Digital technologies - the missing link between climate action transparency and accountability?

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Abstract

The rise of digital technologies poses opportunities and challenges for transparency and accountability in climate governance. This paper examines their impact on information flows and accountability in the context of climate outcomes, analyzing three case examples (World Bank Climate Warehouse, Climate TRACE, and OpenClimate) to assess the potential of digital solutions for data availability and reliability, particularly for non-state actors (NSAs). Using Ostrom's "rules in use" framework, we explore how digital technologies shape transparency outcomes, highlighting challenges and unintended consequences. We analyze how these initiatives frame, design, and implement their rules for digital approaches to define their participants' data collection, purpose, and access rules, all of which are crucial aspects impacting transparency and accountability for the Paris Agreement. Our findings reveal uncertainties in the operationalization of the rules for these digital technologies that undermine the potential to enhance transparency. Three key issues emerge: (1) establishing appropriate rules to govern data quality for accuracy and credibility; (2) addressing power imbalances to foster inclusive and equitable transparency; and (3) aligning rules in use across digitally enabled solutions to promote coordination and facilitate polycentrism in the post-Paris climate regime. These insights shed light on the role of digital approaches in bridging transparency and accountability gaps, emphasizing the need for careful rule design and coordination for effective implementation in global climate governance.

Key Policy Insights

- Digital technologies have the potential to generate new modes of transparency within a polycentric Paris climate governance system, particularly at the level of non-state and subnational actors.
- By comparing three case examples employing digital technologies to improve climate data, we evaluate various formal and informal "rules in use" for generating data and facilitating sharing across actors and initiatives, to enhance transparency and accountability.
- To leverage the potential of digital technologies in advancing transparency and accountability in climate governance, policymakers should prioritize the alignment of rules in use, address power imbalances, and ensure the creation of appropriate rules governing data quality and structure.

Keywords: Climate governance, non-state actors, digital technologies, transparency, Paris Agreement, climate data, accountability

1. Introduction

The complex global climate governance landscape raises new questions regarding the forms and modes of transparency for generating accountability under the Paris Agreement, particularly with the involvement of non-state (e.g., businesses) and subnational government actors (collectively, non-state actors or NSAs).

Self-reported transparency actions are critical to the Paris Agreement's "pledge and review and ratchet" (Hale, 2020) mechanism through the Enhanced Transparency Framework (ETF), where countries, but not NSAs, are required to submit a Biennial Transparency Report or BTR. The ETF mandates that both developed and developing countries must regularly report greenhouse gas emissions inventories and information required to track progress towards implementing and achieving their nationally-determined contributions (UNFCCC, 2023a; Winkler et al., 2017). Consequently, these national reports are considered an important component of the Global Stocktake, which occurs every five years to provide an aggregate review of national government progress towards collective mitigation, adaptation, and finance goals as part of the Paris Agreement's ratchet mechanism (UNFCCC, 2022b). Yet, neither the ETF nor the Paris "rulebook" provide explicit guidance for NSAs' transparency reporting, despite the growing emphasis placed on their contributions to global mitigation efforts. UN Secretary-General Antonio Guterres, for instance, convened a High Level Expert Group (HLEG) specifically aimed at developing guidelines for credible corporate, subnational, and financial institution net-zero targets (UN News, 2021) based on the rapid proliferation of NSAs "racing" to pledge their own decarbonization goals (UNFCCC, 2021).

The Paris Agreement's "transparency of action" approach (A. Gupta & Van Asselt, 2019) is starting to translate to NSAs, with an announcement in June 2023 of a new "Recognition and Accountability Framework" specifically for NSAs (UNFCCC, 2023b). This Framework builds on HLEG's recommendations to enhance the integrity of NSA net-zero commitments through regular reporting of greenhouse gas emissions data, aiming to develop processes and systems to authenticate and validate these data through the UNFCCC-managed Global Climate Action Portal (UNFCCC, 2023b). Although this Framework represents progress in aligning non-state actors' (NSAs) accounting with the ETF for countries, a significant question arises regarding how NSAs will ensure compliance with these standards. Existing methods for NSAs to report GHG emissions or verify emissions reductions are frequently "costly, error-prone, and time consuming, often relying on manual processes and in-person surveys" (World Bank, 2022b). Even when voluntary initiatives, like the European Union Global Covenant of Mayors for Climate Energy, the largest transnational city climate network with more than 10,000 members, require baseline and monitoring emissions inventories from their members, only a small fraction have submitted and reported these data (Hsu, Tan, et al., 2020; Hsu et al., 2022). These variable membership standards and levels of compliance with them result in heavily imbalanced data and information flows, with the vast majority of NSA information and data coming from Europe and the Global North (Hsu et al., 2016; Kuramochi et al., 2021).

To remedy this gap, digital technologies such as Earth observation (EO) satellites, Internet of Things (IoT) sensors interconnected through smart digital ecosystems, machine learning (ML) and artificial intelligence (AI), and distributed ledger or blockchain technologies (Große-Bley & Kostka, 2021; Hsu, Khoo, et al., 2020; Kloppenburg et al., 2022; Kostka et al., 2020; Schletz, Hsu, Mapes, et al., 2022) are being discussed as a potential antidote. These technologies demonstrate the potential to address key climate data, information, and transparency challenges for not just NSAs but actors at multiple scales: EO and IoT data are being seen as alternatives to self-reported data since satellites regularly monitor the Earth remotely, and sensors can collect high-resolution data in near real-time in smart infrastructure systems (Hsu, Khoo, et al., 2020). Combined with Artificial Intelligence (AI) and Machine Learning (ML) algorithms (Rolnick et al., 2019; Wang et al., 2009), these new data streams can then be integrated and

analyzed efficiently and at a massive scale, potentially integrating with distributed ledgers (commonly known as blockchain technology) within a decentralized, transparent system to automatically track climate actors and actions (Schletz, Hsu, Mapes, et al., 2022).

Scholars analyzing these technologies, however, are raising important questions about how their framing, design, and implementation, including the overarching systems of rules, can significantly impact transparency and accountability (Große-Bley & Kostka, 2021; Kloppenburg et al., 2022; Kostka et al., 2020; Schletz, Hsu, Robiou Du Pont, et al., 2022). To contribute to this discourse, we are specifically examining how "rules in use" or "institutional rules" (Ostrom 2005) are being conceptualized for the creation of new or improved data transparency by investigating the following questions: Which actors participate in the generation of digital solutions, who collects information and for what purpose, as well as who has access to the results -- these are all questions that necessitate further interrogation, considering that many of these digitized efforts are being driven by private actors and institutions. Since prior research has found carbon-based accountability frameworks to narrowly serve the interests of those designing and implementing them (Green & Kuch, 2022), there are legitimate concerns regarding whether the increasing decentralization and privatization of digitalized monitoring efforts are displacing or crowding out the development of transparency approaches based on public legal requirements. This crowding out could lead to a decrease in transparency overall, due to competing incentives for self-gain, profit or even protecting the confidentiality of data, as forewarned by Gupta & Mason (2016) .

Given these concerns, this paper explores questions of how digital solutions can effectively tackle the increasing complexity of climate data and action reporting for numerous actors (including NSAs), tasked with generating inventories and progress implementation reports. Additionally, it examines the impact of the rules in use, which encompass the actual practices, norms, and conventions followed by the actors in a given context, irrespective of formal codification (Ostrom, 2005). These rules in use play a crucial role in guiding actors' decisions and behaviors, significantly influencing transparency and accountability within the reporting process. With the involvement of multiple levels of actors, particularly the new requirements for non-state actors, the importance of well-defined and appropriately designed rules in use becomes even more critical for these digitalized solutions. Our aim is to explore these questions of how rules in use are being framed, design and implemented through three examples of digitalized solutions that aim to enhance data collection, availability, and transparency for multiple types and levels of actors. We organize the paper as follows: Section 2 provides an overview of our methodological approach, Section 3 gives an overview of the significance of rules in use for transparency generation through digital technology, Section 4 presents a detailed analysis of our three case examples, Section 5 provides a discussion, followed by a brief conclusion.

2. Methods and data

A critical examination of the rise of digital technologies and their implications for transparency governance and accountability for climate outcomes is needed. Definitional discrepancies aside, Florini (2007) defines transparency as "the degree to which information is available to outsiders that enables them to have informed voice in decisions and/or to assess the decisions made by insiders." Transparency is presumed as a core tenet in "making visible who is doing what" and holding Parties accountable (A. Gupta & Van Asselt, 2019). It is built on the fundamental belief that information holds significance and

has the potential to empower individuals and organizations alike (K. S. Gupta, 2008). Accountability is directly enabled by transparency and the availability, accuracy, and reliability of data by allowing stakeholders to access and scrutinize the reported information, enabling peer review and public oversight to ensure that the information presented genuinely represents the Party's actions and progress. Within the climate governance landscape, transparency is "multi-directional," since information is generated from a "wide array of state and non-state actors, as well as consumers and citizens" rather than solely from governments or other stakeholders (A. Gupta & Mason, 2016). A significant and expanding assumption that has emerged in the discourse surrounding information disclosure and transparency in global environmental governance pertains to whether new technologies, by diminishing transaction costs, facilitate increased scrutiny (Kloppenburg et al., 2022; Mason, 2008).

It is imperative, therefore, to undertake a broader examination of digital technologies' impact on information flows and transparency within a governance context. In other words, the rules in use (Ostrom, 2005) -- how digital technologies influence the creation, dissemination, and utilization of information -- are critical to understanding whether they generate the intended transparency required for greater accountability at multiple scales. Rules in use are the institutional rules that actors perceive to be in force, governing their decisions and behavior in a specific context and encompass the actual practices, norms, and conventions followed by the actors in a given setting, regardless of whether they are formally codified or not (Ostrom, 2005). Rules in use play a critical role in shaping the incentives, constraints, and opportunities that actors face in a social-ecological system and may evolve over time as a result of actors' interactions and learning processes. Informational rules, one of the seven types rules in use, refer to the rules that determine the types of information that must be provided, who is responsible for providing it, and how it must be presented or shared (Ostrom, 2005). Informational rules are essential for enabling the exchange of information among actors and facilitating coordinated action in a social-ecological system. They can influence the transparency, accuracy, and accessibility of information, thereby affecting the decision-making processes and the overall performance of governance arrangements.

For this paper, we look at how such rules in use affect which actors participate, who collects information and what type, for which purpose, as well as who has access. These are all questions that impact the accuracy, credibility, and quality of the data and ultimately whether these approaches contribute to much-needed transparency and accountability for the Paris Agreement. We selected three case examples -- the World Bank Climate Warehouse, Climate TRACE, and OpenClimate -- where actors and institutions are seeking to improve some aspect of climate data generation, harmonization, or access. Drawing on these cases, we examine digital technology's potential to enhance transparency and accountability in the post-Paris climate system. These digitalized approaches have arisen in part since self-disclosed climate data, through platforms like the CDP (formerly known as Carbon Disclosure Project), have been shown to have limited in utility for research on governance, given their varied and often incomplete nature of data collection (Gilligan & Vandenbergh, 2020; Knox-Hayes & Levy, 2011). Thus, digitalized approaches, such as satellite remote sensing, promise to provide more regular, consistent and "objective" monitoring for environmental policy and sustainable development goals while reducing reporting costs and burdens for individual actors (Anderson et al., 2017).

While limited and certainly not comprehensive given the growth of digital technology approaches in recent years (Kloppenburg et al., 2022), our choice of these case examples stems from an initial broad

search of recent and emergent projects, announced within a year of initial writing, based on their intentions to "disrupt" or innovate the existing status quo with respect to climate data. With this in mind, we specifically sought to identify one case each that: 1) applied blockchain or distributed ledger technology; 2) utilized AI/ML approaches; 3) focused specifically on digital solutions to enhance NSA data collection and interoperability. We identified these digital solution approaches claiming to enhance climate data availability and transparency through a review of the literature and through the Climate Action Data 2.0 Working Group, which convenes digital technologists, policy practitioners, and researchers to collaborate on digitally-enabled climate action accounting (*CAD2.0*, 2021; Kloppenburg et al., 2022).

We started our case analysis by first conducting a secondary literature search of publicly available information on each of the three cases. This process primarily involved a review of websites and their materials (e.g., white papers, blogs, video, and other multimedia) to write a description detailing the overall purpose and aims as they relate to data and information disclosure. We then contacted the developers (identified either through the respective project websites or through previous personal connections) for each selected case study and conducted semi-structured interviews (see Supplementary Information) with each of them or with "project" staff members who provided general background information and context for each case. For each case, we provide a short description of relevant background, aims, and actors involved. We look in particular at the information pertaining to rules in use, per (Ostrom et al., 1994 and Ostrom (2005)) Institutional Analysis and Development or (IAD) framework, to enhance NSA accountability (section 4.4 and Table 1).

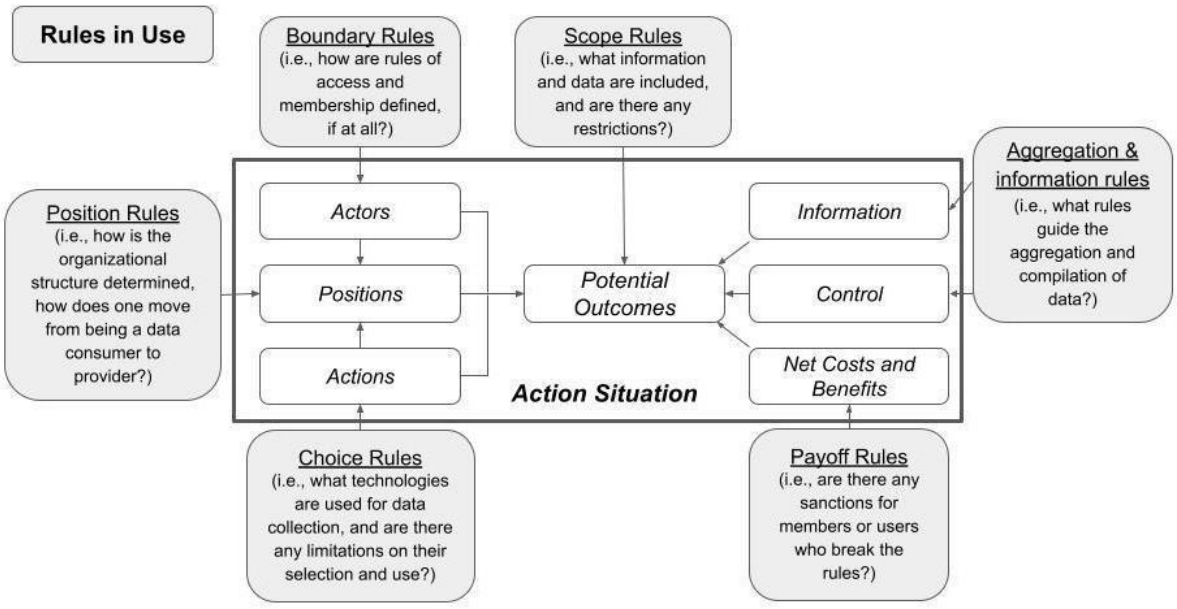
3. Rules in use to generate transparency in data reporting and review

To unpack the various actors, institutions and their impacts on transparency, we use Ostrom's (1994) Institutional Analysis and Development (IAD) framework, which is one of the most applied frameworks in policy science (Carlsson, 2000; Gibson et al., 2005; Imperial, 1999; Rudd, 2004) and has been the basis for empirical research and theoretical development of common-pool resource management (e.g. Gibson et al., 2005; Ostrom et al., 1994; Thomson & Freudenberger, 1997). Critically, the IAD framework "defines a nested arrangement of action situations" that "will elicit a more inclusive or cooperative mode of behavior than narrower issues of implementation (McGinnis, 2011)." It identifies seven sub-types of rules in use, namely position, boundary, choice, aggregation, information, and pay-off rules (Ostrom 2005) (Figure 1).

While we investigate all seven rules in use subtypes in this paper, of particular relevance to our inquiry of digitalized approaches to enhance data transparency and accountability within the global climate governance landscape are "information rules." We understand these information rules as including: who is required to collect information; to what aim; the types of information needed; and ultimately the permissions and prohibitions for communicating across participants (Heikkila and Gerlak 2019; Ostrom 2005). Different rules in use or "shared understandings that refer to enforced prescriptions about what actions (or states of the world) are required, prohibited or permitted" guide their patterns of interaction and the resulting action situation (Ostrom, 1999, p. 50). These rules in use can be both formal (e.g., laws or policies) and informal (e.g., norms, customs, informal rules) (Clement, 2010).

In the Paris Agreement, the rules in use for accounting and transparency for NSAs are vastly different from those for national governments participating in the Paris Agreement. For NSAs, rules in use are self-defined, largely informal, and constantly shifting since NSAs act through largely voluntary pledges on climate mitigation. Few countries have mandatory climate emission disclosure laws,[1] and as a result the availability and transparency of data by which to gauge NSA climate actions -- who is doing what and to what effect -- is limited. NSAs choose what to disclose, to what extent, and within which platforms, resulting in heterogeneous and often incomplete levels of transparency and varying accountability. To compound these transparency challenges, available data on NSA action are primarily drawn from developed countries in the global North (Chan et al., 2018; Hsu et al., 2016; Widerberg & Stripple, 2016), with wider gaps in emerging economies where barriers to assimilating information and enabling evidence-based policy (Dietz et al., 2003) are likely to be exceptionally high.

We interpret how this rules in use framework can be applied in the context of our digital technology case examples to analyze their current or future impact on transparency and accountability in the context of the Paris Agreement. Evaluating who can generate and contribute data, using which technologies, and under what governance arrangement is critical to understanding whether there are structural asymmetries that may stymy transparency. In other words, do the rules help actualize whether the "multi-directional" data and information flows (Gupta and Mason, 2016) required for post-Paris accountability be actualized, or may they worsen existing information, power imbalances and coordination?



[1] A few examples of countries with corporate disclosure regulations, include France (Article 173 of the Law on Energy Transition for Green Growth requires institutional investors and asset managers to disclose climate-related risks and carbon footprint of their portfolios; (Government of France, 2015); the UK became the first G20 country to mandate Britain's largest businesses to disclose climate-related risks in line with the Taskforce on Climate-related Financial Disclosures (UK Government, 2021). The EU's Non-Financial Reporting Directive (2014/95/EU) requires large companies to disclose information on environmental performance, including climate-related risks and greenhouse gas emissions (EU Parliament, 2014). China has also implemented mandatory environmental, social, and governance disclosure (Thomson Reuters, 2022).

Figure 1. The rules in use (gray boxes) as defined in Ostrom's Institutional Analysis and Development framework to describe how they are shaping the elements of the action situation (white boxes) (adapted from Ostrom 2011).

4. Case examples

4.1 Climate TRACE

Launched in 2021, Climate TRACE (which stands for "Tracking Real-time Atmospheric Carbon Emissions"), is a collaborative initiative with more than 100 contributors with WattTime and Transition Zero as its two cofounding organizations (Climate TRACE, 2023b). It includes non-profits, tech companies, and politicians, chiefly former U.S. Vice President Al Gore (Figure 2; Climate TRACE, 2023). With the existence of petabytes of increasingly high-resolution Earth observation data, Climate TRACE asserts they have developed software that can use these data with an "activity-based" approach to measuring the production activity of emissions sources (e.g., power plants, road transport, etc.) rather than directly measuring ambient emissions (e.g., atmospheric concentrations of GHGs) in the way an Earth observation satellite would. Activity-based approaches or "bottom-up" GHG estimation approaches typically measure GHG drivers or indicators, such as fuel consumption, traffic, population, or land area, and apply an emissions factor (e.g., emission or removal of a GHG per unit of an activity) (Bellassen et al., 2015; IPCC, 2006). For example, Climate TRACE uses multispectral satellite imagery to create a heat index to determine production output, which is then used to downscale national-level steel sector emissions to specific steel manufacturing sites (M'Barek et al., 2022). They assert that by doing this, they are able to estimate emissions for specific sources and facilities for 72,612 emitters as of November 2022 that are "more up-to-date" than previous estimates and depend less on information provided by the government (Zhong, 2022).

Climate TRACE makes claims of "bringing radical transparency" to global emissions that "provides open, granular, timely data that makes bigger, better climate action easier" (Climate TRACE, 2021) through providing "independent greenhouse gas emissions tracking" (Climate TRACE, 2022). This claim assumes that current gaps in available climate data are a primary obstacle. The team and organization decided to take a more tech start-up-like approach, forgoing the scientific peer-review procedure in favor of releasing data on their own schedule (Zhong, 2022). The main disadvantage of this approach and the ultimate governance applications it seeks to inform is that its methodology documents vary in their own transparency, often referring to other, external methodologies that lack transparency or peer review (National Academies of Sciences, Engineering, and Medicine, 2022). Additionally, license agreements limit the exposure of proprietary source data, which restricts the data that are actually accessible to the public (National Academies of Sciences, Engineering, and Medicine, 2022). A 2022 National Academy of Sciences, Engineering, and Medicine (NASEM) report on greenhouse gas emissions information for decision-making evaluated Climate TRACE as "low" on transparency since, at the time of evaluation in the summer of 2022, very little public information was available about the initiative's methodology or underlying source data. Since the NASEM report was published in October 2022, more data and methodological details have been released on Climate TRACE's website (Climate TRACE, 2023).

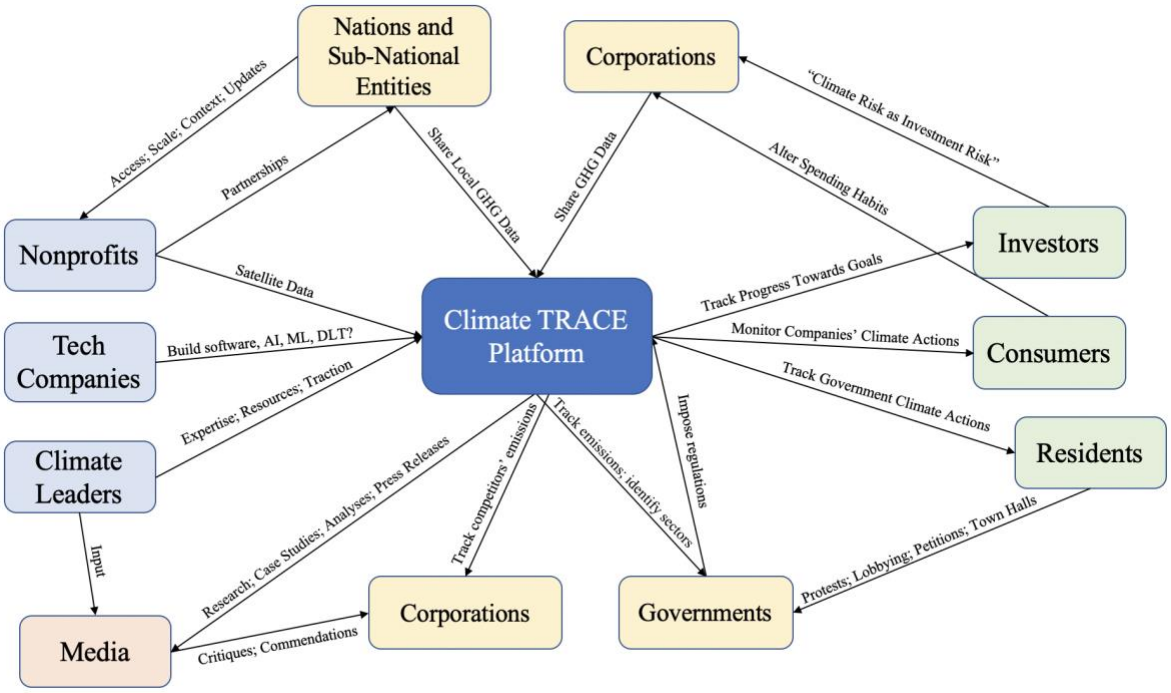


Figure 2. Overview of Climate TRACE stakeholders and information flows between actors (Source: Authors).

4.2 Climate Warehouse

The Paris Agreement poses massive coordination and accounting challenges prohibiting a well-functioning and transparent carbon market where climate assets can be tracked (Marcu & Duggal, 2019). At present, there are 64 different and largely independent carbon pricing instruments operating in diverse regional, subnational, and national jurisdictions (World Bank, 2021). To address this fragmentation of carbon credit data between different registries, the Climate Warehouse (theclimatewarehouse.org) was introduced as an "open-source metadata system" utilizing distributed ledger or blockchain technology. Its purpose is to establish a metadata platform of carbon market activity, aiming to tackle issues related to double counting and enhance confidence in the carbon market (Climate Warehouse, 2023). Prototype development was initially managed by the World Bank's Carbon Market and innovation unit. In December 2022, the Warehouse ownership was transferred into the Climate Action Data trust that is jointly governed by the World Bank, the International Emissions Trading Association (IETA), and the National Climate Change Secretariat Singapore (Climate Warehouse, 2023).

The Warehouse prototype is designed to be a public and open-source platform that aims to contribute to the integrity, transparency, and robust accounting of internationally transferred mitigation outcomes in accordance with Article 6.2 of the Paris Agreement (Figure 3). Article 6.2 includes provisions for countries to use voluntary cooperation mechanisms such as carbon trading to achieve their NDCs (UNFCCC, 2022a). Distributed ledger technologies like blockchain offer a decentralized data storage solution to connect various data and reporting systems (Hsu, et al., 2020; Schletz, et al., 2022). The Warehouse has developed a common taxonomy of related carbon project information, making various registry data 'interoperable' by harmonizing data into a single "meta-registry" through peer-to-peer

connections of other registries (World Bank, 2022a) (Figure 3). Even within automated systems, the level, magnitude, and information collection units often vary, making it challenging to establish a credible, consistent, transparent, and accurate global climate market (World Bank, 2022a). Since data stored on a blockchain is immutable, the Warehouse aims to safeguard transparency by storing all information updates as unique and immutable blocks to allow for traceability across the system (World Bank, 2022a). Establishing rules in use is crucial to standardizing data formats by "developing a common 'language' between registries to address the complexities of conducting transactions" (World Bank, 2019).

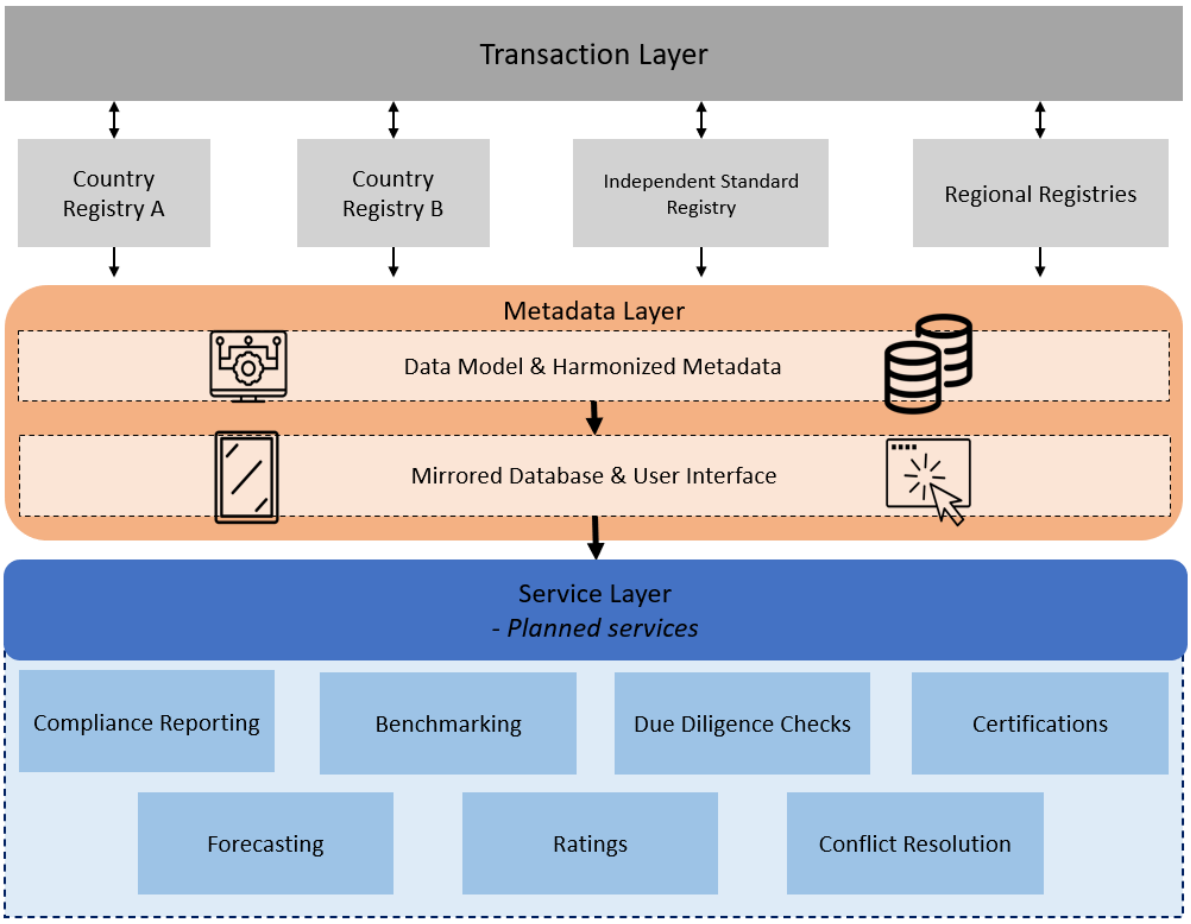


Figure 3. Overview of the components and anticipated functions of the Climate Warehouse (Source: authors, adapted from (World Bank, 2022a).

Common rules enable nations and institutions to connect their systems to the Warehouse and make edits on their end that will be transmitted to all other systems connected to the Warehouse (World Bank, 2022a). Although the Warehouse is not yet fully operational, it has conducted three simulation pilots to allow real-world actors, such as governments and independent standards and carbon registries, to test the meta-data harmonization protocol and blockchain storage components. The Warehouse engaged 30 organizations that participated in Simulation III, the third and final test phase that concluded in December 2022, including national governments (e.g., Chile, Singapore, Chile, Sweden, Switzerland, and Japan), independent standards organizations (e.g., Verra, The Gold Standard, and American Carbon Registry), and technology providers (e.g., the OpenEarth Foundation and Chia blockchain), as well as other organizations (e.g., UNFCCC, Climate Action Reserve, Global Carbon Council, BV Rio). A synthesis report summarizing the key findings of the third and final test phase, called The Simulation III report

(World Bank, 2022a), was released at the end of 2022 and the Climate Warehouse has since focused on creating minimal viable products that can be implemented for broader use.

4.3 OpenClimate

The OpenClimate platform (openclimate.network) developed by digital-technology non-profit OpenEarth Foundation seeks to provide an integrated accounting platform to address NSA climate data complexities due to the interdependence, fragmentation, and disagreement among actors across multiple governance levels (Schletz et al., 2022). Its objective is to integrate and highlight NSA emissions statistics and initiatives, which amount to close to 30,000 commitments to mitigate, adapt, and finance climate solutions (UNFCCC, 2019). Integrating multiple NSA data that suffer from disparate methods of data collecting, reporting standards, progress monitoring, and usage of voluntary markets is a key driver for the OpenClimate platform (Wainstein, 2019).

Launched in November 2022, OpenClimate initially displays emissions data from a range of sources for countries and a select number of subnational entities. Towards the goal of NSA data integration, OpenClimate is developing a nested accounting approach that combines disparate climate-related information from all actors'— nation-states and NSAs — commitments, actions, and policies (Wainstein 2019; Schletz, et al., 2022). The vision is to create a "dashboard that can act as a stocktaking visualization of NSAs and their commitments" (Wainstein, 2019). For example, data disclosed by an individual company (e.g., originally reported and provided through CDP) can be aligned with other digitally-enabled data, such as Earth Observation or sensor data. Since all of these digitally-enabled data, harmonized and tied to a specific actor, are reported within the geographical context of a country, they can be included in the country's national inventory to track the NDC process and then be submitted to support international frameworks like the UNFCCC and the ETF (Figure 4; Schletz, et al., 2022). In parallel to the NSA data integration function, OpenClimate has developed a blockchain-based approach to verifying credentials of reporting entities as a foundation for establishing the trust needed to support carbon market mechanisms. Partnering with British Columbia's (BC) Ministry of Energy, Mines and Low Carbon Innovation, they launched in September 2022 the Energy and Mines Digital Trust initiative as a way for BC companies to verify and share their emissions credentials to the OpenClimate platform (OpenEarth Foundation, 2022).

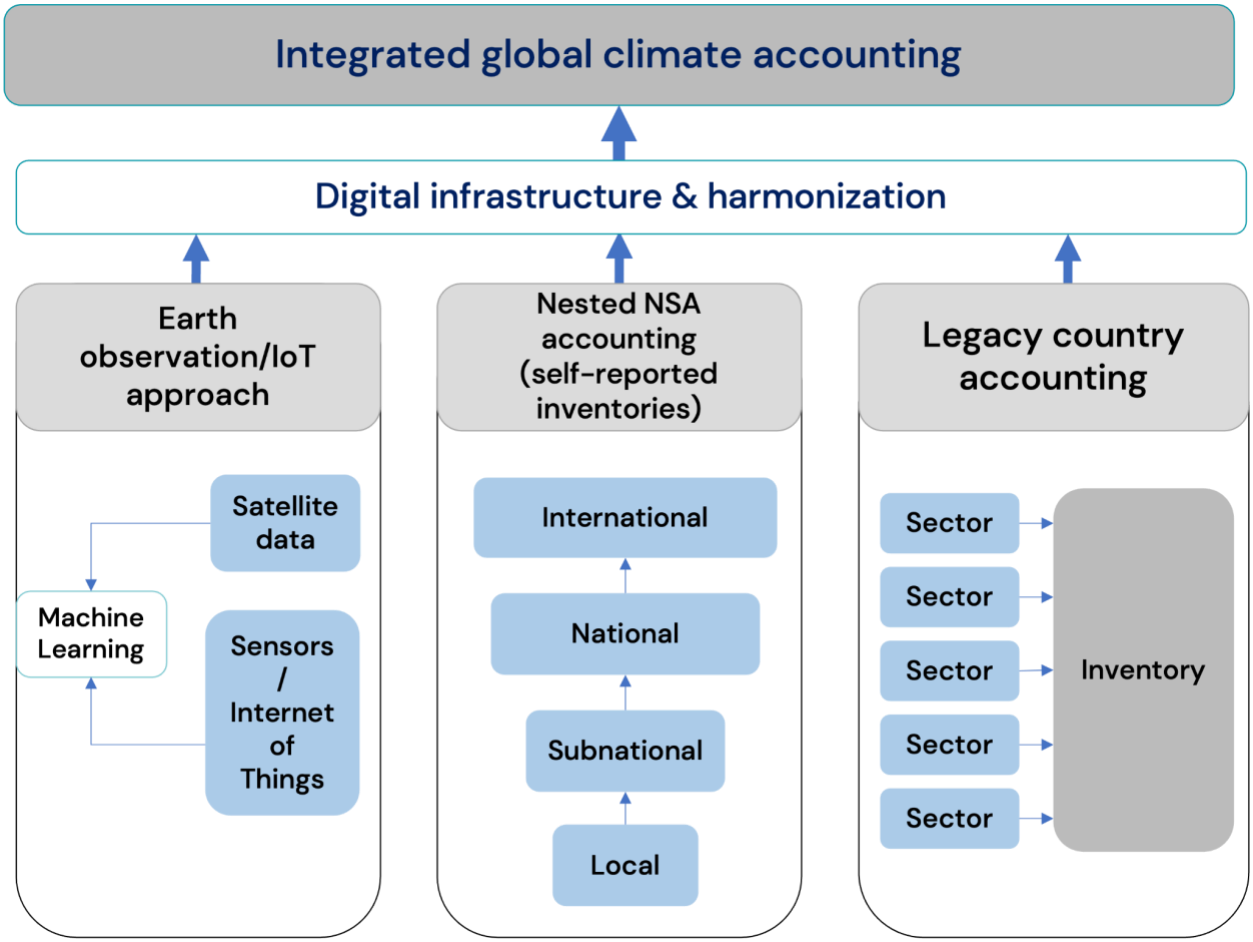


Figure 4. Overview of the OpenClimate nested accounting architecture (Source: adapted from Schletz, et al., 2022).

4.4 Rules in use analysis

While each of the three cases works on creating climate data transparency using emerging digital technologies, the scope and type of information rules applied are very different. In Table 1, we interpret Ostrom's (2011) rules in use (Figure 1) to analyze how each case example defines the boundaries of information production and dissemination for a broader audience. We evaluated project ownership information (i.e., who are the developers of each case example) as well as their goals and aims, and then examined the boundary, position, scope, choice, aggregation, and payoff rules in use for each initiative (Ostrom, 2011).

In summary, the cases were selected to illustrate new digital approaches that 1) utilize AI/ML approaches (Climate TRACE); 2) apply blockchain or distributed ledger technology (Climate Warehouse); and 3) employ digital solutions to integrate across disparate data sources and datasets to enhance data interoperability (Open Climate). Although these digital technology solutions are at varying stages of development, with the Climate Warehouse initiating their pilots the earliest, they are all seeking to improve the availability and transparency of climate data at multiple scales and for a range of audiences and users, including NSAs. They are similar in their scope rules, in that they seek to have broad

geographic and temporal coverage, with the aim to utilize digital technology to integrate multiple datasets through harmonized data structures and schema to ease the usability, interpretability, and ultimately transparency of various entities' climate emissions and actions. In all cases, the developers have, to some extent, limited their scope rules due to what we interpret as technical capacity limitations: the Climate Warehouse limits registry data to 26 key datapoints determined by the World Bank through stakeholder consultation due to storage limitations of blockchain technology; Climate TRACE limits most facility-level data to the 500 largest sources per country; and OpenClimate is manually collecting different datasets, all which require manual harmonization before they can be displayed on their platform. We find each case example falls short in providing clear aggregation rules - publicly-accessible documentation detailing how each case combines and summarizes data across data points, facilities, jurisdictions or other boundaries was the most limited in this aspect. Even when nationally or globally aggregated data are presented alongside NSA or subnational data, the rules for aggregating between the two jurisdictions are unclear (as in the case of OpenClimate), or are still being validated (as in the case of Climate TRACE). Perhaps due to the nascency of these efforts or the limitations of technology choice rules themselves, none of the three case examples provides protocols or detailed information regarding data quality assurance or accuracy. While OpenClimate discusses "verifiable credentials" in the context of the pilot with British Columbia's mining sector (OpenEarth Foundation, 2022), there are no obvious protocols for verifying the accuracy or credibility of data, only the entity providing it. Similarly, in the case of the Climate Warehouse, the World Bank acknowledges that blockchain technology "by itself does not assure data quality or integrity, and data entering the system needs independent quality assurance to ensure that it is reputable before entering the system" (World Bank, 2019).

Table 1. Analysis of the different rules in use for each case example.

	Climate TRACE	**Climate Warehouse / Climate Action Data Trust**	**OpenClimate**
Project ownership information	In 2019, WattTime received a Google AI Impact Challenge grant of $1.7 million to spearhead the collaboration (WattTime, 2019). Officially launched in 2020, Climate TRACE is a network of collective stakeholders of several nonprofits, tech companies, and academic partners (Climate TRACE, 2021).	Originally launched by the World Bank in 2018 (Bloomberg, 2021). Was rebranded as "Climate Action Data Trust" in 2022 and became a joint initiative by the World Bank, as the Climate Action Data Trust, co-owned with the International Emissions Trading Association (IETA), and the National Climate Change Secretariat Singapore, and	Developed as an open-source project by the OpenEarth Foundation starting in 2019. The Open Earth Foundation is the current host of OpenClimate, carrying out both product development and data input tasks but with the option of open-source contribution through Github data and code contributions.

		was officially launched Dec. 7, 2022 (Climate Warehouse, 2023).	Officially released beta version at the COP27 climate summit.
Incentive and aim	Allow better decision-making by expanding the spatial and temporal resolution of facility and sectoral GHG emission information that can be analyzed at multiple scales (facility-level, and aggregated to the national level) (Climate TRACE, 2022).	Support the implementation of the Paris Agreement's Article 6 carbon markets by facilitating the accounting of carbon offset transfers and associated corresponding adjustments of mitigation outcomes under Article 6 of the Paris Agreement. Aims to reduce the risk of double-counting by integrating voluntary and compliance market mechanism accounting (World Bank, 2023).	Supporting the integration of various NSA GHG emissions data sources and mitigation target data that can be used to inform multiple audiences, including global stocktaking efforts. Identify information gaps and deviations between NSA and national accounting – support the nesting of NSA information with subnational and national data (OpenEarth, 2022).
Rules in Use (Ostrom, 2005)			
Boundary rules determine eligibility to enter a position, eligible participants to enter and the process of exiting from any position	Data providers are limited to consortium partners	Launched a specific independent governing board, the CAD Trust, on Dec. 7 2022, based in Singapore. Led by Board and Council of governments and major carbon registries. Includes a Secretariat and Technical Committee and User Forum that works on various operational aspects of the CAD (World Bank, 2022).	OpenEarth Foundation determines which datasets are included in OpenClimate.

Position rules regulate the presence of participants who occupy each position in an action situation	The network specifies three key roles and responsibilities: Consortium partners, advisory and technical experts, and data users as stakeholders. There is no public information available on how to move into or between roles.	The initiative has a governance structure consisting of the following roles: Council, board of directors, secretariat, technical committee, and a user forum. There is no public information available on how to move into or between roles.	The OpenEarth Foundation is coordinating different roles and actively seeking to elicit direct data contributions, with details on how to contribute data through a GitHub repository (OpenEarth Foundation, 2023).
Choice rules determine what actions are required, permitted, or prohibited by participants	Remote sensing (high-resolution satellite imagery and other Earth science data) to observe distinct emission sources (e.g., power or cement plants, etc.), direct measurement, and use of AI/ML to combine datasets (Climate TRACE, 2023b).	Technologies include a blockchain-based metadata platform to connect and aggregate registry information, digital MRV systems, national carbon registries, tokenization instruments, and a one-stop resource platform that enhances knowledge-sharing and capacity-building (World Bank Group, 2023). The World Bank acknowledges they have not yet experimented with other technologies, including AI/ML (World Bank, 2019). At the time of writing, only the blockchain data registry component had been piloted.	Blockchain technology, Decentralized identifiers (DIDs), and verifiable credentials components, will eventually allow entities to contribute "trusted" data (OpenEarth, 2023; Wainstein, 2019).
Scope rules define the range of potential outcomes of their combined interactions	Global – uses a variety of data, such as satellite remote sensing data "direct measurements, and artificial intelligence" (Climate TRACE, 2023a) It covers 11 major sectors of emissions (agriculture,	Registries (i.e., data stored in the Climate Warehouse) are defined as "databases and ledgers that hold records of climate offset and generating projects, their generated units (e.g.,	The primary focus is on NSA GHG emissions and policy target information with the aim of creating 'nested accounting' across all governance levels (Wainstein, 2019). As of May 2023, it includes

	power, manufacturing, transportation, buildings, forestry and land use, waste, mineral extraction, among others) and as of May 2023 includes more than 80,000 facilities, although accessible are the top 500 companies per sector per country, with an indication that for some countries they possess more data. However, only production data are included and not consumption data that points to the drivers of emissions (Whitmee et al., 2023).	mitigation outcomes), and transactions under a market mechanism (e.g., country registries)" (World Bank Group, 2022). The World Bank acknowledges storage limitations for "storing large amounts of attribute information about climate actions," which can include "audit reports and detailed project information" should be stored in other places. Data uploaded by users, therefore, are limited to 26 specific fields defined by the Warehouse (World Bank, 2019).	nearly 60 datasets for both country and NSA-level emission data (OpenEarth Foundation, 2023). It is unclear what decision processes exist for determining which data are incorporated and featured, although there is a Google form available for contributors to submit datasets for consideration of inclusion (OpenEarth, 2023).
Information rules prescribe the available information level, authorize information channels, and establish obligations, permissions, or prohibitions for communicating among participants	The Climate TRACE secretariat (Watt TIME) determines which data providers are selected and how data quality control and assurance procedures are defined, although these determinations are not made publicly available on the website. Dissemination of data to broad audiences such as media, consumers, investors, policymakers, regulators, researchers. Their 2021 white paper mentions "policymakers, advocacy groups, and corporations," as well as regional actors/NSAs, particularly Global South actors that are prone to data	Data quality is the responsibility of the connected registry (World Bank, 2022a). Simulation III participants suggested to introduce more data validation rules and picklist options to improve data quality and harmonization (World Bank, 2022a). Distribution to stakeholder groups (governments, independent certification standards, UNFCCC, exchanges, project developers, verification bodies, buyers and traders, and public and private players) to enable interoperability of carbon market data (World Bank, 2022a).	Open-source access to code and option to contribute data but no quality control and assurance procedures are defined. Dissemination seeks to make data publicly available for a broader audience by harmonizing and integrating the various forms of independent climate data providers. Also, expanding the information base for countries with currently limited accounting capacities to include nested NSA data within subnational and national data (Wainstein, 2019).

	deficits (Climate TRACE, 2021).		
Aggregation rules determine the decision process of whether one participant or a group of participants can take any action	Greenhouse gas emissions data are provided for more than 80,000 sources, unclear method for aggregating and compiling facility-level data at the national and global levels, although the website states their methodology is "undergoing review and validation." It claims to be a source of "independent" accounting" without using government-reported statistics (Climate TRACE, 2021), although the quality of the data are unknown since the aggregation rules are unclear.	The Warehouse provides a data model for the integration of different datasets from the various registry systems. The data model harmonizes data fields across different registries using a common taxonomy for data integration and extraction (World Bank Group, 2022a). Most Simulation III participants provided substantial feedback on the Climate Warehouse data model that confirmed the critical importance of the Climate Warehouse's effort to establish a common carbon data taxonomy, especially in the context of continuously evolving carbon market terminologies and definitions (World Bank Group, 2022a)..	Although "nested accounting" is advertised as a key feature of OpenClimate, the rules for data aggregation are unclear (Wainstein, 2019; OpenEarth, 2023). The portal presents nearly a dozen different options for users to display country-level emissions and mitigation target data, with options to select subnational jurisdictions located within a country, although at the time of writing, the website itself does not provide a way to aggregate NSA data into country-level emissions or otherwise (OpenEarth, 2023). A Python application provides guidance for users to manually aggregate subnational targets to compare them with national efforts (Gloege, 2023).
Pay-off rules are how the required, permitted, or prohibited benefits and costs are	These initiatives at the time of writing have not specified sanctions imposed if users breaking any of the rules		

distributed to participants	

5. Discussion

The three case examples presented in this analysis exemplify the potential of digital technologies in enhancing data availability, accuracy, and reliability to improve transparency of climate actions from multiple actors, in particular NSAs. Examining the rules in use (Ostrom, 2005) concerning digital technologies allows us to assess how these technologies -- through choices of technology, data collection and aggregation, and governance -- shape transparency outcomes. In doing so, we aimed to uncover any potential challenges or unintended consequences as a basis for evaluating whether digital solutions enhance or hinder transparency. However, when considering their operational implementation of rules in use, uncertainties arise regarding whether these digital solutions will enhance transparency generation sufficiently to address accountability issues in global climate governance. This question is especially relevant in the context of multi-level governance challenges and the involvement of NSAs. We bring attention to three sets of issues that offer valuable insights for assessing the role of digitally-enabled approaches as the missing link between transparency and accountability: first, how digital technology approaches can create and define appropriate rules in use to govern data quality; second, whether such approaches can overcome power imbalances that threaten transparency and multi-directional information sharing; and third, how alignment of various rules in use across digitally-enabled solutions can facilitate, rather than hinder, coordination, transparency and accuracy in the post-Paris climate regime. We discuss each point below.

5.1 Rules in use for governing data quality

The critical assumption underlying each of the digital technology approaches examined to climate data and transparency is that more data and greater disclosure result in greater accountability (Ciplet et al., 2018; A. Gupta & Van Asselt, 2019; Mason, 2020). In reality, various factors can contribute to the lack of accountability within climate governance, beyond the availability of data. In private corporate disclosure efforts, for example, A. Gupta & Mason (2016) note the dearth of evidence regarding the effectiveness of CDP and other corporate carbon disclosure initiatives in holding actors accountable (e.g., the Global Reporting Initiative; see Dingwerth & Eichinger, 2010). In addition to the “lack of specificity and comparability” in these self-disclosure initiatives (Dingwerth & Eichinger, 2010), another reason may be due to the accuracy and quality, which includes structural consistency, of the information disclosed (A. Gupta & Mason, 2016). While digitally-enabled approaches like Climate TRACE and OpenClimate could address the issue of specificity, by providing more disaggregated and granular data at facility and local units level, our examination of these examples reveals a gap in rules broadly governing quality. As described in the preceding section, these cases’ scope and boundary rules for information collection and dissemination have the potential to enhance the comprehensiveness and coverage of existing data, since entities lack the option to “cherry-pick” and self-select which data to disclose. However, it is crucial to include provisions for data quality, as highlighted by the Climate Warehouse (World Bank, 2019), to ensure that the resulting data is uniformly structured, accurate and reliable - necessary preconditions for transparency to enhance rather than hinder accountability (National Academies of Sciences, Engineering, and Medicine, 2022). As described in Section 4.4, none of the selected case examples provide scope or

choice rules in use that have criteria for evaluating data quality or specify rules for when data may be rejected due to the lack of quality. Since data quality is central to digital transparency (Matheus et al., 2021), the absence of quality data could present barriers to transparency, if data are inaccurate, misformatted, or lack clear ownership.

5.2 The potential to shift power dynamics

According to Mol (2008), the structure and rules concerning information, informational processes, and informational technologies are a crucial element, resource, and domain of power struggles in environmental governance across institutions. Established institutions have a crucial role in setting basic environmental quality norms and standards for "successful informational governance, for instance, with respect to the codification of new developments, the sanctioning of transparency and disclosures, the organizing and facilitating of informational processes, the verification of information or the verification of auditors and so on" (Mol, 2008). As such, transparency and information disclosure initiatives have the potential, through their rules in use definitions, to empower certain groups or interests over others, reshaping power dynamics in a governance system in a more or less inclusive way (Ciplet et al., 2018). As Green and Kuch (2022) observe, "Carbon-based accountability frameworks, in short, have well served the narrow interests of carbon-intensive states and firms, financial actors, and the expert community of carbon managers," leading many to contend whether such systems and the "opaque, elite-dominated forms of governance they enable" provide the transparency required to hold these actors accountable.

Digitalized technologies could reshape power dynamics in the post-Paris climate governance system in both positive and negative ways. On one hand, as Green and Kuch (2022) forewarn, the boundary, scope, position, and choice rules that specific initiatives choose to employ could result in greater information asymmetries and further entrench selected, elite interests. Gordon (2016) warns that accountability schemes that rely on information disclosure alone "privileges particular modes of knowledge and skill sets and silences others;" this underscores the importance of examining the stakeholders who bear the costs of implementing accountability (e.g., boundary rules). Such approaches could also do the opposite: decentralize and democratize data and information flows so that no one institution or set of actors disproportionately controls them. In our three cases, the boundary and position rules for determining governance on the surface appear to be more inclusive and reflective of the heterogenous set of actors in the global climate governance landscape, including both state and non-state actors. Each case example's governing body includes a multitude of subnational, non-state and private, as well as national and intergovernmental institutions, which, on the surface appears to be more inclusive than state-centered or UNFCCC-centric transparency initiatives. Additionally, distributed ledgers (e.g., OpenClimate, Climate Warehouse) promise to allow individual actors to maintain data sovereignty, since such decentralized frameworks are immutable and entirely transparent to observers (Schletz, Hsu, Mapes, et al., 2022). Automated data collection and verification techniques, aided by AI/ML, could also obviate the need for powerful data and information intermediaries, such as "auditors, verifiers, and certifiers of disclosed information." Such intermediaries have greatly benefited from a growing emphasis on data accounting and reporting in climate governance (A. Gupta & Mason, 2016). In this sense, digitally-enabled approaches could foster more inclusive transparency by lowering barriers to participation and potentially accelerating review and verification through the use of AI/ML tools as illustrated in our case examples.

5.3 Aligning rules in use to improve NSA coordination and transparency

The absence of well-defined rules in use beyond these initiatives at the global scale hinders their full

potential. Specifically, the alignment of the various rules within and across climate data communities is crucial to facilitate consistent data and transparency and help global understanding of climate actions' impact. The three initiatives examined here have the role of creating, expanding, and aligning "information and institutional capacities" through evolving rules in use for NSA data to be nested within national jurisdictions for consideration into the ETF or the UNFCCC's new NSA Recognition and Accountability Framework by using digital approaches. However, in our examination of each case, we found a lack of clear aggregation rules for relating data at multiple scales to higher levels in a way that would allow for the greater stocktaking required by the Paris Agreement and to meet the demand for comprehensive and holistic assessments of climate actions and progress. Thus associated rules in use at the national and international levels are needed to determine how parallel transparency frameworks – e.g. one for national governments and the other for NSAs - will provide the necessary mechanisms for accountability and ensure that transparency efforts effectively capture all actions and progress of all relevant stakeholders.

The creation of well-defined rules in use for the integration of these crucial new data streams at multiple levels, supported by digital technologies, holds the potential to unlock the myriad benefits envisioned by Ostrom's proposed remedy for collective-action-based governance systems. A system, characterized by diverse, multi-levelled actors with overlapping decision-making centers, operating autonomously yet interacting and coordinating their actions (Ostrom, 2010), is already embodied by the Paris Agreement and can be described as "polycentric" (Dorsch & Flachsland, 2017; Jordan et al., 2015). For Ostrom (2010), a "combination of structural features" is required to enhance and facilitate the needed trust and coordination within a polycentric system. In this context, coordination is grounded on "an overarching system of rules" (Pahl-Wostl & Knieper, 2014); this may comprise both informal information sharing and learning as well as more formal coordination such as monitoring systems or conflict resolution (Dorsch & Flachsland, 2017; Galaz et al., 2012). To realize such a polycentric climate governance system, global rules in use regarding the generation and dissemination of information are critical to achieve its intended benefits.

6. Conclusion

In conclusion, a critical examination of the rise of digital technologies and their implications for transparency governance and accountability in climate outcomes is crucial. Transparency, by making visible who is doing what, is built on the premise that information disclosure empowers accountability for individuals and organizations. In the context of climate governance, data and information flows are multi-directional, involving a wide array of state and non-state actors, consumers, and citizens. However, the assumption that new technologies automatically facilitate increased scrutiny and transparency needs further scrutiny, considering the political and economic structures shaping these solutions.

To understand the impact of digital technologies on information flows and transparency, it is important to examine the rules in use, which encompasses how these technologies influence the creation, dissemination, and utilization of information. Rules in use, both formal and informal, play a critical role in shaping incentives, constraints, and opportunities for actors in a social-ecological system. Information rules, in particular, determine the types of information to be provided, responsible parties, and how it should be shared.

In this paper, three case examples, namely the World Bank Climate Warehouse, Climate TRACE, and OpenClimate, were analyzed to assess the potential of digital technologies in enhancing transparency and accountability in the post-Paris climate system. These digitalized approaches emerged as alternatives to self-disclosed climate data, which have limitations in utility and data collection. The case studies were chosen based on their disruptive or innovative intentions regarding climate data and their focus on enhancing non-state actor data collection and interoperability. Although these digital initiatives are still in their nascent stages, it is crucial to analyze the rules in use of each approach, which encompass various aspects such who participates and which technologies are used, who collects information, for what purpose, and who has access to it. Understanding these rules is essential in evaluating the accuracy, credibility, and quality of data and their contribution to transparency and accountability for the Paris Agreement.

It is evident from our analysis that the rules in use for accounting and transparency vary for different actor groups in the Paris Agreement. Non-state actors operate under self-defined and often informal rules, resulting in heterogeneous levels of transparency and accountability. This limited transparency is compounded by incomplete and non-comparable data, particularly in emerging economies. To evaluate whether digital solutions enhance or hinder transparency, three sets of issues offer valuable insights. First, the creation and definition of appropriate rules in use to govern data quality by digital technology approaches are crucial. Second, addressing power imbalances that hinder multi-directional information sharing is essential for these approaches to succeed. Finally, aligning various rules across digitally-enabled solutions can facilitate coordination and enhance polycentrism in the post-Paris climate regime.

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References

Anderson, K., Ryan, B., Sonntag, W., Kavvada, A., & Friedl, L. (2017). Earth observation in service of

the 2030 Agenda for Sustainable Development. *Geo-Spatial Information Science*, *20*(2), 77–96.
Bellassen, V., Stephan, N., Afriat, M., Alberola, E., Barker, A., Chang, J.-P., Chiquet, C., Cochran, I., Deheza, M., & Dimopoulos, C. (2015). Monitoring, reporting and verifying emissions in the climate economy. *Nature Climate Change*, *5*(4), 319–328.
CAD2.0. (2021). Accessed May 21, 2023. https://wiki.climatedata.network/
Carlsson, L. (2000). Policy networks as collective action. *Policy Studies Journal*, *28*(3), 502–520. https://doi.org/10.1111/j.1541-0072.2000.tb02045.x
Chan, S., Falkner, R., Goldberg, M., & van Asselt, H. (2018). Effective and geographically balanced? An output-based assessment of non-state climate actions. *Climate Policy*, *18*(1), 24–35. https://doi.org/10.1080/14693062.2016.1248343
Ciplet, D., Adams, K. M., Weikmans, R., & Roberts, J. T. (2018). The transformative capability of transparency in global environmental governance. *Global Environmental Politics*, *18*(3), 130–150.
Clement, F. (2010). Analysing decentralised natural resource governance: Proposition for a "politicised" institutional analysis and development framework. *Policy Sciences*, *43*(2), 129–156. https://doi.org/10.1007/s11077-009-9100-8
Climate TRACE. (2021). *Bringing Radical Transparency to Global Emissions*. Accessed Sept. 9, 2022. https://climatetrace.org/public/papers/2021/ClimateTRACE_BringingRadicalTransparencytoGlobalEmissions_FullReport.pdf
Climate TRACE. (2022). News. Accessed May 15, 2023. https://climatetrace.org/news/climate-trace-releases-first-comprehensive-independent
Climate TRACE. (2023a). *Our Approach*. Accessed May 15, 2023. https://climatetrace.org/our-approach
Climate TRACE. (2023b). *Our Story—Climate TRACE*. Accessed May 15, 2023. https://climatetrace.org/our-story
Climate Warehouse. (2023). *Climate Action Data (CAD) Trust | World Bank Climate Warehouse*. https://www.theclimatewarehouse.org/work/climate-action-data-(cad)-trust
Dietz, T., Ostrom, E., & Stern, P. C. (2003). The Struggle to Govern the Commons. *Science*, *302*(5652), 1907–1912. https://doi.org/10.1126/science.1091015
Dingwerth, K., & Eichinger, M. (2010). Tamed transparency: How information disclosure under the global reporting initiative fails to empower. *Global Environmental Politics*, *10*(3), 74–96.
Dorsch, M. J., & Flachsland, C. (2017). A Polycentric Approach to Global Climate Governance. *Global Environmental Politics*, *17*(2), 45–64. https://doi.org/10.1162/GLEP_a_00400
Directive 2014/95/EU of the European Parliament and of the Council of 22 October 2014 amending Directive 2013/34/EU as regards disclosure of non-financial and diversity information by certain large undertakings and groups Text with EEA relevance, CONSIL, EP, 330 OJ L (2014). http://data.europa.eu/eli/dir/2014/95/oj/eng
Florini, A. (2007). Introduction. The Battle Over Transparency. In A. Florini (Ed.), *The Right to Know* (pp. 1–16). Columbia University Press. https://doi.org/10.7312/flor14158-intro
Galaz, V., Crona, B., Österblom, H., Olsson, P., & Folke, C. (2012). Polycentric systems and interacting planetary boundaries—Emerging governance of climate change–ocean acidification–marine biodiversity. *Ecological Economics*, *81*, 21–32. https://doi.org/10.1016/j.ecolecon.2011.11.012
Gibson, C. C., Andersson, K., Ostrom, E., & Shivakumar, S. (Eds.). (2005). *The samaritan's dilemma: The political economy of development aid*. Oxford University Press.
Gilligan, J. M., & Vandenbergh, M. P. (2020). A framework for assessing the impact of private climate governance. *Energy Research & Social Science*, *60*, 101400. https://doi.org/10.1016/j.erss.2019.101400
Gloege, L. (2023). *OpenClimate Python Client Documentation—OpenClimate pyClient 0.1.0 documentation*. https://openclimate-pyclient.readthedocs.io/en/latest/index.html
Gordon, D. J. (2016). The Politics of Accountability in Networked Urban Climate Governance. *Global Environmental Politics*, *16*(2), 82–100. https://doi.org/10.1162/GLEP_a_00357
Government of France. (2015). *Law no. 2015-992 on Energy Transition for Green Growth (Energy*

Transition Law)—Climate Change Laws of the World. https://climate-laws.org/document/law-no-2015-992-on-energy-transition-for-green-growth-energy-transition-law_aea3
Green, F., & Kuch, D. (2022). Counting Carbon or Counting Coal? Anchoring Climate Governance in Fossil Fuel–Based Accountability Frameworks. *Global Environmental Politics*, *22*(4), 48–69. https://doi.org/10.1162/glep_a_00654
Große-Bley, J., & Kostka, G. (2021). Big Data Dreams and Reality in Shenzhen: An Investigation of Smart City Implementation in China. *Big Data & Society*, *8*(2), 205395172110451. https://doi.org/10.1177/20539517211045171
Gupta, A., & Mason, M. (2016). Disclosing or obscuring? The politics of transparency in global climate governance. *Current Opinion in Environmental Sustainability*, *18*, 82–90. https://doi.org/10.1016/j.cosust.2015.11.004
Gupta, A., & Van Asselt, H. (2019). Transparency in multilateral climate politics: Furthering (or distracting from) accountability?: Transparency in climate politics. *Regulation & Governance*, *13*(1), 18–34. https://doi.org/10.1111/rego.12159
Gupta, K. S. (2008). A comparative analysis of knowledge sharing climate. *Knowledge and Process Management*, *15*(3), 186–195. https://doi.org/10.1002/kpm.309
Hale, T. (2020). Catalytic Cooperation. *Global Environmental Politics*, *20*(4), 73–98. https://doi.org/10.1162/glep_a_00561
Heikkila, T., & Gerlak, A. K. (2019). Working on learning: How the institutional rules of environmental governance matter. *Journal of Environmental Planning and Management*, *62*(1), 106–123.
Hsu, A., Cheng, Y., Weinfurter, A., Xu, K., & Yick, C. (2016). Track climate pledges of cities and companies. *Nature*, *532*(7599), 303–306. https://doi.org/10.1038/532303a
Hsu, A., Khoo, W., Goyal, N., & Wainstein, M. (2020). Next-Generation Digital Ecosystem for Climate Data Mining and Knowledge Discovery: A Review of Digital Data Collection Technologies. *Frontiers in Big Data*, *3*, 29. https://doi.org/10.3389/fdata.2020.00029
Hsu, A., Tan, J., Ng, Y. M., Toh, W., Vanda, R., & Goyal, N. (2020). Replication Data for: Performance determinants show European cities are delivering on climate mitigation. *Nature Climate Change*, *10*(11), 1015–1022. https://doi.org/10.7910/DVN/IJ4DDI
Hsu, A., Wang, X., Tan, J., Toh, W., & Goyal, N. (2022). Predicting European cities' climate mitigation performance using machine learning. *Nature Communications*, *13*(1), 7487. https://doi.org/10.1038/s41467-022-35108-5
Imperial, M. T. (1999). Institutional analysis and ecosystem-based management: The institutional analysis and development framework. *Environmental Management*, *24*(4), 449–465. https://doi.org/10.1007/s002679900246
IPCC. (2022). *Working Group III — IPCC*. https://www.ipcc.ch/working-group/wg3/
IPCC. (2006). *I2006 IPCC Guidelines for National Greenhouse Gas Inventories, prepared by the National Greenhouse Gas Inventories Programme, eds. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, K. Tanabe. Japan: IGES. - Google Search*.
Jordan, A. J., Huitema, D., Hildén, M., Van Asselt, H., Rayner, T. J., Schoenefeld, J. J., Tosun, J., Forster, J., & Boasson, E. L. (2015). Emergence of polycentric climate governance and its future prospects. *Nature Climate Change*, *5*(11), 977–982. https://doi.org/10.1038/nclimate2725
Kloppenburg, S., Gupta, A., Kruk, S. R. L., Makris, S., Bergsvik, R., Korenhof, P., Solman, H., & Toonen, H. M. (2022). Scrutinizing environmental governance in a digital age: New ways of seeing, participating, and intervening. *One Earth*, *5*(3), 232–241. https://doi.org/10.1016/j.oneear.2022.02.004
Knox-Hayes, J., & Levy, D. L. (2011). The politics of carbon disclosure as climate governance. *Strategic Organization*. https://doi.org/10.1177/1476127010395066
Kostka, G., Zhang, X., & Shin, K. (2020). Information, technology, and digitalization in China's environmental governance. *Journal of Environmental Planning and Management*, *63*(1), 1–13. https://doi.org/10.1080/09640568.2019.1681386
Kuramochi, T., Smit, S., Hans, F., Horn, J., Lütkehermöller, K., Nascimento, L., Emmrich, J., Höhne, N.,

Hsu, A., Mapes, B., Wang, X., Roelfsema, M., Chan, S., Deneault, A., Nagasawa, B. de S., Mohan, M., Whitney, M., Brehm, J., Hassel, J., … Hale, T. (2021). Global climate action from cities, regions and businesses. 2021 edition. *NewClimate Institute, Data-Driven EnviroLab, Utrecht University, German Development Institute/Deutsches Institut Für Entwicklungspolitik (DIE), CDP, Blavatnik School of Government, University of Oxford*. https://newclimate.org/2021/06/23/global-climate-action-from-cities-regions-and-businesses-2021/

Marcu, A., & Duggal, V. K. (2019). *Negotiations on Article 6 of the Paris Agreement: Road to Madrid*. Asian Development Bank. https://doi.org/10.22617/WPS190559-2

Mason, M. (2008). Transparency for Whom? Information Disclosure and Power in Global Environmental Governance. *Global Environmental Politics*, *8*(2), 8–13. https://doi.org/10.1162/glep.2008.8.2.8

Mason, M. (2020). Transparency, accountability and empowerment in sustainability governance: A conceptual review. *Journal of Environmental Policy & Planning*, *22*(1), 98–111.

Matheus, R., Janssen, M., & Janowski, T. (2021). Design principles for creating digital transparency in government. *Government Information Quarterly*, *38*(1), 101550.

M'Barek, B. B., Phillpott, M., & Daniloff, C. D. (2023). *Manufacturing sector: Steel*. Climate TRACE. https://github.com/climatetracecoalition/methodology-documents (Original work published 2022)

McGinnis, M. D. (2011). An Introduction to IAD and the Language of the Ostrom Workshop: A Simple Guide to a Complex Framework. *Policy Studies Journal*, *39*(1), 169–183. https://doi.org/10.1111/j.1541-0072.2010.00401.x

Mol, A. P. J. (2008). *Environmental reform in the information age: The contours of informational governance*. Cambridge University Press.

National Academies of Sciences, Engineering, and Medicine. (2022). *Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward.* The National Academies Press. https://doi.org/10.17226/26641

OpenEarth Foundation. (2022). *Open Climate*. Accessed May 15, 2023. https://www.openearth.org//projects/openclimate

OpenEarth Foundation. (2023). *OpenClimate Contributor Guide*. Notion. Accessed May 15, 2023. https://www.notion.so

OpenEarth Foundation. (2023). *OpenClimate/API.md at develop · Open-Earth-Foundation/OpenClimate*. GitHub. Accessed May 15, 2023. https://github.com/Open-Earth-Foundation/OpenClimate

Ostrom, E. (1999). Coping with Tragedies of the Commons. *Annual Review of Political Science*, *2*(1), 493–535. https://doi.org/10.1146/annurev.polisci.2.1.493

Ostrom, E. (2005). *Understanding institutional diversity*. Princeton University Press.

Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change*. https://doi.org/10.1016/j.gloenvcha.2010.07.004

Ostrom, E. (2011). Background on the Institutional Analysis and Development Framework. *Policy Studies Journal*, *39*(1), 7–27. https://doi.org/10.1111/j.1541-0072.2010.00394.x

Ostrom, E., Gardner, R., & Walker, J. (1994). *Rules, Games, and Common-Pool Resources*. University of Michigan Press. https://doi.org/10.3998/mpub.9739

Pahl-Wostl, C., & Knieper, C. (2014). The capacity of water governance to deal with the climate change adaptation challenge: Using fuzzy set Qualitative Comparative Analysis to distinguish between polycentric, fragmented and centralized regimes. *Global Environmental Change*, *29*, 139–154. https://doi.org/10.1016/j.gloenvcha.2014.09.003

Rolnick, D., Donti, P. L., Kaack, L. H., Kochanski, K., Lacoste, A., Sankaran, K., Ross, A. S., Milojevic-Dupont, N., Jaques, N., Waldman-Brown, A., Luccioni, A., Maharaj, T., Sherwin, E. D., Mukkavilli, S. K., Kording, K. P., Gomes, C., Ng, A. Y., Hassabis, D., Platt, J. C., … Bengio, Y. (2019). *Tackling Climate Change with Machine Learning*. https://doi.org/10.48550/ARXIV.1906.05433

Rudd, M. A. (2004). An institutional framework for designing and monitoring ecosystem-based fisheries management policy experiments. *Ecological Economics*, *48*(1), 109–124.

https://doi.org/10.1016/j.ecolecon.2003.10.002
Schletz, M., Hsu, A., Mapes, B., & Wainstein, M. (2022). Nested Climate Accounting for Our Atmospheric Commons—Digital Technologies for Trusted Interoperability Across Fragmented Systems. *Frontiers in Blockchain*, *4*. https://doi.org/10.3389/fbloc.2021.789953
Schletz, M., Hsu, A., Robiou Du Pont, Y., Durkin, L., Yeo, Z. Y., & Wainstein, M. (2022). Climate data need shared and open governance. *Nature*, *610*(7930), 34–34. https://doi.org/10.1038/d41586-022-03123-7
Thomson, J., & Freudenberger, K. (1997). *Crafting institutional arrangements for community forestry*. https://www.semanticscholar.org/paper/Crafting-institutional-arrangements-for-community-Thomson-Freudenberger/d1a5a849a32f6b932076ce34fc3b081aac3d5316
Thomson Reuters. (2022, October 6). *China moves to standardize fragmented ESG reporting landscape*. Thomson Reuters Institute. https://www.thomsonreuters.com/en-us/posts/news-and-media/china-esg-reporting/
UK Government. (2021). *UK to enshrine mandatory climate disclosures for largest companies in law*. GOV.UK. https://www.gov.uk/government/news/uk-to-enshrine-mandatory-climate-disclosures-for-largest-companies-in-law
UN News. (2021). *COP26: Enough of 'treating nature like a toilet' – Guterres brings stark call for climate action to Glasgow | | UN News*. https://news.un.org/en/story/2021/11/1104542
UNFCCC. (2019). *Global Climate Action Portal*.
UNFCCC. (2021). *Race To Zero Campaign*. https://unfccc.int/climate-action/race-to-zero-campaign
UNFCCC. (2022a). *Decision 6/CMA.4: Matters relating to cooperative approaches referred to in Article 6, paragraph 2, of the Paris Agreement*. https://unfccc.int/sites/default/files/resource/cma2022_10a02_adv.pdf#page=2
UNFCCC. (2022b). *Global Stocktake*. https://unfccc.int/topics/global-stocktake/global-stocktake#eq-1
UNFCCC. (2023a). *Introduction to Transparency | UNFCCC*. https://unfccc.int/Transparency
UNFCCC. (2023b). *Message To Parties and Observers—Recognition and Accountability Framework for non-Party stakeholder climate action*. https://unfccc.int/documents/629136
Wainstein, M. E. (2019). *Leveraging blockchain for a global, transparent and integrated climate accounting system*. https://uploads-ssl.webflow.com/6197b240c9016848a0540bda/6216dafaa7125c17951d847d_61c4d9568083e2187b08e1df_Whitepaper_OpenClimate.pdf
Wang, H., Ma, C., & Zhou, L. (2009). A Brief Review of Machine Learning and Its Application. *2009 International Conference on Information Engineering and Computer Science*, 1–4. https://doi.org/10.1109/ICIECS.2009.5362936
WattTime. (2019). *WattTime Chosen as Google AI Impact Grantee*. https://www.watttime.org/news/watttime-chosen-as-google-ai-impact-grantee/
Whitmee, S., Anton, B., & Haines, A. (2023). Accountability for carbon emissions and health equity. *Bulletin of the World Health Organization*, *101*(2), 83-83A. https://doi.org/10.2471/BLT.22.289452
Widerberg, O., & Stripple, J. (2016). The expanding field of cooperative initiatives for decarbonization: A review of five databases. *WIREs Climate Change*, *7*(4), 486–500. https://doi.org/10.1002/wcc.396
Winkler, H., Mantlana, B., & Letete, T. (2017). Transparency of action and support in the Paris Agreement. *Climate Policy*, *17*(7), 853–872. https://doi.org/10.1080/14693062.2017.1302918
World Bank. (2019). *Summary Report: Simulation on Connecting Climate Market Systems*. World Bank. https://documents1.worldbank.org/curated/en/128121575306092470/pdf/Summary-Report-Simulation-on-Connecting-Climate-Market-Systems.pdf
World Bank. (2021). *State and Trends of Carbon Pricing 2021* [Serial]. World Bank. https://doi.org/10.1596/978-1-4648-1728-1
World Bank. (2022a). *Climate Warehouse Simulation III Final Report*. World Bank. https://documents1.worldbank.org/curated/en/099605009212233328/pdf/IDU09ef226cf0a663041d60869f07078d1af9fd3.pdf

World Bank. (2022b). *Digital Monitoring, Reporting, and Verification Systems and Their Application in Future Carbon Markets*. World Bank. https://doi.org/10.1596/37622

World Bank. (2023, March 7). *Why data infrastructure is key for a transparent carbon market*. https://blogs.worldbank.org/climatechange/why-data-infrastructure-key-transparent-carbon-market

Zhong, R. (2022, November 9). Who's Driving Climate Change? New Data Catalogs 72,000 Polluters and Counting. *The New York Times*. https://www.nytimes.com/2022/11/09/climate/climate-change-emissions-satellites.html