Sustainable Social Development 2026, 4(4), 8709.
https://doi.org/10.23812/ssd8709

Article

Inclusive governance and sustainable development challenges in solar radiation management

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CITATION

Ramos Y, Schmidt, L, Santos FD. Inclusive governance and sustainable development challenges in solar radiation management. Sustainable Social Development. 2026; 4(4): 8709.
https://doi.org/10.23812/ssd8709

ARTICLE INFO

Received: 26 May 2026
Revised: 13 July 2026
Accepted: 15 July 2026
Available online: 23 July 2026

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Abstract: Solar Radiation Management (SRM) is increasingly attracting attention in scientific and policy discussions due to its potential to partially offset anthropogenic climate change. At the same time, SRM raises major governance, ethical, and sustainable development challenges, particularly regarding legitimacy, participation, and unequal institutional capacities between countries. While research and governance discussions continue to expand, actors from the Global North (GN) remain dominant in agenda-setting and decision-making processes, whereas the Global South (GS), despite its disproportionate vulnerability to climate impacts, remains comparatively underrepresented. This article examines SRM governance through the lens of inclusive governance and sustainable development. It argues that governance arrangements lacking transparency, accountability, and equitable participation risk reinforcing existing inequalities in global environmental governance and undermining Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action), SDG 16 (Peace, Justice and Strong Institutions), SDG 10 (Reduced Inequalities), and SDG 17 (Partnerships for the Goals). Drawing on a qualitative literature review and a case study of the SRM Non-Use Agreement, the article analyzes the evolution of SRM debates and the structural factors shaping participation in governance discussions. Recent institutional assessments, including the United Nations Environment (UNEP) Program Solar Radiation Modification Working Paper further highlight major governance gaps, scientific uncertainty, and asymmetries in research capacity between developed and developing countries. The analysis explores governance mechanisms capable of strengthening transparency, participation, and ethical safeguards in emerging SRM governance frameworks. Beyond documenting existing governance gaps, this article makes three contributions. First, it combines a structured literature review with an empirical analysis of the SRM Non-Use Agreement to examine participation asymmetries. Second, it identifies the institutional factors that continue to constrain meaningful Global South participation in emerging SRM governance debates. Third, it proposes governance mechanisms that translate principles of inclusive governance and sustainable development into operational pathways for future SRM governance.

Keywords: solar radiation management (SRM); inclusive governance; sustainable development; sustainability governance; global south (GS), climate justice; polycentric governance; SRM non-use agreement

1. Introduction

The persistent gap between global emission trajectories and the targets established under the Paris Agreement underscores the urgency of climate mitigation [1]. [2]. Despite expanding mitigation and adaptation efforts, global greenhouse-gas emissions continue to rise and climate impacts are intensifying. In this context, SRM

has emerged as a controversial potential climate intervention. While some researchers consider SRM a possible risk-reduction tool, critics emphasize environmental, ethical, and geopolitical risks, particularly in the absence of robust governance frameworks [3]. Recent geopolitical developments highlight the fragility of the institutional landscape in which SRM governance would need to operate. According to SRM360 [4], the announced withdrawal of the United States from several international climate institutions, including the UNFCCC and the Intergovernmental Panel on Climate Change (IPCC), could weaken multilateral forums that traditionally coordinate climate governance. Such developments risk creating governance vacuums precisely at a moment when anticipatory governance arrangements for emerging climate interventions are increasingly necessary. The United Nations Environment Program (UNEP) emphasizes in its paper [1] that current scientific evidence does not support SRM as a viable climate solution and underline the existence of major knowledge gaps, governance uncertainties, and asymmetries in research capacity between developed and developing countries. The report also stresses the importance of transparency, precaution, and inclusive international dialogue in any future consideration of SRM-related research or governance discussions [1]. Scholars therefore emphasize that any consideration of SRM must be accompanied by transparent, inclusive, and internationally legitimate governance mechanisms [5,6]. To date, however, SRM debates have been dominated by institutions and actors from the GN, while countries and communities in the GS, many of which face the greatest climate vulnerability, have had limited influence in shaping research agendas or policy discussions [7,8]. This asymmetry raises fundamental questions of climate justice and global governance. SRM governance therefore cannot be treated solely as a technical or scientific challenge, but also as a sustainability governance issue involving legitimacy, equity, participation, and institutional accountability under conditions of scientific uncertainty. Governance arrangements lacking transparency and inclusiveness risk undermining institutional trust and reinforcing global inequalities addressed in the SDGs framework. Recent governance initiatives illustrate this imbalance. Analysis presented later in this paper shows that Global South (GS) institutions represent only a minority of signatories to the SRM Non-Use Agreement despite many developing countries being among those most exposed to climate change impacts. This participation gap provides the empirical motivation for the present study.

This paper examines the continuing marginalization of the GS in SRM governance debates and explores pathways toward more inclusive governance frameworks, combining a literature review on SRM science and governance with a case study of the SRM Non-Use Agreement [9] and analyzing how governance activism interacts with broader institutional dynamics. It also integrates three perspectives: the scientific and historical context of SRM proposals and associated uncertainties, the ethical and participatory debates surrounding emerging climate governance and a GS lens to governance discussions through an analysis of the SRM Non-Use Agreement and related governance initiatives. Together these perspectives highlight a central argument: effective SRM governance requires not only scientific knowledge but also institutional legitimacy and meaningful participation from countries and communities historically marginalized in global climate decision-making. Accordingly, this study seeks not only to document governance asymmetries

but also to explain their institutional drivers and identify practical governance mechanisms capable of strengthening inclusive participation. This analytical framework also enables the paper to distinguish between descriptive governance gaps identified in the literature and operational governance recommendations aimed at strengthening inclusive participation in future SRM governance arrangements.

The analysis is informed by four complementary perspectives: Inclusive governance, climate justice, polycentric governance, and the principle of Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC), which together provide the analytical lens for interpreting the findings.

2. Materials and methods

The terms Global North (GN) and Global South (GS) are commonly used to describe persistent economic and geopolitical inequalities between industrialized and developing regions. The GN generally includes North America, Western Europe, and parts of East Asia, while the GS encompasses most of Africa, Latin America, South and Southeast Asia, and parts of Oceania [10]. Although geographically imprecise, the North-South framework remains widely used in discussions of development, global governance, and climate justice. In climate governance debates, these asymmetries are reflected in the principle of the CBDR-RC, embedded in the United Nations Framework Convention on Climate Change (UNFCCC). The principle recognizes that while all states share responsibility for addressing climate change, they do not share equal historical responsibility or institutional capacity [11,12]. These asymmetries are particularly visible in emerging debates around SRM. Research funding, modelling capacity, and governance discussions remain concentrated in institutions located in the GN, raising concerns that technological pathways could reproduce historical patterns of technological control and decision-making [13]. Recent UNEP assessments similarly note that SRM governance discussions remain characterized by unequal research capacities, fragmented governance structures, and divergent geopolitical perspectives, reinforcing concerns regarding legitimacy and equitable participation in emerging climate intervention debates [1].

The literature review was conducted between September 2025 and July 2026 using the Scopus and Web of Science databases, complemented by reports and policy documents published by international organizations including the UNEP, the World Meteorological Organization (WMO), the IPCC and other relevant institutions involved in climate governance. Search terms included combinations of “solar radiation management”, “solar geoengineering”, “SRM governance”, “Global South”, “climate justice”, “inclusive governance”, “polycentric governance”, and “CBDR-RC”. Publications were selected based on their direct relevance to the governance, institutional, ethical and sustainable development dimensions of SRM. Both peer-reviewed publications and authoritative institutional reports were considered where they contributed to understanding emerging governance debates. Duplicate records and publications focusing exclusively on the physical or engineering aspects of SRM without governance implications were excluded from the analysis. The initial search yielded 101 records. Following title and abstract screening, duplicate removal, and relevance assessment, 58 publications and institutional reports were retained for

detailed qualitative analysis. Publications were coded according to four analytical dimensions: (i) scientific uncertainties, (ii) governance frameworks, (iii) equity and Global South participation and (iv) sustainable development implications. Coding was conducted manually using an iterative thematic analysis to identify recurring governance themes across the literature.

This review is described as a structured qualitative literature review rather than a formal systematic review because its objective was not to provide an exhaustive synthesis of all SRM publications, but to analyze the principal governance debates, institutional developments and policy proposals relevant to the research questions. To minimize selection bias, predefined search terms, explicit inclusion criteria, multiple complementary data sources, and cross-validation between academic literature, institutional reports, and the empirical case study of the SRM Non-Use Agreement were employed throughout the analysis. This methodological approach is consistent with qualitative governance research seeking analytical depth rather than statistical representativeness. SRM refers to proposed interventions designed to reduce global temperatures by reflecting a portion of incoming solar radiation back into space. The most widely discussed techniques include Stratospheric Aerosol Injection (SAI) and Marine Cloud Brightening (MCB) [14]. A related technique, Cirrus Cloud Thinning (CCT), operates through modification of longwave radiation processes rather than solar reflection [15,16]. Governance in this context refers to the formal and informal institutions, rules, and decision-making processes that shape SRM research, development, and potential deployment. Because SRM interventions could generate transboundary impacts, governance debates intersect with broader questions of international law, climate justice, and global institutional legitimacy [9,17]. Applying a GN-GS perspective therefore highlights not only technological questions but also distributive and procedural justice concerns. The differentiated vulnerabilities and capacities between regions imply that governance frameworks must address both the distribution of risks and benefits and the participation of affected communities in decision-making processes [18].

This methodological approach combines a structured qualitative literature review with an empirical case study of the SRM Non-Use Agreement. The triangulation of academic literature, institutional reports, and empirical governance analysis provides the basis for interpreting participation asymmetries and identifying governance mechanisms applicable to future SRM governance [3,9,19,20].

The second component of the methodology focuses on the SRM Non-Use Agreement as a case study of governance activism. The analysis examines the initiative's objectives, patterns of endorsement, and the distribution of signatories across geographic regions and disciplinary backgrounds. Particular attention is given to the representation of GS institutions and stakeholders. By combining literature synthesis with case-based governance analysis, the study explores how transparency, inclusion, and accountability function as key governance principles in emerging SRM debates.

To enhance the robustness of the qualitative analysis, findings from the literature review were triangulated with publicly available policy documents, institutional reports, and the empirical analysis of the SRM Non-Use Agreement.

3. Results and discussion

3.1. Literature review and context

3.1.1. Scientific and historical overview

Anthropogenic emissions of greenhouse gases (GHG), particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), have significantly increased atmospheric concentrations since the industrial revolution, intensifying the greenhouse effect and driving global climate change [2,21]. Fossil-fuel combustion and land-use change remain the dominant sources of these emissions. Recent assessments indicate the accelerating pace of warming: According to the WMO, the global mean surface temperature reached approximately 1.55 °C above pre-industrial levels in 2024 [22]. This trend highlights the widening gap between current emission trajectories and the temperature goals of the Paris Agreement. Three broad categories of response to climate change are commonly identified: mitigation, adaptation, and climate engineering. Mitigation aims to reduce greenhouse-gas emissions and enhance carbon sinks, while adaptation focuses on reducing vulnerability to climate impacts. Climate engineering proposals include both Carbon Dioxide Removal (CDR) and SRM [21,23].

SRM refers to interventions designed to reflect a fraction of incoming solar radiation in order to reduce global temperatures. The most frequently discussed approaches include SAI and MCB [14]. These approaches aim to increase planetary albedo and thereby offset part of the warming caused by GHG. The idea of deliberately modifying Earth's radiative balance has historical roots. Modern scientific debate about SRM intensified after Crutzen who proposed exploring Stratospheric Aerosol Injection (SAI) as a possible response to insufficient mitigation efforts [24]. The proposal triggered extensive debate among scientists, with critics emphasizing potential risks including changes in precipitation patterns, ozone depletion, and uneven regional climate effects [25]. Observations following the 1991 eruption of Mount Pinatubo provided insights into aerosol-induced climate effects. The eruption temporarily cooled global temperatures and altered precipitation patterns, particularly in tropical regions [26]. These observations have informed modelling studies examining potential SRM impacts on hydrological cycles and monsoon systems.

Another widely discussed risk is the possibility of "termination shock", a rapid warming that could occur if SRM deployment were abruptly halted while greenhouse-gas concentrations remained high [27]. Such scenarios highlight the long-term dependency that large-scale SRM deployment could create. MCB represents another proposed SRM approach. By increasing the reflectivity of low marine clouds, the technique aims to reduce incoming solar radiation and cool surface temperatures. Although some small-scale field experiments have been proposed or conducted, uncertainties remain regarding environmental effects, effectiveness, and governance implications [28,29].

Overall, while modelling studies suggest SRM could temporarily offset some warming, significant uncertainties remain regarding regional climate impacts, ecological consequences, and socio-political risks. Recent UNEP assessments further conclude that existing scientific evidence remains insufficient to support SRM

deployment, reinforcing the importance of precautionary governance alongside continued mitigation and adaptation efforts [1]. These uncertainties have intensified calls for robust governance frameworks capable of ensuring transparency, accountability, and equitable participation in SRM research and decision-making processes.

3.1.2. Equity arguments for SRM research

Some researchers argue that although uncertainties remain regarding the regional impacts of SRM geoengineering, modelling studies suggest that the aggregate risks associated with SRM side effects may be smaller than the risks associated with unmitigated climate change [30]. examine the global and distributional impacts of SRM on socio-economic outcomes using macroeconomic climate impact models [31]. Their findings suggest that although results vary across model specifications, global income inequality between countries could be lower in scenarios combining climate change with SRM than in scenarios without SRM intervention. However, such model-based conclusions do not resolve the broader ethical and governance challenges associated with solar geoengineering. Wagner emphasizes the risk of mitigation deterrence or moral hazard, whereby the perceived availability of geoengineering could reduce political incentives for emissions reductions, thereby exacerbating long-term and intergenerational inequities [30]. From this perspective, SRM governance remains ethically problematic unless research and potential deployment are clearly subordinated to mitigation efforts. Horton and Keith advance a justice-based argument for conducting SRM research, including field experiments [32]. They argue that opposing research could effectively condemn developing countries to suffer the consequences of climate change caused largely by emissions from wealthier countries. In this interpretation, refusing to explore SRM options could represent a failure to address global climate inequities. This argument implicitly assumes that developing countries support SRM research as a strategy aligned with their interests. Critics have described the equity justification for SRM research as potentially paternalistic or, in some cases, reflective of forms of "expertise imperialism" arguing that expert interpretations of equity require continued scrutiny [33]. Evidence from political forums suggests that many countries in the GS remain cautious or opposed to SRM. For example, the 20th African Ministerial Conference on the ENvironment (AMCEN) held in Nairobi in July 2025, reaffirmed African countries' rejection of SRM technologies, emphasizing the significant environmental, ethical, and geopolitical risks associated with such interventions. Concerns also arise from the possibility that SRM deployment could be undertaken unilaterally by technologically advanced states. Estimates suggest that the costs of implementing SAI could be far lower than the costs of global mitigation strategies, potentially enabling one or a small number of states to deploy SRM without international consensus [34]. As noted in the U.S. National Academies report on climate intervention, a single nation, corporation, or group of actors with sufficient resources could theoretically deploy albedo-modification technologies in the absence of international coordination [23].

Such scenarios raise serious governance concerns. If SRM technologies were deployed unilaterally, countries with limited political or economic power could be placed in the position of passive observers, despite potentially facing significant

environmental impacts. This scenario highlights the importance of governance frameworks capable of preventing unilateral deployment and ensuring that vulnerable regions participate meaningfully in decision-making processes.

Recent assessments further emphasize that scientific uncertainties remain substantial, particularly regarding regional climate responses in tropical regions that are critical for GS societies [3,14]. These uncertainties reinforce the need for governance arrangements capable of integrating both scientific knowledge and justice considerations. Beyond distributive impacts, equity in SRM governance must therefore address epistemic justice: Who defines research priorities, whose knowledge is considered legitimate, and whose uncertainties shape risk assessments. These governance asymmetries are not merely procedural: They influence whose knowledge informs international policy discussions, whose priorities receive research funding, and ultimately whose interests shape the future governance architecture of SRM. Ensuring meaningful GS participation in agenda-setting, data access, and decision-making processes is essential to preventing equity arguments from being used to justify technological pathways that remain structurally dominated by GN actors.

3.1.3. Ethical and participatory frameworks

Ethical evaluation of SRM turns on three intertwined questions: (a) who decides whether, what, and where to research; (b) who benefits and who bears risk, across regions and generations; and (c) what counts as legitimate knowledge and consent in plural societies. Environmental sociology shows that legitimacy is co-produced by institutions, publics, and media narratives; it cannot be retrofitted after technical choices are locked-in [35]. Thus, SRM governance must move from expert-centric consultation to co-deliberation that recognizes diverse cultural values and vulnerability profiles. Developing more integrated, inclusive and fair governance models requires transparency of information and the active involvement of key societal stakeholders in decision-making processes, ensuring that perceived local and regional risks and vulnerabilities are considered [36]. Therefore, in order to ensure this process is inclusive, a multilayered participation design is required: (1) Deliberative mini-publics convened in GS regions likely to face strong hydrological sensitivity (monsoon affected regions, Sahel, small islands), with results feeding into scientific scenario design; (2) Standing citizens' panels attached to regional bodies (AU, ASEAN, CARICOM) to review SRM research proposals and advise on veto/consent; (3) Participatory impact framing that surfaces non-temperature metrics (food security, water access, cultural heritage, displacement risk), bridging natural and social indicators; and (4) Transparency charters for SRM projects, acknowledging the mediating role of journalism and credible public communication in legitimacy formation [37,38].

Such processes should explicitly include youth and Indigenous governance traditions, consistent with evidence that younger cohorts and frontline communities prioritize justice, accountability, and long-term stewardship [39]. When paired with open archives of models, code, and experimental protocols, these measures transform participation from one-off hearings into continuous governance. Taken together, these practices can shift SRM from a technocratic exercise to a deliberative process grounded in cultural pluralism and intergenerational equity [40]. Existing scholarship

stresses that without early-stage engagement of GS actors, SRM governance risks replicating patterns of exclusion found in previous global environmental agreements [20,41]. Participatory challenges directly inform our recommendations for inclusive governance in our conclusive section as we outline operational steps to embed GS leadership structurally in SRM governance frameworks. Embedding these participatory mechanisms early in the research process increases institutional legitimacy and strengthens the social acceptability of future governance arrangements.

3.2. Global south governance gaps and the non-use agreement

A focused case study of the SRM Non-Use Agreement reveals the underrepresentation of GS signatories, reinforcing broader trends of exclusion : we argue that GS nations could increasingly become influential participants in future SRM governance debates, although their future position will depend on political priorities, scientific capacity, and evolving international governance arrangements.

Geopolitical shifts also complicate the SRM governance landscape. China's early completion of its 2030 renewable energy goals and sustained investment in green-electricity reforms reinforce its structural leverage in the global energy transition [42]. China's rapid electrification may strengthen its capacity to influence future climate and SRM governance discussions, although the implications for international governance remain uncertain [43]. Meanwhile, India's increasingly fragmented and evolving climate governance further shapes the range of plausible SRM governance pathways [44].

Limited focus on SRM research on human dimensions remains concerning: most studies have concentrated on the natural science aspects, leaving substantial knowledge gaps regarding potential impacts on society and the environment. Key questions remain unanswered, such as SRM's ability to preserve human life, mitigate climate-induced stress on ecosystems, and ensure agricultural reliability and water availability. The need for comprehensive research to inform decision-making on SRM implementation has recently been raised again by negotiations at the United Nations Environment Assembly [45].

A growing body of scholarship argues that SRM research and development risks being fundamentally unjust when driven by a relatively narrow and socially homogeneous group of actors largely based in high-income countries, often funded by billionaires or philanthropic foundations and framed through technocratic or quasi-military logics that neglect the structural causes of climate injustice [46]. Such dynamics reinforce concerns about epistemic capture, legitimacy deficits, and the reproduction of GN dominance in emerging climate interventions. This underscores the urgent need for globally inclusive and deliberative governance frameworks capable of counterbalancing existing technological, financial, and political asymmetries between the GN and the GS [1,3,47]. Without such safeguards, SRM governance risks replicating the very inequalities it purports to address, thereby undermining both its ethical justification and its political viability.

A "call for non-use", referring to a global initiative launched by over 60 leading climate scientists and governance specialists on 17 January 2022 advocate for an International Non-Use Agreement on Solar Geoengineering and calls for at least five

core commitments, including (1) No public funding: prohibit national funding agencies from supporting the development of solar geoengineering technologies; (2) No outdoor experiments: ban outdoor experiments of solar geoengineering technologies; (3) No patents: refrain from granting patent rights for technologies related to solar geoengineering; (4) No deployment: commit not to deploy solar geoengineering technologies if they are developed by third parties and (5) No support in international institutions: discourage support for solar geoengineering in international institutions.

Over 600 signatories from 53 countries endorsed the initiative, but a comparatively small share are affiliated with GS institutions, underscoring the asymmetry the Agreement seeks to address. These patterns of activism and participation highlight a central tension: how to reconcile precaution with inclusion, an issue we take up in the Discussion section. These signatories comprise academics, including scholars and researchers from universities and research institutes; governance experts specializing in climate policy, environmental law, and sustainability governance; civil society representatives, such as members of non-governmental organizations and environmental advocacy groups; as well as concerned individuals who support the initiative in a personal capacity. While this diversity might suggest a broad consensus on the importance of caution and governance in SRM, it is prudent to examine and analyze these signatories from different perspectives, including countries and areas of research and expertise. We have observed that 24 % of the signatories are women, 75 % are men, and the gender of 1 % of signatories was not unidentified. In total, we identified 630 signatories who indicated their country (a total of 53 countries) across six regions of the world. To illustrate the geographical distribution of institutional support for the SRM Non-Use Agreement, **Figure 1** presents the regional affiliation of identified signatories.

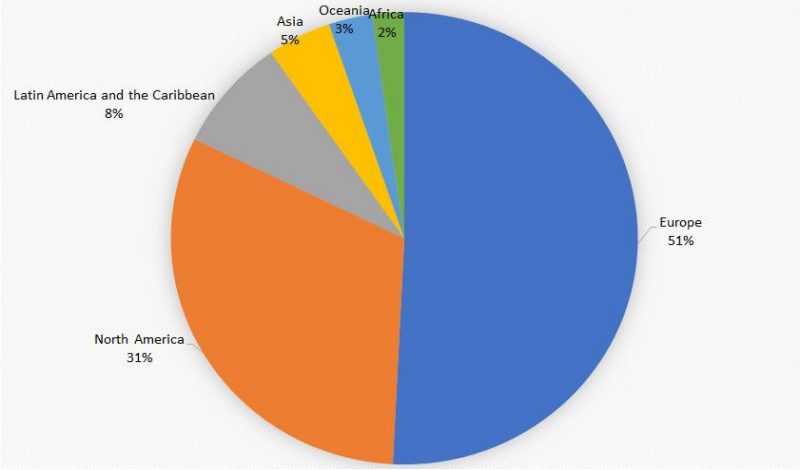


Figure 1. Distribution of signatories by country/region , GS underrepresentation highlighted. Source: Solar Geoengineering Non-Use Agreement [48].

Figure 1 illustrates a marked regional imbalance among the signatories of the SRM Non-Use Agreement. More than four-fifths of identified signatories are affiliated with institutions located in Europe and North America, whereas participation from Africa, Latin America, Asia, and Oceania remains comparatively limited. Although

the Agreement advocates precaution and global responsibility, its support base remains concentrated within Global North institutions, illustrating the participation asymmetry discussed throughout this article.

To better understand the diversity of expertise represented within the Non-Use Agreement, the professional backgrounds of signatories were classified into broad disciplinary categories. The classification in **Table 1** provides an indication of the balance between natural sciences, social sciences, governance, law, engineering and other disciplines participating in SRM governance debates.

Table 1 presents the classification framework used to categorize signatories according to their primary disciplinary expertise.

Table 1. List of categories of signatories per area of research/academic topic.

Category 1	Category 2	Category 3
Environmental Studies	Sustainability and Development	Law
Environmental/Climate Science	Sustainability Studies	General law
Climate Governance and International Development	Sustainability	International Law
Climate Change and Development	Circular Economy	Earth System Law
Environmental Change	Transition Governance	Environmental Law
Environmental Politics	Urban Futures	
	Development Studies	Climate Change and Geography
Social, Policy and Governance	Peace and Development	Climate Change
Social Sciences and humanities	Conflict Resolution, Human Security, and Global Governance	Climate Hazards
Political Science	International Relations	Geography and Spatial Sciences
Criminology		
Journalism	Economics	Geography
Policy and Governance		
Environmental Policy/Governance		Engineering and technology
Global Sustainability Governance		Engineering
Public affairs		Technology/Engineering
Public Health		Energy
		Biology
		Anthropology and Sociology:
		Anthropology
		Sociology
		Gender Studies
		Indigenous Studies

Figure 2 summarizes the disciplinary backgrounds of the identified signatories.

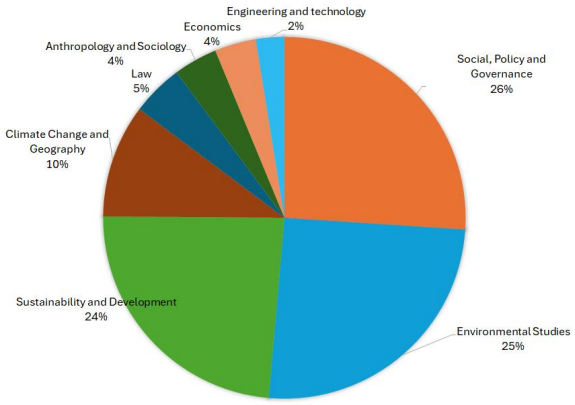


Figure 2. Areas of research/ academic topic of the signatories, Source: Solar Geoengineering Non-Use Agreement [48].

Figure 2 shows that the majority of signatories come from environmental sciences, sustainability, and governance disciplines, whereas engineering, economics, and technological disciplines remain comparatively less represented. This multidisciplinary composition confirms that SRM governance is increasingly discussed as a societal and governance challenge rather than solely as a technological issue.

Youth perspectives are particularly relevant for SRM governance. Drawing on Botto et al. [39], **Table 2** synthesizes key recommendations emerging from recent studies on youth engagement in SRM governance.

Table 2. Youth involvement in SRM governance. Inspired from Botto et al. [39]. SRM and youth perspectives on its governance. UN sustainable development.

Key issues	Recommendations
▪ Global warming: current climate actions are insufficient to meet the Paris Agreement's 1.5-2°C goal. ▪ SRM might appear as a tool, as it could artificially cool the planet, potentially reducing some of the negative impacts of climate change. ▪ Risks and limitations: SRM does not address the root causes of climate change and is not a substitute for mitigation and adaptation efforts. ▪ Lack of governance: there is no formal international framework governing SRM, and it remains a controversial topic. Decisions on SRM will significantly impact younger and future generations, necessitating their involvement in governance discussions.	➔ Informing and educating young people about SRM, its science, benefits, and risks, through early education and interdisciplinary approaches. ➔ Consulting and collecting youth perspectives through surveys and public meetings to indirectly involve them in SRM governance. ➔ Collaborating: empower young people to organize and form ideas and facilitate collaboration with governments through advisory boards and youth-led programs. ➔ Involving directly youth in policymaking by recruiting them as policy advisers and researchers in SRM projects.

Climate justice stakeholders and social movements advocating against geoengineering include environmental NGOs, Indigenous communities, anti-technology activists, farmers and food movements, youth climate movements, civil society groups, and academic networks. Many express concerns over environmental, social, and geopolitical risks [46]. A broad spectrum of organizations and communities voice concerns about SRM and geoengineering. Environmental NGOs such as Greenpeace, Friends of the Earth, and the Environmental Defense Fund warn about environmental risks, uncertain effectiveness, and the risk of diverting attention from emissions reductions. Indigenous peoples, including the Indigenous Environmental Network, the International Work Group for Indigenous Affairs, FIDEP Foundation, and AbibiNsroma Foundation, oppose geoengineering as a threat to their rights, lands, and traditional knowledge, describing it as a continuation of colonial and ecocidal practices. Anti-technological groups like the ETC Group and HOME Alliance reject large-scale climate manipulation due to risks, lack of consent, and failure to address root causes. Farmer and food sovereignty movements such as La Via Campesina and Friends of the Earth International fear impacts on agriculture and food security. Climate justice organizations, including the Climate Justice Alliance, argue that technological fixes undermine systemic transformation. Civil society groups like the Center for International Environmental Law and Geoengineering Monitor highlight

governance and equity concerns. Some scientific bodies, including the Climate Overshoot Commission, call for a moratorium. Developing countries and small island states, notably the Alliance of Small Island States, reject SRM, while youth movements such as Fridays for Future, SRM Youth Watch, and Operaatio Arktis emphasize intergenerational justice and inclusive governance.

While no SRM deployment has progressed beyond planning, the allocation of public funds and recent UN discussions suggest that a simple "non-use" position may not suffice. The Stratospheric Controlled Perturbation Experiment (SCoPEx) case shows how scientific ambition, public opposition, and governance uncertainty intersect. Emerging GS-led research hubs, such as those facilitated by the Degrees Initiative could act as platforms for South-South knowledge exchange and GN engagement on equal footing [47]. Regional bodies such as the AU, ASEAN, and the Community of Latin American and Caribbean States (CELAC) could form SRM working groups to coordinate positions, share expertise, and negotiate collectively in global forums. From a governance theory perspective, applying polycentric governance means GS participation should occur across multiple levels, from regional collaborations to UNFCCC negotiations, amplifying GS influence in agenda-setting and decision-making [49]. Bridging justice-oriented climate activism and institutional governance could help ensure SRM pathways align with humanitarian, ecological, and equity principles. In this sense, lessons from earlier research-first frameworks such as the Solar Radiation Management Governance Initiative (SRMGI) and international governance issues on climate engineering report demonstrate how transparency, disclosure, and early stakeholder engagement can be designed into governance from the outset, but they also reveal that without GS leadership, these safeguards risk reproducing existing asymmetries [50,51].

This case study therefore underscores two intertwined realities: (i) GS nations' structural under-representation in SRM governance debates, and (ii) the existence of vibrant but fragmented climate justice movements that could, with adequate institutional support, influence the trajectory of SRM governance toward inclusivity and precaution [13,18]. Strengthening GS participation requires capacity-building, targeted funding, integration of social science into SRM R&D, and formal mechanisms for youth, Indigenous, and community stakeholders [9]. The Observatoire Défense & Climat adds that GS states must also anticipate security dimensions, such as attribution disputes, militarization, and escalation risks, if they are to engage effectively and avoid being sidelined in techno-diplomatic arenas [52].

The insights from this case study, particularly regarding GS advocacy potential and the structural barriers to participation, directly inform the discussion of governance risks and opportunity pathways presented in Section 3.3. They also highlight the need for governance designs that bridge activism and institutional policymaking, thereby avoiding the siloed approaches that have weakened previous global climate agreements [48]. The Annual Review of Environment and Resources (ARER) and the report issued by the German Environment Agency (UBA) further emphasize that SRM governance must be iterative, precautionary, and justice-centered, warning against unilateral deployment and urging mechanisms that explicitly link SRM oversight to mitigation and adaptation finance [53,54]. Without such integration, GS perspectives risk being treated as symbolic rather than substantive [54,55]. In this

light, the Non-Use Agreement debate becomes a critical test case: can global governance move beyond prohibitive logics to actively embed GS leadership, capacity-building, and equity safeguards [9]? Without such integration, non-use risks reproducing the very asymmetries it seeks to avoid. Addressing this tension, between precautionary prohibition and inclusive empowerment, marks the core governance challenge that our discussion explores, highlighting both the risks of fragmentation and the opportunities for reimagining multilateralism. Indeed, Jinnah and Dove stress that each milestone in SRM governance, whether through CBD precautionary decisions, the SRMGI's research-first principles, or contested debates held at the occasion of the United Nations Environment Assembly (UNEA), has revealed the asymmetry of GS participation, underscoring the systemic nature of these governance gaps [9].

3.3. Discussion

The integration of scientific knowledge, ethical debates, and governance analysis reveals a persistent asymmetry in SRM discourse: while research capacity and modelling efforts are advancing, governance frameworks remain fragmented and GS participation remains limited. SRM therefore occupies a critical juncture in climate governance, where technical capabilities are expanding faster than institutional arrangements capable of ensuring legitimacy and equitable participation. From a sustainable development and sustainability governance perspective, SRM governance challenges extend beyond scientific coordination to encompass institutional legitimacy, distributive justice, participatory inclusion, and long-term institutional accountability. The case study of the SRM Non-Use Agreement illustrates both the potential and the limitations of governance activism. While the initiative represents an attempt to establish precautionary norms around solar geoengineering, the relatively limited participation of institutions from the GS reflects broader structural asymmetries in climate governance debates. These asymmetries raise questions about whether governance initiatives can adequately represent those most vulnerable to climate impacts. The findings therefore suggest that future SRM governance should not be evaluated solely according to scientific effectiveness, but equally according to its capacity to reduce structural inequalities in participation, knowledge production, and institutional influence between the Global North and the Global South.

At the same time, the absence of robust governance frameworks creates risks of unilateral or poorly coordinated experimentation. Recent assessments by UNEP further emphasize that governance arrangements for SRM remain insufficiently developed relative to the pace of scientific and technological advances [1]. UNEP highlights persistent uncertainties regarding environmental impacts, institutional oversight, and equitable participation in decision-making, particularly for developing countries with limited research capacities. Without transparency regarding research activities and intentions, SRM research could contribute to geopolitical mistrust or conflictual attribution of climate impacts. Transparency and international oversight are therefore essential to avoid secrecy, reduce misinterpretation of scientific activities, and foster cooperative governance. This need for transparency and international dialogue was also highlighted during the UNEP-WMO consultative workshop on

SRM held in Geneva in 2025, where participants emphasized the importance of inclusive consultation processes, improved information-sharing, and enhanced participation from developing countries in future governance discussions [55]. In this context, anticipatory governance approaches become increasingly important to ensure that precaution, transparency, participation, and equity are integrated into governance discussions before technological pathways become institutionally or politically entrenched. Meaningful participation is equally critical. SRM governance intersects with questions of intergenerational justice, cultural values, and development priorities. Ensuring participation from Indigenous communities, small island states, least developed countries, and youth constituencies is essential to legitimacy and long-term policy acceptance [39]. As highlighted in the UN "Pact for the Future" removing barriers to youth participation and improving representation in decision-making structures is increasingly recognized as a central component of legitimate global governance [56].

Despite these challenges, opportunities exist for the GS to shape SRM governance trajectories. Emerging initiatives such as the Degrees Initiative's regional research hubs and early dialogue platforms within regional organizations suggest that GS actors can play a more active role in shaping the research and governance agenda, provided that sustained institutional support and capacity-building mechanisms are secured. Regional political organizations such as the African Union (AU), ASEAN, and the Community of Latin American and Caribbean States (CELAC) could play a coordinating role by establishing regional SRM working groups to consolidate scientific expertise, develop shared governance positions, and strengthen negotiation capacity in international forums. Coalition-building among GS states has historically influenced global environmental governance negotiations and could similarly shape emerging SRM debates [7]. Operationalizing the principle of Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC) in the SRM context would therefore require targeted capacity-building, including scientific infrastructure, monitoring capabilities, and governance expertise in GS countries [8]. Such efforts would enable meaningful participation in both research and governance processes. **Table 3** proposes a governance architecture translating these principles into practical institutional mechanisms, including transparency registries, consent procedures for field experiments, capacity-first sequencing of research investments, safeguards addressing termination risks, and the integration of social indicators into climate modelling. These mechanisms aim to operationalize equity and inclusion in SRM governance while aligning emerging governance structures with broader sustainable development and sustainability governance objectives.

The governance mechanisms proposed below derive directly from the literature review, the case-study findings, and recent international policy discussions. Together they illustrate how broad governance principles can be translated into practical institutional arrangements capable of strengthening transparency, participation, and accountability. Building upon the literature review and empirical findings, **Table 3** proposes operational governance mechanisms.

Table 3. Proposed governance mechanisms to operationalize equity and inclusion in SRM governance.

Governance mechanism	Description / implementation pathway	Supporting references
1. Registry and disclosure	Establish a WMO/UNEP/WIPO (World Intellectual Property Organisation) SRM «Transparency Registry» to record funding sources, patent ownership, model configurations, and any proposed field activity. Registry listing should be a mandatory precondition for receiving public or international grants, ensuring transparency and traceability.	[20,55,57]
2. Consent and veto	Adopt a «Regional prior informed consent» rule for outdoor SRM studies with possible transboundary impacts, empowering GS blocks (AU, ASEAN, CARICOM) to issue binding conditions or vetoes before trials proceed.	[9,13,18]
3. Capacity-first sequencing	Allocate climate-finance windows (e.g., GCF readiness) to strengthen GS research nodes for modelling, stratospheric monitoring, and ethical-legal review before approving new field tests. Ensures technical and institutional parity.	[37,47]
4. Termination-risk safeguards	Require credible termination and compensation plans, including ramp-down scenarios and liability mechanisms, integrated into all experimental designs to avoid abrupt climate shocks and protect vulnerable regions.	[14,27,53]
5. Social metrics in models	Mandate to consider non-temperature indicators, food and water security, displacement risk, distributional outcomes, in SRM modelling and evaluation (e.g., GeoMIP protocols), aligning with Global South priorities and social legitimacy.	[3,35,40,58]

Collectively, these mechanisms illustrate how governance principles can be translated into practical institutional arrangements supporting SDGs 10, 13, 16, and 17.

This package operationalizes CBDR-RC by pairing differentiated responsibilities (data provision, monitoring, risk coverage) with differentiated capabilities (finance, technology, institutional capacity). Crucially, it rebalances agenda-setting power: GS actors shape scenarios and conditions upstream, rather than reacting downstream to "faits accomplis". In short, uncertainty reduction and justice advancement must proceed together, or not at all. In practical terms, the five instruments translate normative equity principles into implementable rules, linking transparency, consent, capacity, termination safeguards, and social metrics across polycentric institutions, thereby aligning predictability work with enforceable inclusion.

4. Conclusions and recommendations

Our article examined the persistent underrepresentation of the GS in emerging debates on SRM governance. Through a review of scientific, ethical, and governance literature and a case study of the SRM Non-Use Agreement, the analysis highlights how structural asymmetries in research capacity, funding, and institutional participation continue to shape SRM governance discussions. From a sustainability

governance perspective, SRM illustrates the broader challenge of governing emerging climate interventions under conditions of scientific uncertainty, geopolitical fragmentation, and uneven institutional capacities. The findings suggest that SRM governance cannot be treated solely as a technical or scientific challenge. Because potential interventions could generate transboundary environmental and socio-economic impacts, governance frameworks must address questions of legitimacy, equity, and participation from the earliest stages of research and policy development.

Recent institutional discussions, including the UNEP Solar Radiation Modification Working Paper, further reinforce concerns regarding major knowledge gaps, governance uncertainties, uneven research capacities, and the absence of globally agreed governance frameworks for SRM-related activities [1]. Three governance principles emerge as particularly important:

- Governance must be inclusive, embedding GS actors in research agenda-setting, knowledge production, and decision-making processes. Meaningful participation requires not only consultation but also leadership roles for GS institutions in shaping research priorities and governance frameworks;
- Governance must be transparent, ensuring open access to research data, modelling outputs, and governance deliberations. Transparency is essential to building trust and preventing unilateral technological trajectories that could exacerbate geopolitical tensions;
- Governance must be ethically grounded, integrating principles of climate justice, precaution, and intergenerational responsibility. Because SRM decisions could affect future generations and vulnerable communities, governance structures must incorporate mechanisms capable of reflecting diverse societal values.

These governance principles directly support the objectives of the SDGs by linking climate-risk management (SDG 13) with institutional accountability (SDG 16), equitable participation across regions (SDG 10), and strengthened international cooperation (SDG 17).

Our study also highlights a central governance paradox: while SRM research and modelling capabilities are advancing rapidly, governance arrangements remain underdeveloped and unevenly distributed. As noted by Jinnah and Dove, the historical evolution of SRM governance has been characterized by fragmented institutional developments and recurring participation asymmetries, suggesting that governance deficits are not temporary anomalies but structural features of the current SRM landscape [8]. Without proactive governance design, emerging SRM trajectories risk reinforcing existing inequalities in global climate decision-making. In this context, anticipatory governance approaches become increasingly important to ensure that precaution, transparency, participation, and equity are integrated into governance discussions before technological pathways become institutionally or politically entrenched. To address this challenge, several practical steps could strengthen GS participation in SRM governance:

- Establish a GS SRM research fund under international climate finance mechanisms to support independent GS-led research and capacity-building.
- Mandate transparency reporting within the UNFCCC system on SRM-related research funding, patents, and experimental activities.

- Create regional SRM ethics and governance panels within organizations such as the African Union, ASEAN, and CARICOM to review proposed research activities and advise national governments.
- Strengthen North-South research partnerships between GS universities and GN technical institutions to promote reciprocal knowledge exchange rather than one-way technology transfer.
- Explicitly incorporate CBDR-RC principles into emerging SRM governance frameworks, ensuring differentiated responsibilities in technology development, monitoring, and decision-making.

The measures listed above combine normative commitments with operational governance mechanisms grounded in both climate justice principles and polycentric governance theory. By creating overlapping centers of expertise and decision-making authority, they offer a pathway toward more legitimate and inclusive SRM governance.

Ultimately, the future trajectory of SRM governance is likely to depend not only on scientific advances, but also on whether global institutions succeed in embedding equity, transparency, and meaningful Global South participation into governance arrangements from the earliest stages of research and policy development.

Ultimately, the legitimacy of future SRM governance will depend not only on scientific innovation but equally on the willingness of international institutions to embed equity, transparency, and meaningful participation at the center of decision-making.

Author contributions: Conceptualization, YR, FDS; methodology, YR, FDS; validation, YR, FDS and LS; formal analysis, YR, FDS; investigation, YR, FDS, LS; resources, YR, FDS, LS; data curation, YR; writing: original draft preparation, YR; writing: review and editing, YR, FDS; visualization, YR; supervision, FDS, LS; project administration, YR. All authors have read and agreed to the published version of the manuscript.

Ethical approval: Not applicable.

Informed consent statement: Not applicable.

Acknowledgments: AI use disclosure: the co-authors used an AI-assisted language tool solely for language editing, grammar correction, and improvement of readability. The authors reviewed, revised, and validated all manuscript content and take full responsibility for the accuracy, originality, interpretation, and conclusions presented in this work. No AI tool was used to generate the research design, analysis, findings, references, or conclusions.

Conflict of interest: The authors declare no conflict of interest.

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