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A portrait of the different configurations between digitally-enabled innovations and climate governance

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ABSTRACT

Rapid societal transformations are required to keep global average temperature rise well below 2 °C by 2050. An increasingly diverse set of initiatives are leveraging digital technologies to transform society. Given the rapid pace at which these initiatives emerge and the accelerated rate of technological innovation, few connections are made as to their common approaches and motivations. To address this, we developed a database of such initiatives from around the world. We propose a categorization of four types of strategies: data mobilization, optimization of existing strategies, incentivizing and automating behavioural change, and enhancing participation and empowerment of individuals. We analyse connections between types of strategies through the lens of the Earth System Governance framework's original 5 A's – Architecture, Agency, Adaptiveness, Accountability, and Allocation & Access. This work provides a first step towards understanding how digitally-enabled initiatives are contributing to re-imagining climate governance.

1. Introduction

There is increasing recognition that rapid and far-reaching societal transformations will be necessary to keep global average temperature rise well below 2 °C, as per the Paris Agreement on climate change (Westley et al., 2011; IPCC Masson-Delmotte et al., 2018; DeFries et al., 2012; Hackmann and St. C lair, 2012; Shove et al., 2012; O' Brien, 2016; Horowitz, 2016). By transformations, we refer to deep changes in how we comprehend systems, how we need to adapt them, and how to reach out to a diversity of stakeholders aiming at a common goal to actively achieve it (Waddock, 2020).

The role of governance and politics in discussions about transformations, and the importance of the dominant societal narratives that underlie and lock us into current governance systems, are critical issues requiring increased academic attention (Waddock, 2020; Patterson et al., 2017; Luers et al., 2020). For societies to transition, they must transform from the 20th century governance model, that embody centralized power structures, top down approaches, and rigid establishments to one that is more iterative, agile, accountable, and interactive with state and non-state actors engaging across different levels of governance, in order to address complex issues (Shah, 2004; Brodie Rudolph et al., 2020), such as climate change in the 21st century. Many also identify the importance of trust between diverse actors as key to addressing climate change and creating the new forms of collaboration and engagement needed to transform climate governance (Luederitz et al., 2017; Schulz et al., 2020; Luers, 2021).

In this paper, we seek to explore the potential of transformations in and of governance regimes. We know that climate mitigation governance has thus far not been able to effectively address the scale of the climate crisis (Boehm et al., 2021; Future Earth The Earth League WCRP, 2021; United Nations Environment Programme, 2019). Though the role of non-state actors has become increasingly central (Hale et al., 2021), at both higher and lower levels compared to state (Bakker and Ritts, 2018), the complex 'maze' of international multilateralism still remains poorly understood (Kim, 2013, 2020; Dorsch and Flachsland, 2017). We believe (following 15) that there is a deep need to therefore re-imagine our current governance regimes and to shift practices and mindsets into the 21st century.

One process that is undoubtedly transforming society is global digitalization (Luers et al., 2020; Luers, 2021). For example, between 2000 and 2009 alone, the number of internet users worldwide almost quadrupled (Arnaldi et al., 2010), creating a more connected society

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with a strong potential for information access and thus empowerment. Could the digital age be leveraged to transform the way we govern climate mitigation?

There is a proliferation of climate action leveraging digital technologies that have emerged over the past decade (see e.g., (World Economic Forum, 2020), (Global Enabling Sustainability Initiative (GeSI), 2020) for an overview). For example, the application of machine learning, a subset of artificial intelligence (AI; algorithms that automate human processes) (World Economic Forum, 2020; Sustainability in the Digital Age (SDA), 2020), has been recorded across a diverse range of sectors including energy, transport, agriculture, industry, and geoengineering (Rolnick et al., 2019). By using statistical models and algorithms to analyse data, including large datasets such as big data, machine learning helps to reduce greenhouse gas emissions in various ways including through better forecasting, prediction, and efficiency gains (Rolnick et al., 2019; - Report on Turning Digital, 2019). Satellite, drone imagery, and remote sensing help monitor environmental conditions and are leveraged to provide support for different climate initiatives such as landscape restoration work, among others (World Economic Forum, 2020; Sustainability in the Digital Age (SDA), 2020). In addition, blockchain technologies, a type of digital ledger, have been used to track supply chains or facilitate transactions for decentralized renewable energy markets (Schulz et al., 2020; Russo, 2020; FAO ITU, 2019). Cloud computing, conducting otherwise on-site computing services via the internet, enables many on-demand services and facilitates the sharing of software, data, and analytical tools, thus strengthening and advancing the applications of other digital technologies such as big data analysis, spatial modelling, and more (Boehm et al., 2021; United Nations Environment Programme, 2019; Yang et al., 2017). Other digital technologies such as digital twins (i.e. digital models of physical landscapes or complex ecosystems that are based on real-time data) strengthen climate decision making through improved modelling and simulations (- Report on Turning Digital, 2019). The uptake of simpler technologies such as mobile phones and online data or collaborative platforms also create multiple opportunities for climate action through increased connectivity, collaboration, and community engagement (Sustainability in the Digital Age (SDA), 2020). Emerging technologies also include smart grids; these digitally empowered grids optimize the energy sector by analyzing energy supply and demand, paving the way for more renewable energy in communities and cities (World Economic Forum, 2020; Global Enabling Sustainability Initiative (GeSI), 2020).

At the same time, initiatives must also take caution when leveraging these digital tools for climate action. There are concerns that the digital age is perpetuating existing inequalities such as the digital divide, risking further exclusion of those with no access to digital technologies in decision making processes and access to solutions (Sustainability in the Digital Age (SDA), 2020). Ethical questions around privacy and safety, accessibility, and the environmental impact of new technologies are also on the rise (Sustainability in the Digital Age (SDA), 2020). If digital solutions are not powered by low carbon sources, the environmental footprint of the technology sector will continue to grow (e.g. (Luers et al., 2020), (Sustainability in the Digital Age (SDA), 2020), (Vinuesa et al., 2020)).

As more and more of these digitally-enabled climate initiatives emerge worldwide, it is a critical moment in time to take stock of what is out there and to explore how the functional operation of these initiatives is related to environmental governance. The goal of this paper is to spark discussions and further investigations into how digitally-enabled initiatives may actually re-shape climate governance. In addition, we hope that this showcase of inspiring initiatives will promote more connections among them, within and between regions, a key challenge in environmental governance (Bakker and Ritts, 2018), especially in the global south (Cieslik et al., 2018). Indeed, such countries often lack resources and show fragile organization, thus hindering the transformative potential of their initiatives. Connectivity has been proposed as an effective tool to overcome these issues in environmental management (Cieslik et al., 2018). Connectivity has the potential to improve governance by gathering the strength and resources of several initiatives to achieve a shared goal. Indeed, transdisciplinary collaborations (e.g. data sharing) are often sought out in environmental governance as environmental issues are complex and multifaceted, yet such connections are not common in part due to the challenge of standardising big data from various sources (Bakker and Ritts, 2018). However, similar to the uptake in transdisciplinary collaborations seen in the twenty-first century on environmental monitoring technologies, based on technological innovations (Bakker and Ritts, 2018), we will hopefully observe a similar trend in the application of these technologies for governance. One encouraging example of this trend is the creation of the interdisciplinary Earth System Governance journal in 2019, associated with the already existing conference of the same name. Its editorial board showcases that interdisciplinary approach with for instance experts from the fields of governance, ecology, digitalization, sociology, and anthropology.

1.1. *Framing governance*

In this paper, we employ the term 'governance' as the well-established definition of earth-system governance "the interrelated and increasingly integrated system of formal and informal rules, rule-making systems, and actor-networks at all levels of human society (from local to global) that are set up to steer societies towards preventing, mitigating, and adapting to global and local environmental change and, in particular, earth system transformation, within the normative context of sustainable development" ((Biermann et al., 2010), p.279).

Also drawing on the foundational work of the Earth System Governance Project from which this definition emerged, we seek to understand and characterize the landscape of digitally-enabled climate mitigation initiatives (i.e. initiatives leveraging digital technologies) through the conceptual lenses of five priority analytical problems identified by Frank Biermann and colleagues (Biermann et al., 2010). Known as the "five A's", these represent key challenges in governance which are still highly relevant today (Patterson et al., 2017; Biermann et al., 2010). (i) Architecture, the first "A", includes the social norms, foundational principles, and other types of institutions that together form the structure of a governance system. (ii) Agency refers to the capacity of a stakeholder (meaning any individual affected by or who can affect a particular policy problem, its impacts, or the solutions being explored) to exercise power over or otherwise influence those outcomes, a capacity which can change over time. (iii) Adaptiveness is a term which covers a number of ways in which social groups can change as a result of changes to the environment – either in response to or in advance of environmental change. (iv) Accountability, closely linked to legitimacy, refers to the authority and acceptance of democratic governance structures. (v) Finally, allocation and access, which together form the final "A", address how the risks, responses to, and benefits of global environmental change are distributed amongst a population. While we acknowledge the critical advances made since with the 2018 Earth System Governance Science and Implementation Plan (Earth System Governance Project, 2018), we believe that a foundational analysis of this emerging landscape through the 5 As is a first step towards better understanding and call on future research to analyse digitally-enabled climate mitigation initiatives through updated research lenses.

Exploring a diversity of digitally-enabled initiatives through the lens of the 5 A's will enable us to understand how the initiatives in the database address the five key challenges in governance and help explore their potential to re-imagine climate governance. First, we will present an overview of a database we have compiled of digitally-enabled climate mitigation initiatives, including information on how these were categorized based on their strategy for influencing climate governance. We identify four broad categories of strategies adopted by these initiatives to help govern climate mitigation: (Westley et al., 2011) data mobilization (i.e. to strengthen decision-making) (IPCC Masson-Delmotte et al., 2018), optimization of existing strategy (DeFries et al., 2012), incentivizing and automating behavioural change, and (Hackmann and St. C lair, 2012) enhancing participation and empowerment. We then examine these four categories, or types of strategies for influencing climate governance, through the lens of the Earth System Governance 5 A's to identify the potential that each strategy holds to achieve successful governance; governance that will lead society to limit global warming to 1.5 °C, thus preventing major negative impacts on humanity that would be extremely difficult, or even impossible, to adapt to for current and future generations (IPCC Masson-Delmotte et al., 2018). We conclude by reflecting on the potential and downfalls of digitally-enable climate initiatives and the types of strategies they employ for influencing climate governance, key differences between the global north and the global south, the central role of truth, and suggestions for future research.

2. Methods

Following methodologies adopted by other climate governance databases, we sought to combine approaches of iterative, expert-based searches such as that used by a transnational climate governance initiative database, the geographically-based systematic search used by a survey of urban climate change experiments (Cast á n Broto and Bulkeley, 2013), and by a study of climate governance through urban partnerships (Westman and Broto, 2018). Through these combined approaches, we developed a systematic search methodology as described below to identify initiatives using a keyword system, an inclusion criterion, and a set of indicators to analyse the selected initiatives.

This database should not be regarded as comprehensive but as indicative and representative of the emergence of experimentation and potential for leverage points in the digitally-empowered climate governance space.

2.1. Search methodology

A systematic search was conducted between January 4 and July 16, 2021. A small team of researchers co-developed a keyword matrix to frame the search protocol through a series of iterative consultation sessions ((Cast á n Broto and Bulkeley, 2013), (Westman and Broto, 2018)for similar approaches; Table 1; see (Bulkeley et al., 2012),). The Digital Disruptions for Sustainability (Dˆ2S Agenda;,27) served as the initial knowledge base for the direction of these iterative processes which were led by experts working at the intersection of digital technology and climate governance. To begin, two groups of keywords were specified, the first targeting keywords used in climate mitigation and governance from different perspectives (see (Luers et al., 2020), (Hsu and Rauber, 2021)) and the second targeting digital technologies leveraged in sustainability and climate action (see 25,26 for examples). The two groups were then combined to form the keyword matrix. These keyword combinations were tested and those that did not generate new search hits were removed. These included negative-emissions, climate mass mobilization, behaviour change emissions, climate democracy, green economy, carbon neutral, and greenhouse gas.

Three different search engines were used. Google was chosen as the mainstream search engine given its global popularity, Qwant was chosen as the privacy-based search engine due to its proprietary indexing, and DuckDuckGo was chosen as the deep web search because it indexes the deep web through a proprietary index and it does not serve individualized results. Regionally-specific search engines (e.g. Baidu, Yantrax) were not used because of our lack of ability to do so in a globally comprehensive way. Searches were limited to the first two results pages, excluding suggested ads and videos if applicable (i.e. (Hale et al., 2021; Bakker and Ritts, 2018), (Kim, 2020; Arnaldi et al., 2010), and (- Report on Turning Digital, 2019; Russo, 2020) results per Google, Qwant, and DuckDuckGo search respectively).

Following the implementation of the first search protocol, which yielded 201 entries, the research team discovered that entries were heavily skewed to the Global North. A secondary keyword matrix was then developed, testing keywords derived from more global south focused work on climate mitigation (see (ClimateWorks Foundation Good Energies Foundation Dalberg Advisors, 2020; NAMA Registry; FAO, 2015; The UN says climate, 2022)), in order to help reduce biases that were clearly present in the first keyword matrix. The same search engines and search protocol were employed using this secondary keyword matrix (Table 2). The research team quickly noted that most initiatives found in the secondary search (~80%) had a clear link to climate mitigation but did not explicitly mention mitigation as a goal of their efforts. These initiatives were classified as having a strong potential for impact on 'reducing the sources or enhancing the sinks of greenhouse gases' but not having mitigation as a specified goal.

Initiatives found using this keyword search were included in the database if they met the following inclusion criteria (i) clear link (i.e. direct or indirect) toward reducing the sources or enhancing the sinks of greenhouse gases (GHGs); (ii) leverage digital tools to achieve their climate mitigation goals as per the four conceptual digital disruptors of unprecedented transparency, intelligent systems, mass collaboration, and mixed reality (from 10); and (iii) clearly aim to influence, impact, or otherwise inform decision-making – including governmental as well as non-governmental decision-making.

Table 1
Keyword matrix of terms searched to identify candidates for inclusion in the database. Two groups of keywords were combined to generate 88 different search terms. Group 1 included keywords related to digital technologies, and group 2 included keywords related to climate mitigation. A keyword from Group 1 (e.g. climate mitigation) was combined with a keyword from Group 2 (e.g. digital) in order to form the search term (e.g. climate mitigation digital).

Group 1	Group 2
Digital	Climate mitigation
Digital technology	Emission reduction
Blockchain	Indigenous land rights
Satellite	Nature-based solutions climate
Machine learning	Climate open information
Artificial intelligence	Carbon markets
Big data	Paris agreement
Internet of things	Green transition
	Decarbonization
	Green transformation
	Climate policy

Table 2
Secondary keyword matrix of terms searched to reduce biases toward the Global North in our initial search and identify additional candidates for inclusion in the database. In this case, an overarching element was added to the search ("digital climate") and combined with each search term composed of a combination of Group 1.2 and Group 2.2.

	Group 1.2	**Group 2.2**
Digital climate +	Africa	Renewable energy
	Asia	Energy storage
	Pacific	Agriculture
	Latin America	Smart agriculture
	Caribbean	Regenerative agriculture
		Natural farming
		Net zero
		Soil restoration
		Land restoration
		Forest conservation
		Urban transport*
		Industry
		Smart cit*
		Data analytics platform

2.2. Analysis

The digitally-empowered climate mitigation initiatives in the database were analysed to define the main strategy they employ to influence climate governance.

The foundation for these strategies were derived from existing literature, the Digital Disruptions for Sustainability (Dˆ2S Agenda), which explores the potential of the digital age to disrupt the rules, power structures, and mindsets within economic, governance, and cognitive systems (Sustainability in the Digital Age (SDA), 2020). This includes, but is not limited to, the use of digital tools to increase access to and transparency of data, enhance engagement of stakeholders, increase precision and accuracy of data, and to target and nudge individuals (Sustainability in the Digital Age (SDA), 2020).

This foundation was applied and tested against initiatives within the database to define dominant strategies through iterative sessions conducted by the expert-led group that also identified the keyword matrix. Four main strategies emerged from these discussions that helped identify how the selected digitally-enabled initiatives aim to influence climate governance.

The four strategies include:

(1) Data mobilization (i.e. to strengthen decision-making): Initiatives that aim to influence climate governance by increasing access to data
(2) Optimization of existing strategy: Initiatives that increase the efficiency or accuracy of existing strategies
(3) Incentivizing and automating behavioural change: Incentivizing human behaviours through targeted information sharing, rewards-based mechanisms or automating behavioural changes by changing default options to sustainable alternatives
(4) Enhancing participation and empowerment: Empowering citizens to contribute to climate governance by shifting power dynamics, creating local leadership, or through knowledge sharing initiatives.

Through similar iterative processes, initiatives were reviewed and grouped under one of the four strategies that most aligned with the approach adopted to influence climate governance. Although some initiatives qualified for more than one, the most dominant strategy was adopted by the team by pursuing a parsimony-driven approach to increase efficiency and simplicity.

After characterizing initiatives from the database, we explored the categories of strategies through the lens the 5 A's, using the following indicators for each A as a proxy. These indicators facilitated the understanding of how the internal functioning of the various initiatives addresses those main challenges in Earth System Governance, helping to characterize the landscape of initiatives out there, and serves as a basis for comparison between the different categories of initiatives.

(1) **Architecture**: To understand the first A, we divided our analysis into two steps. First, we explored the relationship between directly or indirectly addressing GHG emissions and digitally-enabled climate mitigation initiatives. Then, we similarly analysed the goals or principles underlying the overarching objective to reduce the sources or enhance the sinks of greenhouse gas emissions. More precisely, we analysed which of the following underlying 9 rationales are espoused as the main goal/principle of each initiative (noting that an initiative can have more than one underlying rationale): (Westley et al., 2011) biodiversity and ecosystem conservation; (IPCC Masson-Delmotte et al., 2018) expanding carbon offsetting, carbon credit, and other environmental commodity markets; (DeFries et al., 2012) food and water security, and sustainable agriculture; (Hackmann and St. C lair, 2012) improving air quality; (Shove et al., 2012) increasing energy use efficiency and optimization; (O' Brien, 2016) increasing renewable energy applications; (Horowitz, 2016) strengthening private sector sustainability accounting and reporting; (Waddock, 2020) supporting renewable energy or carbon policies; (Patterson et al., 2017) supporting unspecified environmental policies.
(2) **Agency**: We analysed the actors involved in each initiative as a proxy to understand its current functional relationship to the challenge of agency. Namely, we looked at both the type of stakeholder group(s) engaged in each initiative (i.e. academic/research institutions, civil societies, national governments, private sector, regional unions) and also the number of organizations engaged for those initiatives that are conducted as partnerships. Here, we define partnership in the context of agency with partners involved in decision-making as opposed to financial partnership.
(3) **Adaptiveness**: Bases on their approaches, we characterized each initiative in the database regarding the type of adaptation intended, following (45, p.117), as either (a) business-as-usual ("investment in existing development"), (b) incremental adjustment ("marginal changes"), or (c) transformation ("fundamental change to the functioning of systems").
(4) **Accountability**: For each initiative, we indicated to whom it is accountable, which can include more than one group. The groups to which an initiative may be accountable based on their nature in the database analysis are: electorate and political communities for public initiatives, consumers and employees for private groups, and social networks for voluntary organizations, following (Kramarz and Park, 2016). We expanded on their definition of 'social networks' in order to provide more detailed information on accountability to, e.g., boards of directors, advisory groups, etc. Another important determinant of accountability differences is the source of funding to which initiatives become accountable to (Alam et al., 2020) as funding dynamics "shape the production of knowledge" ((- Report on Turning Digital, 2019; Russo, 2020), p.6). We recorded the source(s) of funding of each initiative for a more comprehensive analysis of accountability.
(5) **Allocation and Access**: Here we focused on the scale at which co-benefits (e.g. environmental protection, reduced costs) can accrue; we did not address the risks of climate change per se since this is beyond the scope of analysis for this paper. We assume that the main benefits of initiatives aiming to mitigate climate change are global in scope, since mitigating climate change has benefits and also risks for all. We analyse whether additional co-benefits can accrue (following (Stechow et al., 2016) for their framing of co-benefits to climate mitigation) at a local scale (impacting one or more local communities), at a national scale, or at a multinational scale. For initiatives where mitigation is an indirect goal, we considered all benefits outside of mitigation, including the main goal of the initiative.

As one of the aims of this work was to provide a first simple but representative sample of initiatives leveraging digital tools to achieve climate mitigation, the conducted analysis was limited to information found online, for example via the intiatiative's websites or LinkedIn pages. For each analysis comparing the four categories of climate governance strategies to the 5 A's, we ran a Chi-squared (χ^2) test using a Monte-Carlo permutation approach (i.e. 10,000 replications) as cells within our contingency tables with counts lower than 5 were quite common on average (Motulsky, 2021). Since this study is of an exploratory nature, we used Bonferroni-corrected P-values (i.e. P-value * total number of tests performed to account for multiple comparisons (Motulsky, 2021). Significant results were interpreted using mosaic plots in combination with Pearson's residuals. A mosaic plot depicts the proportion of observations that falls within each factor level combination represented as rectangles (i.e. a larger proportion means a larger rectangle). The shading of rectangles is automatically determined based on Pearson's residuals. A blue shading indicates that the observed frequency for that combination of factor levels is greater than what would be expected if the two factors were independent, and red is the opposite. A darker shade represents a larger deviation from independence. As an example of a mosaic plot interpretation, the proportion of initiative employing data mobilization strategies with their underlying rationale being to expand carbon offsetting, carbon credit, and other environmental commodity markets appears in red in Fig. 1, indicating that the combination of this strategy with this rationale is significantly less likely compared to other factor level combinations. We performed all statistical tests in R (3.5.2; (R: The R Project for, 2021)) using the *chisq.test()* function for χ^2 tests, and the *mosaic()* function of the *vcd* package (Meyer et al., 2006) for mosaic plots and Pearson's residuals.

3. Results

3.1. Taking stock

After applying our inclusion criteria, we retained 176 initiatives in our database, with more than 12% of them operating in different regions than their headquarters or partner locations. For example, Rainforest Connection, is a non-profit organization based in California, USA, that uses Internet of Things (IoT) such as sensors and mobile devices to detect illegal deforestation in South America, Africa and Asia. We identified 11 groups of digital tools employed by the initiatives to directly or indirectly achieve climate mitigation; namely:

(1) artificial intelligence (AI) and machine learning (N = 70); computer algorithms able to complete work that used to be dependent upon human cognitive abilities (World Economic Forum, 2020)
(2) big data analytics (N = 8); set of digital tools allowing for the analysis of enormous amount of data (World Economic Forum, 2020)
(3) blockchain (N = 46); secure digital recording and validation of transactions (World Economic Forum, 2020)
(4) cloud computing (N = 11); digitally-centralized use of advanced information technology for a wide range of applications (Global Enabling Sustainability Initiative (GeSI), 2020)
(5) communication and collaborative platforms (N = 59); digital spaces to facilitate exchanges between individuals on the internet (Flew et al., 2019)
(6) digital twins (N = 6); virtual reproductions of things and concepts, often used to make predictions (Jones et al., 2020)
(7) drones (N = 5); mobile vehicles that are flown and operated remotely (World Economic Forum, 2020)
(8) mobile and digital access (N = 17); suit of technologies providing access to the internet (Global Enabling Sustainability Initiative (GeSI), 2020)
(9) satellite (N = 42); technologies allowing the gathering of earth system data from space (Pan et al., 2021)
(10) sensors (N = 30); technologies that measure and/or store environmental variables (Tironi and Valderrama, 2021)
(11) smart grids (N = 2); analyse data from information and communication technologies to optimize energy systems (Langendahl et al., 2016)

By reviewing existing literature and the database, we identified four strategies for how the digitally-enabled initiatives strive to influence climate governance. These strategies reflect the ultimate mechanism through which each initiative strives to influence climate governance systems in order to support climate mitigation.

(1) Data mobilization (i.e. to strengthen decision-making; N = 74)

These initiatives strive to provide more accurate, comprehensive, or easily accessible data to inform evidence-based decisions. This can involve new ways of collecting, storing, or sharing data. Many initiatives achieve that goal through the use of a variety of digital monitoring and reporting tools, which are intended to feed into verification schemes (e.g. for carbon offset/credit systems). The main tool identified for this category was satellites (i.e. 64% of initiatives using satellites are

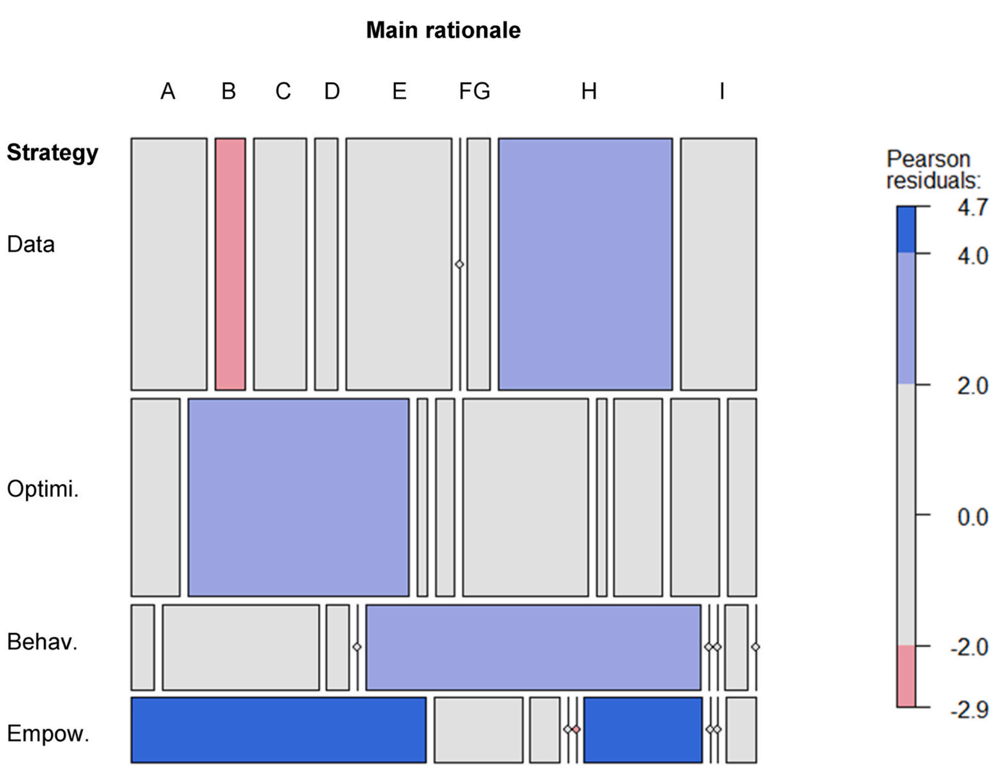

Fig. 1. Architecture. Mosaic plots (N = 176) of the proportion within each of the four identified categories of strategies (i.e. data mobilization (*Data*); optimization of existing strategy (*Optimi.*); incentivizing and automating behavioural change (*Behav.*); enhancing participation and empowerment (*Empow.*)) of the main underlying rationales of the initiatives (i.e. biodiversity and ecosystem conservation (*A*); expanding carbon offsetting, carbon credit, and other environmental commodity markets (*B*); food and water security, and sustainable agriculture (*C*); improving air quality (*D*); increasing energy use efficiency and optimization (*E*); increasing renewable energy applications (*F*); strengthening private sector sustainability accounting and reporting (*G*); supporting renewable energy or carbon policies (*H*); supporting unspecified environmental policies (*I*)).

employing this strategy).

(2) Optimization of existing strategy (N = 58)

These initiatives aim to optimize existing climate mitigation strategies including carbon markets, intergovernmental negotiations, nature-based solutions, public scientific information, divestment, and negative-emissions technologies. Some are wide-reaching and highly institutionalized, for example operating at the international level or under the auspices of the United Nations Framework Convention on Climate Change; others are more focussed in national or even localized contexts. The main tool identified for this category was blockchain (i.e. 61% of initiatives using blockchain are employing this strategy).

(3) Incentivizing and automating behavioural change (N = 25)

The goal of these initiatives is to influence human behaviour through targeted information sharing, rewards-based mechanisms, or automating behavioural changes by changing default options to sustainable alternatives. The main digital tool identified for this category was sensors (i.e. 30% of initiatives using sensors are employing this strategy), the information from which was combined with other tools to trigger behavioural change.

(4) Enhancing participation and empowerment (N = 19)

The goal of this set of initiatives is to encourage participation in decision-making and/or to empower individual citizens to engage more directly in governing climate mitigation, such as empowering citizens to take ownership of climate mitigation projects, for example by providing surveillance tools owned by local communities to protect forests. The main tools identified for this category were drones (i.e. 60% of initiatives using drones are employing this strategy) and mobile digital access (i.e. 39% of initiatives using mobile and digital access are employing this strategy).

3.2. Relating to the 5 A's of Earth System Governance

We now reflect on how the different strategies, adopted by digitally-enabled climate initiatives that influence climate governance, embody key aspects of Earth System Governance. We explored the interplay between indicators for each of the 5 A's as described in the section "*Analysis*" above, and the four categories of strategies.

(1) Architecture

The first step of our architecture analysis revealed that a direct goal of the majority of the initiatives (75%) in our database is to mitigate climate change by reducing GHG emissions. Conversely, the rest of the initiatives indirectly tackles reductions in GHG emissions, for instance by conserving forests to promote biodiversity and/or maintain cultural ecosystem services, which in turn indirectly leads to carbon fixation. When comparing this data to the four categories of strategies, the initiatives directly or indirectly aiming to mitigate climate change by reducing GHG emissions are not distributed significantly differently between the four types of strategies ($\chi^2 = 12.30$, corrected $P = 0.054$).

The second step of our architecture analysis shows that the different rationales behind each initiative are distributed significantly differently between the four categories of strategies ($\chi^2 = 117.53$, corrected $P < 0.001$; Fig. 1). Data mobilization strategies are employed more frequently by initiatives whose aim is to support renewable energy or carbon policies and relatively less so by initiatives whose goal is to expand environmental commodity markets (Fig. 1). Such initiatives tend to optimize existing strategies. As an example of an initiative in the data mobilization category of strategies, Village Data Analytics combines satellite imagery and AI to provide data to decision-makers and investors on various market opportunities, such as solar energy in rural villages located in Africa and Asia. Regarding the optimization of existing strategy category, Xpansive for example aims to improve the accuracy and transparency of commodity markets. To reach their goal, they use deep data to value environmental commodities such as renewable energy more accurately and use blockchain to ensure transparent transactions on its digital platform.

Initiatives employing a strategy around enhancing participation and empowerment are more often found to have goals around biological conservation and renewable energy applications as opposed to targeting energy use efficiency and optimization. Indeed, initiatives focusing on that rationale, striving towards efficiency and optimization, tend to employ strategies to incentivize and automate behavioural changes instead (Fig. 1). The Brooklyn Microgrid Project is an example of a participatory governance strategy that promotes renewable energy. It is a community-led initiative that allows residents to sell their excess solar energy to others in the neighbourhood using a simple mobile application. Local communities are able to directly contribute to the city's energy supply. Oracle's Opower utilities software on the other hand uses AI and behavioural science with the objective to increase energy efficiency by providing consumers in-depth information on their energy consumption patterns to encourage behavioural change.

(2) Agency

Governments were not identified as the sole leading actor of any of the initiatives in our database. However, they are often found to lead groups in partnership with other types of actors (e.g. civil society). For example, Global Forest Watch is a partnership of 23 partners including Government agencies, such as USAID, the Foreign Commonwealth & Development Office in the UK and the Swedish International Development Cooperation Agency, among others: civil society organizations such as World Resources Institute and the United Nations Environment Programme, the private sector, and academia. The partnership uses digital technology and tools with the aim of increasing the monitoring of forests across the world. Following our analysis of the relationship between leading actor groups and the four categories of strategies identified, we observe a dominance of the private sector overall (52% of all initiatives). However, we did not detect any significant differences in the distribution of leading actor groups between the four categories of strategies ($\chi^2 = 25.85$, corrected $P = 0.11$).

(3) Adaptiveness

No initiative approach, was categorized as exhibiting resistance, and the majority of them (N = 157) were classified as exhibiting incremental adjustments, with a minority of transformations (N = 19). Adaptation types were significantly segregated within categories of strategies ($\chi^2 = 139.24$, corrected $P < 0.001$). Without exception, all initiatives focusing on incremental adjustments were from three categories of strategies: data mobilization, optimization of existing strategies, and incentivizing and automating behavioural change. Similarly, all initiatives with approaches exhibiting characteristics of transformation employed a strategy around enhancing participation and empowerment. For example, the MappingForRights initiative operating in the Congo Basin has been recognized for its transformative and participatory form of forest governance (awarded the awards/information-and-communications-technology-solutions" title = "https://cop23.unfccc.int/climate-action/un-global-climate-action-awards/information-and-communications-technology-solutions">UN Global Climate Action Award for ICT Solutions). Using low tech tools provided by the initiative, members of the community act as local forest guardians by mapping and monitoring their lands. This data is then used to inform forest planning and management that are consequently based on common community goals.

(4) Accountability

Our database being largely dominated by the private sector, initiatives from that sector should be accountable towards their consumers and employees (as per 24). However, we detected no significant patterns in the distributions of groups that initiatives are accountable to between the four categories of strategies ($\chi^2 = 17.84$, corrected $P = 0.051$).

No significant patterns emerged from the distribution of funding sources between the four categories of strategies ($\chi^2 = 25.53$, corrected $P = 0.87$). We could not identify the funding sources for 29 initiatives (16%).

Similarly, in our third analysis of accountability, the proportion of each governing body did not differ between the categories of strategies ($\chi^2 = 15.96$, corrected $P > 0.99$). Interestingly, the vast majority of initiatives (64%) did not provide any information on their governing bodies on their websites.

(5) Allocation

Strong patterns emerged from our allocation analysis. The majority of initiatives in our database have multinational co-benefits (58%). The distribution of the scales of co-benefits accruement was significantly different between the four categories of strategies ($\chi^2 = 91.56$, corrected $P < 0.001$; Fig. 2). Initiatives employing the strategy of data mobilization (i.e. to strengthen decision-making) are more likely to have multinational co-benefits that accrue at the regional scale as opposed to the local scale, possibly due to the granularity of data not being sufficient to benefit local efforts. Geospatial mapping initiatives such as Global Land Analysis & Discovery and The Carbon Source$_2$ that focus on disseminating data on natural resource stocks have the potential to contribute to landscape and biodiversity conservation in different regions of the world. Conversely, co-benefits are likely to be local rather than multinational for initiatives focusing on enhancing participation and empowerment as a strategy to influence climate governance (Fig. 2). For example, The Kayapo Project and the Landmark initiative local conservation projects aim at digitally empowering indigenous communities so they can better protect their local lands.

The category of strategies that is most likely to accrue co-benefits on a national scale is the incentivizing and automating behavioural change group. This category includes initiatives such as the Carbon Intensity API in the UK that uses machine learning to provide energy forecast data nation-wide, including information on source and associated carbon intensity, with the goal to incentivize consumers to use low emission energy. Lastly, initiatives using optimization of existing strategies did not have any noticeable patterns in terms of the scale of their co-benefits.

4. Discussion and conclusion

4.1. Understanding strategies to influence climate governance

Identifying and analysing the four strategies to influence climate governance through the lens of the Earth System Governance 5 A's is a useful exercise to understand the mechanisms through which these strategies influence and hence have the potential to re-imagine current climate governance systems. This digital innovation potential has already been put forward by other scholars for environmental governance more generally (Bakker and Ritts, 2018). Our analysis highlighted how different strategies employed by digitally-enabled climate governance initiatives embody key aspects of Earth system governance. Strategies evolving around data mobilization (i.e. to strengthen decision-making; e.g. policy) are the most common and tend to have multi-national co-benefits due to their generally global approach (e.g. satellite imagery). However, in terms of adaptiveness, such initiatives

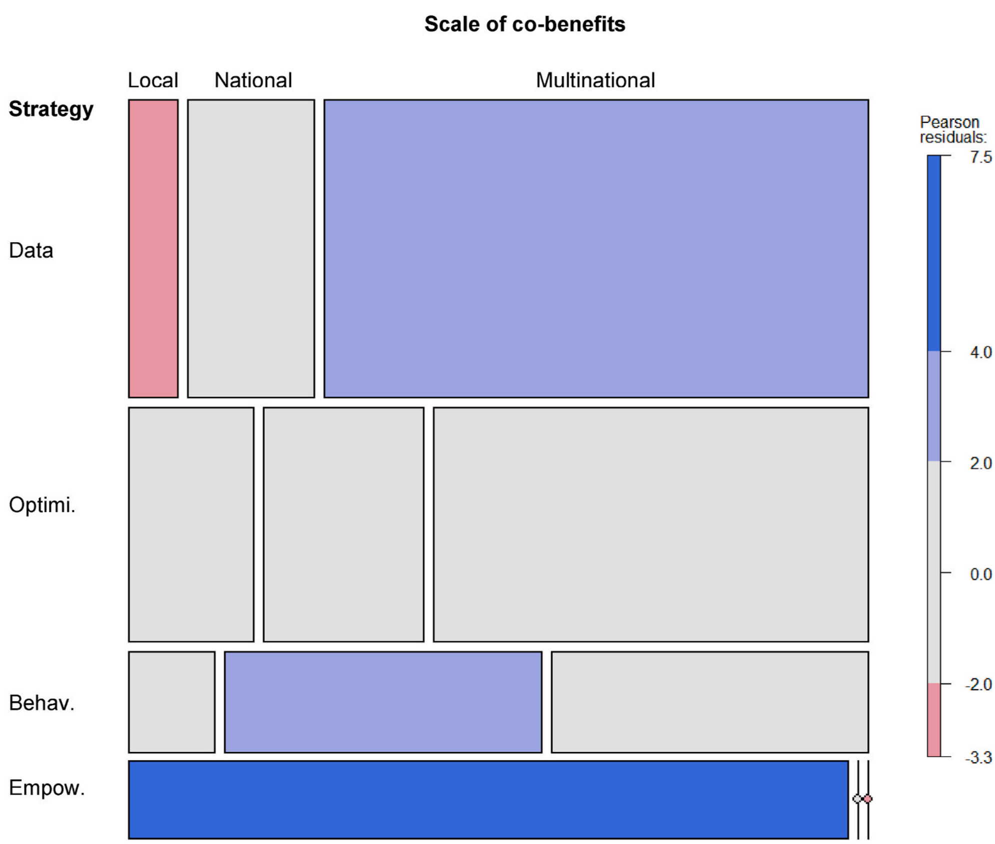

Fig. 2. Allocation. Mosaic plots (N = 176) of the proportion within each of the four identified categories of strategies (i.e. data mobilization(*Data*); optimization of existing strategy (*Optimi.*); incentivizing and automating behavioural change (*Behav.*); enhancing participation and empowerment (*Empow.*)) of the scale of co-benefits (i.e. local, national, and multinational).

may tend to only lead to incremental changes to existing mechanisms instead of deeper transformative adaptations to address the core issues of climate change (e.g. power of principle GHG emitters in influencing decision-making). On the other hand, initiatives aiming at transformative change are the minority. They tend to employ strategies around enhancing participation and empowerment of local communities in climate governance (e.g. initiatives striving to support local stewardship and biological conservation of land by ensuring local access to and control over digital tools employed for surveillance and communication). Such local and targeted initiatives have true transformative potential through enabling transitions in the rules, power and mindsets within a system (Meadows, 1999) and might be the key to achieve the 2050 climate mitigation goals.

Interestingly, the highest number of initiatives found using the primary and secondary search protocols to populate the database were categorized as data mobilization (i.e. to strengthen decision-making) or else as optimize existing strategies by leveraging digital technologies. In the current "post-truth era" characterized by a lack of rationality in decision-making (Machen and Nost, 2021), data mobilization might not be the key strategy to transform climate governance as it would only tend to update rather than transform governance (Nost and Goldstein, 2022). The expected abundance of data in the future has even been identified as an obstacle to efficient environmental governance; on one hand due to reliability issues of open-source data (e.g. citizen science;, 20), on the other hand based on the increased reliance on algorithm-based decision-making which points toward hegemony within governance (e.g. accountability is now placed on the algorithm itself, emphasis is placed on governing greenhouse gases rather than main emitters; difficult-to-measure important variables are excluded;, 59). To optimize existing strategies, initiatives often aim at expanding or improving existing environmental commodity markets through new technologies such as blockchain. This technology can foster more efficient and trusted transactions when appropriately embedded within broader regulatory systems and multilateral processes (Sadawi et al., 1772; Schulz and Feist, 2020). However, our analysis shows that the other two categories of strategies – namely, incentivizing or automating behavioural change and enhancing participation and empowerment – have a more comprehensive approach to applying the 5 A's.

The incentivizing and automating behavioural change category often focuses on improving energy use efficiency through the incremental optimization of existing incentives in both the industrial and public sectors. As demand drives energy production, raising public awareness and promoting sustainable energy consumption behaviour could make a significant difference in the fight against climate change (Zell-Ziegler et al., 2021). Despite not being transformative in nature, these incremental behavioural changes as a whole could lead to deep societal transformation over time (Pelling et al., 2015; Sandberg, 2021). In support of this theory, we found that initiatives adopting this strategy may result in co-benefits (e.g. reduced energy expenditures, improved air quality) at a larger scale (i.e. accruing at the national scale). The role and potential of behavioural and lifestyle changes positively contributing to governmental energy policies is a growing area of interest, with several policy makers pushing for an integration of those changes as a strategy to reduce GHG emissions (Zell-Ziegler et al., 2021; Samadi et al., 2017).

The four strategies described in this paper highlight the potential of digital technologies to re-imagine climate governance. Indeed, through their ability to increase access and transparency of data, improve current mechanisms in place, incentivize or automate sustainable behaviour, reach actors at a global scale, and decentralize systems by empowering and increasing engagement of local stakeholders, digital technologies can help accelerate climate action and successfully mitigate climate change; a challenge society has failed to overcome so far. Digitalization has already been shown to improve governance efficiency overall (Gritsenko and Wood, 2022), including in the context of environmental governance, for instance through the use of AI to improve not only the efficiency, but also the accuracy of data collected for water governance (Wei, 2021). Information technology is another digital tool that helps empower communities to participate in water governance (Hsu et al., 2020), and strengthen transdisciplinary collaborations and predictive power by facilitating big data sharing (Bakker and Ritts, 2018). An additional example is how digital technologies can help empower communities to participate in the transition to a sustainable agriculture, and gather transparent data (Kruk et al., 2021). However, still little is known about the effect of information and knowledge on environmental governance (Kostka et al., 2020), despite the fact that they are known to contribute to transformative power (Mol, 2008). Finally, caution must be taken when leveraging these technologies to avoid contributing to the unintended consequences of the digital age (e.g. (Gritsenko and Wood, 2022), (Kruk et al., 2021)), such as increasing barriers to participation (e.g. 68) and failing to increase the diversity of stakeholders influencing governance (e.g. (Tarantino, 2020)). Technology alone is not enough to solve environmental challenges (e.g. (Rolnick et al., 2019),59 (Brombal, 2020),). However, the variety of climate predictions and solution suggestions stemming from digital innovations can spark transformative political debate (Machen and Nost, 2021). This is key as even though technological solutions are available, and some have been for a while, without political and societal will, these cannot be scaled at a global level for climate action (Rolnick et al., 2019).

4.2. Regional differences

Our search protocol highlighted the lack of visibility for initiatives in the global south that explicitly target climate mitigation as a goal (see also our section below on "Reflections on methodology and future research needs"). An important goal, then, of adding the secondary search protocol and including initiatives that clearly have an impact on climate mitigation but where mitigation is not specified as a goal, was to highlight promising initiatives based in the global south with the potential to leverage digital technologies to impact climate governance but which are not currently being recognized – or, potentially, funded – as such.

Several initiatives in the global south show significant potential for co-benefits in addition to strengthening climate governance, for example by giving power back to local communities in conserving their lands. Such efforts have the potential to lead to ecosystem and biodiversity protection and/or restoration, which in turn affect climate mitigation (i.e. indirect effects) through the maintenance and development of carbon sinks (Sabattini et al., 2021). However, when mitigation initiatives are in the hands of the private sector, which largely dominates our database, pervasive effects can lead to the loss of natural habitat (e.g. unsustainable extraction of natural resources (MacDonald, 2010),), and to the displacement of local communities (Conservation in the Anthropocene, 2021).

4.3. The central role of trust

Many have explored the central role that trust between climate governance actors plays in mitigation (e.g. 22,61, (Cologna and Siegrist, 2020), (Suiseeya et al., 2021)). Trust is present to some extent in several of the interactions between the categories of strategies and the 5 A's described in this study: trust in partnerships, regional unions, and boards of directors; trusted relationships between consumers/employees and the private sector, voters/electorate and their government, and between local communities and digitally-enabled initiatives; trust in the digital innovations; trust in transformative changes; and trust in information and data, e.g. about incentives for behavioural changes, or the sustainability of the technology in question. Deep collaborations, where collaborators commit to behavioural changes at the cost of individual interests, are the types of relationships that have the highest potential to lead to stronger climate governance (Suiseeya et al., 2021). Unfortunately, such collaborations are rare in practice due to a lack of trust between agents. For instance, trust between local communities in the global south and a non-governmental organization from the global north might be challenging to achieve as the global north is the main emitter of GHGs (Suiseeya et al., 2021). At the same time, there is a perceived lack of trust between influential tech companies and the public at large, exemplified by ongoing discussions about "surveillance capitalism" and algorithmic bias ("We Make Them Dance, 2019).

Thus, in order to build trust between agents, decision-making should not only be transparent, diverse, equitable, and inclusive (e.g. include Indigenous representatives on the boards of directors of initiatives aiming at empowering them), but actors should be provided with the necessary information and capacity to understand and respect one another. Without the necessary institutional, regulatory and procedural elements to create trusting relationships, however, climate governance is and will remain unsuccessful (Suiseeya et al., 2021). Technology alone will not be able to solve these problems in climate governance, but it may facilitate trust-building under specific conditions. Further in-depth qualitative research is urgently needed to ascertain the extent to which specific technology-related initiatives are including and achieving trust-related objectives in their practices.

For example, distributed ledger technology (DLT), including blockchain solutions, could potentially be leveraged for trust-building among actors in climate mitigation governance and lead to more successful cooperation and higher levels of trust between participants. In the context of mitigation finance, this can be done by using DLT-based systems to enable transparent, secure and standardized asset transactions, facilitate peer-to-peer data exchange based on clear standards and safeguards, or by automating the direct disbursement of mitigation funds to authorized recipients (e.g. to minimize monetary loss and increase efficiency (Schulz and Feist, 2020),).

However, current discussions on technological sustainability show that high energy consumption remains one of the most pressing challenges for the uptake and scalability of DLT-based systems. It has been pointed out, in particular, that Bitcoin alone uses the same amount of energy per year as a small country (de Vries, 2018). One potential solution for this energy-related dilemma is the imminent transition from Proof-of-Work (PoW; high energy demand) to Proof-of-Stake (PoS; lower energy demand) consensus mechanisms to significantly reduce the overall energy demand of DLTs (Platt and McBurney, 2021). Available research suggests that, on the one hand, the energy consumption per transaction in PoS-based DLT systems is indeed at least two to three orders of magnitude lower than that of conventional PoW systems such as Bitcoin, and, on the other hand, that even some of the existing PoS solutions such as Ethereum 2.0 might not be the ideal solution for the energy problem when compared to other PoS-based systems such as Hedera Hashgraph due to key architectural differences (UCL Centre for Blockchain Technologies, 2021).

Accordingly, there is a critical need to better understand how the usability of DLTs is shaped by the design and governance of digital system architectures (Schulz et al., 2020; Schulz and Feist, 2020). Digital innovations such as DLTs are not able to create trust 'out of thin air' and tailored regulatory approaches are still needed to support technology uptake and implementation. Such favorable regulatory environments, ideally in combination with enhanced measurement, reporting, and verification processes, could facilitate targeted and inclusive access to mitigation finance via DLTs and generate new financing sources for sustainable projects (Schulz and Feist, 2020). Promising regulatory initiatives such as the MiCA and DLTR regulations (Digital Finance Package, 2022), the EU taxonomy (Sustainable Finance and EU Taxonomy, 2022) or the European green bond standard (European green bond standard, 2022) point in this direction, and have been designed to tackle underlying problems of regulatory trust. These regulatory developments indicate that DLTs can indeed serve as helpful tools to support trust-building between network participants in mitigation governance based on transparent, secure, and inclusive digital systems. Yet, with regard to energy consumption, independent life-cycle assessments may have to precede the implementation of DLT-based systems to ensure technological sustainability.

4.4. *Reflections on methodology and future research needs*

It is critical to note that the database developed that forms the basis for the analysis presented here is not comprehensive or unbiased. Some sources of bias that are worth calling out in our search methodology include the fact that our search keywords were only in English and we only included initiatives that appeared only on the first two results pages, potentially excluding non-English initiatives with less web presence. Future efforts could expand on the methodology by extending beyond English language searches, further building on the list of keywords employed, and analysing a larger number of results pages, for example. Another source of bias that appeared unexpectedly from our first set of keywords was the under-representation of initiatives from the global south, hence our use of a second set of keywords. This finding highlights potential unconscious biases and/or differences in discursive framing in the context of climate mitigation between the global south and the global north (Doyle and Chaturvedi, 2010). These differences are likely the result of a de-territorialisation approach to solving climate change from the global north versus a post-colonial approach from the majority of the global south (Doyle and Chaturvedi, 2010). In efforts to support future work, the research team made a live version of this database publicly available, to continue collecting digitally-enabled climate strategies. Through a call for additional initiatives, it has grown since, including new initiatives not included in this analysis. The research team plans to continue adding initiatives to this database to capture a wider and more diverse range of applications. For instance, virtual reality is an emerging field whose initiatives could contribute to incentivizing behavioural change through virtual immersion into potential climate scenarios (Machen and Nost, 2021). Another example is the increasing use of robots to implement climate-related policies, such as applying housing energy insulation where workers cannot reach (Machen and Nost, 2021). One potential outcome of seeking such input to the database once it is published is to identify innovative initiatives that go beyond the four categories of strategies identified in our analysis. These could highlight, for example, entirely new systems or governance strategies, which is an important consideration against the backdrop of unleashing socio-cultural transformations towards sustainability.

Another limitation that can be addressed in further research is to identify all relevant strategies associated with an initiative instead of the primary one. This alternative approach would add more depth and nuances to the analysis of the different strategies in relation to the 5 A's. Further analysis could also strive to track the impact different types of initiatives have on environmental sustainability and on environmental governance systems more broadly. It will be important to understand what type of impact initiatives in the database are having on climate mitigation and whether and how they are actually achieving their stated goals. Part of this would require analysing GHG reductions and whether these are offset by energy or resource consumption, for example through standardized life cycle assessments. Furthermore, the current analysis explores how the 5 A's are implemented within the initiatives in the database, grouped into four categories. Future efforts could explore the impact of the initiatives *on* the 5 A's as they apply to broader environmental governance systems. Due to the limitations of the current approach, namely insufficient information about the external impact of different initiatives, we were unable to analyse these critical factors. But follow-up analyses examining how initiatives in the different categories of strategies impact environmental sustainability and influence the characteristics of climate governance systems at different scales (Bakker and Ritts, 2018) will be critical to understand impactful leverage points that require additional support or funding.

One interesting finding was the perfect alignment between transformative efforts and initiatives categorized as employing strategies around enhancing participation and empowerment (see section 3 of the

Results). This finding is likely due to the way that we defined the enhancing participation and empowerment category of strategies in the database, which actually already incorporates the critical aspects of transformative actions. We encourage future research to investigate what makes a digitally-enabled initiative transformative and also to better understand the reasons why we did not find transformative efforts in other categories ((see 45 for some reflections on the topic).

It is also interesting to mention, with regards to technology use, that while AI is the most frequently employed technology overall, it is not dominant within any one category of strategies. While we cannot derive any particular conclusions from this finding, this does have implications regarding the role different technologies can play in different strategies for influencing climate governance, potentially pointing to a more general applicability of AI (e.g. overall improved efficiency) as opposed to other types of technologies.

We also note that an important area for future research will be to shed light on the more precise theories of change of different strategies for how digitally-enabled climate mitigation initiatives can influence climate governance (e.g. how the use of state-of-the-art technology has the potential to strengthen climate governance). In nearly all cases analysed, this information was not readily available. However, research employing interviews or surveys could potentially begin to collect this valuable information (e.g. details on the political selection and use of collected data for decision-making (Bakker and Ritts, 2018) as data is a governed entity (Nost and Goldstein, 2022)), which would in turn allow for a more comprehensive analysis not only of the impact but also of potential means for strengthening sustainable digitally-enabled strategies to re-shape climate governance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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