and tipping point scenarios (Baur et al., 2023).

### 3.2. Dark Carbon Pathways and Implications for Climate Governance

Climate governance has traditionally relied on formal institutional frameworks, international treaties, and centralized regulatory systems. Yet, as the understanding of Earth's carbon dynamics deepens, it becomes increasingly apparent that significant carbon fluxes, collectively termed "dark carbon", remain unaccounted for in both models and policy. These carbon sources, ranging from cryptic biogenic emissions and subterranean seepages to anthropogenic leakages and urban micro emissions, not only escape formal monitoring but also evade structured policy interventions (Molofsky et al., 2025). In this context, informal governance, defined by adaptive, decentralized, and often non-state-led mechanisms, emerges as a critical yet understudied tool in managing dark carbon risks. This section reinterprets the scientific literature on unquantified carbon emissions through the lens of informal governance, synthesizing thematic linkages and highlighting the governance gaps exposed by dark carbon (Dowd et al., 2024).

A central theme in the literature is the persistent mismatch between observed and predicted carbon emissions, suggesting that key fluxes remain excluded from formal carbon accounting. For instance, while volcanic outgassing has long been seen as negligible in anthropogenic carbon budgets, recent estimates show emissions between 65 and 319 $TgCO_2$ annually with considerable uncertainty (Perdichizzi et al., 2024). These emissions, often spatially diffuse and temporally sporadic, are rarely integrated into formal inventories or climate models. Informal science networks, such as independent monitoring groups and satellite-based open-access databases (e.g., Global Volcanism Program), have been instrumental in highlighting these gaps, often preceding formal acknowledgment. This pattern illustrates how informal scientific infrastructures contribute to carbon governance by revealing blind spots informal systems (Gartlinger & Gualini, 2025). Similar dynamics are seen in Arctic methane seeps associated with permafrost thaw and glacial retreat. These geologically driven emissions are triggered by climatic shifts but remain beyond the scope of typical mitigation policies. Losi et al. (2025) document the scale of geologic methane seepage and call attention to its underrepresentation in the IPCC framework. Informal scientific efforts—including collaborations among indigenous communities, Arctic researchers, and citizen scientists—have led to the first detection and long-term tracking of such emissions, illustrating the potential of decentralized, observational networks (Losi et al., 2025).

Biogenic emissions, particularly from peatlands, wetlands, and tropical forest soils, are another area where informal governance plays a pivotal role. These ecosystems exhibit complex, nonlinear responses to climate anomalies, making them difficult to model. Cui et al. (2024) show that methane emissions from tropical wetlands are highly sensitive to microbial shifts caused by hydrological variation. Yet, the inclusion of these emissions in national reporting is uneven at best. In many cases, non-state actors—such as NGOs managing carbon offset projects or academic groups piloting community-based land monitoring—serve as de facto carbon auditors, especially in the Global South. This informal governance fills critical gaps where formal institutions are absent, underfunded, or politically constrained (Cui et al., 2024).

Black carbon (BC) serves as a striking case of divergence between scientific knowledge and policy action. BC is a potent climate forcer with well-documented effects on albedo, particularly in cryospheric regions (X. Wang et al., 2024). However, due to its classification as a short-lived climate pollutant and lack of inclusion under the Kyoto Protocol, BC governance has been patchy. Informal coalitions, such as the Climate and Clean Air Coalition (CCAC), have emerged to address this void. These decentralized partnerships, comprising cities, NGOs, and private sector actors, represent informal governance mechanisms that bypass slow-moving international agreements. Their effectiveness varies, but they demonstrate how informal governance can catalyze targeted action on neglected emissions.

Urban ecosystems are a rapidly growing domain of dark carbon emissions. Once assumed to be carbon neutral or net sinks, urban green spaces are now recognized for their complex interactions with nitrogen cycles, fertilizer use, and VOC emissions. Viola et al. (2016) report measurable emissions from urban lawns managed with synthetic fertilizers. Likewise, emerging studies link microplastic degradation in urban environments with minor yet widespread carbon outputs (Viola et al., 2025). Formal mechanisms for accounting such emissions are rare, particularly in cities lacking robust environmental governance. However, informal actions, ranging from community science projects to local green ordinances and civil society campaigns, are beginning to play a role in monitoring and reducing these emissions.

A parallel trend is visible in oceanic and cryospheric systems, where the dynamic behavior of carbon sequestration processes outpaces formal modeling and policy. Zao et al. (2022) emphasize the variability in oceanic carbon absorption and the risks posed by acidification and stratification (Zhao et al., 2024). Meanwhile, microbial loops and secondary organic aerosol formation, described by Schneider et al. (2024), remain marginal in formal models. These complexities are often navigated through informal academic networks, data-sharing consortia, and open-source modeling initiatives, which collectively enhance the resolution and responsiveness of carbon science (Schneider et al., 2024). Microbial and sedimentary processes also defy straightforward governance. Anaerobic methane oxidation by archaea in ocean sediments is episodic and challenging to monitor yet may represent a significant carbon sink or source depending on context. Here, informal data platforms and peer-driven collaborations are crucial for knowledge diffusion. Similar patterns appear in the study of sulfate-reducing bacteria in wetlands, where local hydrological conditions drive microbial behavior, resisting formal generalization (H. Wang et al., 2024).

Hydrate destabilization and permafrost collapse present high-stakes risks for carbon release, particularly in Arctic marine environments. These events are difficult to forecast, and formal governance mechanisms have not evolved to address their abrupt, nonlinear characteristics. The literature, including Grob et al. (2023) and Schurmeier et al. (2024), points to the role of exploratory science and informal scenario modeling in identifying potential feedbacks. These ad hoc, often underfunded efforts highlight the inadequacy of current institutional tools to address extreme carbon risk (Grob et al., 2023; Schurmeier et al., 2024).

The rise of informal science is paralleled by the growth of informal policy frameworks. Climate clubs, subnational carbon markets, and voluntary offset schemes are increasingly shaping emissions governance. However, the integration of dark carbon into these initiatives remains inconsistent. For example, wildfire emissions, which are highly variable and often misclassified, are rarely addressed in voluntary market protocols despite their massive impact (Pereira et al., 2024). Nevertheless, regional networks of forest managers, indigenous groups, and environmental NGOs often serve as first responders and data providers, filling a vacuum left by formal systems.

## 3.3. Neglected Dimensions: Informal Governance in Comparative Sectors

Despite its growing relevance across global environmental governance, the role of informal governance in climate change remains insufficiently explored in both academic literature and policy frameworks. In contrast to sectors such as public health and disaster risk reduction—where community engagement, local knowledge, and non-state actors are widely acknowledged as integral to resilience strategies—climate governance continues to prioritize centralized, top-down models. For example, in global health initiatives, community-based health workers and informal care networks are routinely recognized for their effectiveness in reaching underserved populations and responding to local needs (Soldo et al., 2024). Similarly, disaster management literature has highlighted the role of informal institutions in early warning dissemination, post-disaster recovery, and risk perception shaping (Nemcikova et al., 2023). These sectors have, to varying degrees, institutionalized mechanisms to integrate informal actors into decision-making processes, a development that remains underdeveloped in the climate policy realm.

Part of this oversight in climate governance stems from a legacy of technocratic environmental management, which privileges standardized metrics, formal institutions, and predictive modeling over context-specific, adaptive governance. While these systems are indispensable for global coordination and accountability, they often marginalize the contributions of non-state and community-based actors who operate outside the bounds of formal regulation. As Lofthouse & Herzberg (2023) and others have argued, climate change presents a “polycentric” governance challenge, where multiple scales and actors must interact dynamically. However, even within this polycentric framework, informal governance tends to be either generalized or under-theorized, lacking the analytical granularity it receives in related fields (Lofthouse & Herzberg, 2023).

Moreover, informal governance has demonstrated effectiveness in managing complex environmental systems under uncertainty, precisely the kind of context that defines climate change. In fisheries management, for instance, community-based monitoring, local tenure systems, and customary enforcement practices have proven resilient against ecological variability and institutional failure (Kumar & Saizen, 2023). These decentralized approaches are often more responsive to local environmental feedbacks and can adapt quickly without the bureaucratic inertia that characterizes formal regimes. Yet, in climate change discourse, such mechanisms are often relegated to the margins, framed as “supplementary” rather than essential to global mitigation and adaptation efforts (Roy et al., 2024). This lack of engagement with informal governance is not merely academic, it has real-world implications for equity and effectiveness. Vulnerable communities, particularly in the Global South, often lack formal institutional support for climate resilience but possess rich knowledge systems and governance practices that are excluded from climate planning. Ignoring these systems exacerbates the climate governance gap and risks perpetuating epistemic injustice. Bridging this divide requires a shift in both research and policy paradigms: from viewing informal governance as ad hoc or temporary to recognizing it as a robust, evolving component of the broader climate governance architecture.

Ultimately, the literature on dark carbon reveals a layered governance landscape. While formal institutions remain central to emissions regulation, they are ill-equipped to handle the dynamic, uncertain, and often invisible characteristics of dark carbon. Informal governance, through networks of scientists, communities, NGOs, and private actors, plays a critical bridging role. These actors not only generate data and mobilize responses but also reshape epistemologies around what counts as carbon and who governs it. As climate models incorporate more feedback-rich variables and as governance frameworks expand to include adaptive, decentralized systems, acknowledging and strengthening these informal mechanisms will be key to a more accurate and equitable carbon regime.

### 3.4. Modelling and Future Pathways

The implication of these dark carbon pathways for climate modeling is profound. Current Earth System Models, though increasingly detailed, rely on relatively smooth, predictable emissions trajectories. However, most of the dark carbon sources exhibit nonlinear behaviors, including thresholds, feedbacks, and tipping points—features more aligned with complex adaptive systems theory than traditional modeling approaches (Chen & You, 2022). Ignoring these elements may produce systematic underestimation of future warming or overconfidence in mitigation targets.

Integration of these emissions into models requires not only better data but also conceptual flexibility. Interdisciplinary data fusion, drawn from geology, ecology, atmospheric chemistry, and artificial intelligence, will be essential. However, the institutional and disciplinary silos that currently fragment climate science remain a major barrier. Realizing this integration demands a structural shift in both research funding and governance. From a policy standpoint, several strategies emerge. National inventories must incorporate carbon uncertainty buffers to account for known unknowns. Carbon markets should be redesigned with contingency margins that reflect non-inventoried emissions. Early warning systems capable of detecting and responding to sudden emissions spikes, such as those from permafrost collapse or megafire events, should be developed and integrated into climate response strategies. Adaptation frameworks must also begin to address the implications of dark carbon, especially in vulnerable regions where unaccounted emissions could exacerbate existing climate stresses (Gidden et al., 2023).

Ultimately, confronting the challenge of dark carbon requires a paradigm shift. Rather than viewing the carbon cycle as a deterministic system subject to top-down control, policymakers and modelers must begin to treat it as an emergent, adaptive network with multiple, interacting uncertainties. Only through this lens can governance become responsive to the real complexity of Earth’s climate dynamics—and only then can international climate action reflect the true scope of the problem.

## 4. DISCUSSION AND RECOMMENDATIONS

### 4.1. Policy Integration, Monitoring Challenges, and Strategic Recommendations

The policy landscape surrounding climate change mitigation is heavily reliant on accurate and comprehensive carbon accounting. However, the concept of dark carbon complicates this endeavor by exposing significant knowledge gaps in how emissions are detected, reported, and integrated into national and international governance structures. Despite advancements in satellite monitoring and remote sensing, many dark carbon pathways remain elusive to current observation techniques and therefore absent from policy discourse and regulatory frameworks. As a result, there is a growing risk that existing mitigation strategies may be misaligned with the true trajectory of global carbon dynamics.

Monitoring dark carbon emissions presents numerous technical and institutional challenges. Many sources of dark carbon, such as permafrost methane, sub-oceanic outgassing, or episodic volcanic releases are highly spatially heterogeneous and temporally sporadic. This volatility limits the reliability of static monitoring stations or routine satellite passes to provide comprehensive data. Additionally, limited research funding, lack of standardization, and fragmented jurisdictional oversight have hindered the development of a cohesive global monitoring framework. For instance, while the European Space Agency's Copernicus program has improved methane detection capabilities, many regions with suspected dark carbon activity lack satellite coverage or ground validation, particularly in the Global South. The uneven geographic distribution of monitoring infrastructure also exacerbates environmental justice concerns, as communities in data-sparse regions may be disproportionately impacted by undetected emissions (Thépaut et al., 2018).

At the national level, greenhouse gas inventories often rely on self-reported data guided by IPCC protocols, which primarily account for well-characterized emission sources. The omission of dark carbon leads to systemic underestimation, with potential downstream effects on emissions trading schemes, carbon taxation, and climate finance allocation. For example, countries dependent on fossil fuel exports may underreport fugitive emissions from extraction processes, while tropical nations with expansive wetlands or peatlands may lack the capacity to measure diffuse methane releases. Moreover, black carbon and volatile organic compound (VOC) emissions are frequently excluded from climate metrics due to classification complexities, despite their substantial climatic and health impacts. This results in skewed cost-benefit analyses and ineffective prioritization of mitigation interventions (Li et al., 2020).

To rectify these deficiencies, a multi-pronged strategy for policy integration is required. First, emission inventories should adopt probabilistic reporting methods that incorporate uncertainty bounds for suspected dark carbon sources. This approach acknowledges the presence of unmeasured fluxes while providing policymakers with risk-adjusted data for planning. Second, capacity-building initiatives—particularly in low-income countries—must be expanded to support ground-based monitoring and research on cryptic emission pathways. International partnerships, such as those established under the Paris Agreement's Enhanced Transparency Framework, could be leveraged to facilitate data sharing, technical training, and co-development of measurement methodologies. The inclusion of dark carbon into global carbon budgeting frameworks demands the expansion of Earth System Models (ESMs) to account for threshold behaviors and feedback mechanisms (Bonan & Doney, 2018). Currently, most models operate under deterministic assumptions that fail to capture the nonlinearities inherent in dark carbon dynamics. Incorporating stochastic elements and agent-based sub models that simulate microbial activity, sediment fluxes, or cryosphere collapse could improve model fidelity. Additionally, machine learning techniques should be employed to analyze high-dimensional datasets from environmental sensors, offering real-time insights into anomalous carbon fluxes that traditional statistical models may overlook.

Also, climate policy instruments such as carbon markets and offset programs must evolve to accommodate the uncertainty and heterogeneity of dark carbon emissions. Traditional offset schemes based on reforestation or methane capture may be insufficient if major emissions originate from unaccounted or uncontrollable sources. Instead, flexible instruments that prioritize system resilience and adaptive management should be developed. This includes scenario planning tools that model policy outcomes under different levels of carbon accounting uncertainty and the integration of early-warning systems that detect environmental anomalies indicative of emission surges.

### 4.2. Communication and Stakeholder Engagement

Public communication and stakeholder engagement must be enhanced to build trust and understanding around the complexities of dark carbon. The term itself requires clearer definition in climate discourse, alongside transparent discussions about its implications for equity, responsibility, and action. Education campaigns, policy briefs, and citizen science programs can demystify dark carbon pathways and foster more inclusive climate dialogues (Nyhan et al., 2022). Indigenous knowledge and local ecological observations should be respected and incorporated into dark carbon monitoring efforts, especially in ecosystems like boreal forests and wetlands where Western scientific presence is limited.

Therefore, the effective integration of dark carbon into environmental policy and governance frameworks is not merely a technical challenge, it is a conceptual and political imperative. As evidence of unaccounted emissions continues to mount, ignoring these sources risks undermining the credibility of climate action and delaying critical interventions. By reforming monitoring systems, recalibrating policy instruments, and embracing uncertainty as a core feature of the carbon cycle, the global community can move toward a more holistic and effective climate governance regime.

## 5. CONCLUSION

In this review, we have explored the concept of dark carbon—unaccounted-for carbon sources that are often omitted from Earth System Models (ESMs) and global carbon accounting frameworks. These pathways, ranging from subterranean methane releases to microbial fluxes and anthropogenic leakages, significantly affect global carbon budgets and climate governance. Despite their potential impact, dark carbon processes remain largely hidden within current climate models, leading to discrepancies between predicted and observed atmospheric carbon concentrations. Our synthesis of 80 studies reveals a multifaceted landscape of dark carbon fluxes, many of which present non-linear, episodic, and spatially diffusing emissions that challenge traditional carbon modeling methods. We highlighted several crucial dark carbon sources, including volcanic outgassing, thawing permafrost, and unreported methane leaks from fossil fuel infrastructure. Similarly, we examined biogenic and microbial contributions to carbon cycling that are often overlooked due to data limitations, inconsistent modeling approaches, or lack of standardized measurement protocols. These gaps in understanding have significant implications for future climate predictions and global governance efforts aimed at mitigating climate change.

The implications of these overlooked carbon sources are twofold. Firstly, they necessitate an overhaul of existing carbon accounting frameworks to incorporate dynamic and potentially volatile carbon fluxes that are not captured by conventional models. Secondly, they challenge the notion of static carbon sinks and sources, emphasizing the need for adaptive, flexible governance that can respond to the evolving and unpredictable nature of carbon emissions. While this review has identified several key areas of dark carbon research, notable gaps persist. One of the most pressing gaps is the lack of standardized, high-resolution data across different dark carbon sources, particularly those from subterranean processes and microbial fluxes. As climate models become increasingly sophisticated, the integration of these processes requires high-quality datasets that span both temporal and spatial scales. The development of such datasets, possibly through international collaborations and open-access data initiatives, remains a critical research frontier.

Another significant gap exists in the measurement of fugitive emissions from oil, gas, and coal infrastructure. While technological advancements have improved the detection of such emissions, large-scale, high-frequency monitoring systems are still insufficient to capture the full extent of leakage. Research into low-cost, high-resolution sensing technologies, coupled with satellite-based monitoring systems, could help fill this gap. Furthermore, enhancing collaboration between the private sector, academia, and governmental bodies is crucial for improving emissions reporting and verification processes.

In terms of biogenic and microbial carbon sources, much remains to be done to fully understand the complexities of soil respiration, methane fluxes, and carbon turnover in both terrestrial and aquatic ecosystems. The role of microbial communities in these processes remains a particularly challenging area of study due to the dynamic and site-specific nature of microbial interactions with the environment. Advances in metagenomics and computational modeling may offer new insights into the intricate relationships between microbes and carbon fluxes, yet interdisciplinary approaches that combine microbiology, ecology, and carbon modeling remain scarce. Furthermore, the role of secondary organic aerosols (SOAs) in global carbon dynamics is a relatively under-explored area that warrants further attention. While growing evidence suggests that SOAs may contribute significantly to radiative forcing and cloud formation, their complex chemical and physical properties hinder their integration into climate models. A better understanding of the formation, transformation, and climatic impacts of SOAs is essential for more accurate climate predictions.

Future research may focus on bridging the gap between scientific understanding and policy implementation. The complexities of dark carbon processes require a coordinated effort to develop integrated carbon models that can capture the full scope of carbon emissions, from direct anthropogenic sources to more indirect, natural processes. Future models should incorporate non-linear feedbacks, thresholds, and time lags, which are characteristic of many dark carbon sources. These models should also account for regional variations, as dark carbon emissions often display significant geographical heterogeneity.

One promising avenue for advancing research is the application of machine learning and artificial intelligence (AI) techniques to identify patterns in complex datasets. The integration of AI into carbon modeling could help uncover hidden correlations and provide more accurate forecasts of future carbon fluxes. For example, AI could be used to process remote sensing data from satellites to detect emissions from previously underreported sources such as methane leaks or forest fires. Additionally, AI could assist in automating the process of integrating new data into existing models, thereby improving the accuracy of climate predictions. Another key area for future research is the development of more robust governance frameworks that can incorporate dark carbon processes into international climate policy. Given the global nature of carbon emissions and the transboundary implications of dark carbon sources such as BC and methane, effective governance must move beyond national borders and adopt a more holistic approach to emissions management. This includes the creation of new regulatory mechanisms that can track and verify dark carbon emissions, as well as policies that incentivize the reduction of such emissions in both the public and private sectors.

On a more local level, there is a need for localized studies that examine the specific dynamics of dark carbon pathways in different ecosystems. For example, studying the interaction between microbial communities and soil carbon in tropical forests or examining the methane release potential of thawing permafrost in Arctic regions could yield valuable insights into the spatial and temporal variability of dark carbon emissions. These studies would not only help refine global climate models but also inform regional policy decisions regarding carbon mitigation and adaptation strategies.

Finally, future research should also focus on the development of more effective communication strategies to raise awareness of dark carbon sources among policymakers and the general public. Currently, many dark carbon pathways remain poorly understood or neglected in climate discussions. Raising awareness through scientific publications, media outreach, and educational initiatives can help drive action on both the local and global levels. Effective communication strategies will be essential to garner public support for policies that address these hidden emissions and foster greater accountability in carbon reporting.

In conclusion, dark carbon presents a significant challenge to both climate science and governance. While recent advancements in carbon modeling have shed light on some of these hidden emissions, much work remains to be done. Bridging the gaps in data, measurement, and governance will be crucial for improving the accuracy of climate predictions and ensuring effective mitigation strategies. By incorporating dark carbon pathways into climate models and policy frameworks, we can take a more comprehensive approach to addressing global carbon dynamics and meeting the ambitious climate targets set by international agreements.

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