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Solar radiation modification: Why precaution means non-use

Margaretha Wewerinke-Singh [a,b,*], Heleen M. Bruggink [c], Dana Ruddigkeit [d], Aarti Gupta [e], Varun Mohan [c], Jennie C. Stephens [f], Stacy D. VanDeveer [g], Sean Low [e], Wolfgang Cramer [h]

[a] University of Amsterdam, the Netherlands
[b] University of Fiji, Fiji
[c] Utrecht University, the Netherlands
[d] German Environment Agency, Dessau, Germany
[e] Wageningen University and Research, the Netherlands
[f] ICARUS Climate Research Centre, National University of Ireland Maynooth, Ireland
[g] University of Massachusetts Boston, USA
[h] Mediterranean Institute of Marine and Terrestrial Biodiversity and Ecology (IMBE), CNRS, Aix-Marseille University, IRD, Univ. Avignon, France

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ABSTRACT

In May 2026 the United Nations Environment Programme released a working paper finding that solar radiation modification (SRM) is not currently a viable climate response, while framing continued research under globally coordinated oversight as the prudent course. This Perspective argues that this prescription rests on four misconceptions recurring across a decade of high-profile SRM assessments: (1) that more research can resolve what are, at root, political and legal problems; (2) that the precautionary principle licenses experimentation rather than constraining it; (3) that advocating restriction amounts to silencing debate; and (4) that participation in research governance can substitute for the power to decide. Engaging the 2024-2025 advisory opinions of the International Tribunal for the Law of the Sea, the Inter-American Court of Human Rights and the International Court of Justice, and the human right to science, the Perspective shows that international law supports the opposite conclusion: precaution, correctly understood, means non-use.

1. Introduction

Proposals to research and develop solar radiation modification (SRM) are gaining renewed institutional traction. Over the past five years, a series of high-profile assessments and policy initiatives — among them the United States National Academies' recommendation of a coordinated federal research programme (NASEM, 2021), the White House research plan that followed (OSTP, 2023), and the Climate Overshoot Commission's call to expand SRM research while pausing deployment and large-scale outdoor experiments (Climate Overshoot Commission, 2023; see also UNEP, 2023) — have converged on a common storyline: SRM is potentially highly risky and lacks governance, yet more research, including outdoor experimentation, is the prudent response. That storyline trades on four recurring misconceptions: that more research can resolve what are, at root, political and legal problems; that the precautionary principle licenses experimentation rather than constraining it; that advocating restriction amounts to silencing debate; and that participation in research governance can substitute for the power to decide. Each has a legal dimension, and each is contradicted by the very evidence these assessments assemble.

The most recent and most authoritative example is a working paper released by the United Nations Environment Programme (UNEP) on 12 May 2026 (UNEP, 2026). Its headline finding is unequivocal: current knowledge does not support SRM as "a viable climate response" (p. 18). The working paper is commendably candid about why. SRM models cannot resolve regional or long-term outcomes, and projected benefits rest on idealised scenarios that "assume globally coordinated governance, stable deployment over time and well-controlled interventions" (p. 4). Research funding is concentrated overwhelmingly in high-income countries (p. 14). And deployment would carry grave risks: uneven changes in rainfall, monsoons and drought that threaten food and water security in vulnerable regions; ecological disruption, with ocean

* Corresponding author. Amsterdam Law School, University of Amsterdam, Nieuwe Achtergracht 166, 1018 WV, Amsterdam, the Netherlands.
E-mail addresses: m.j.wewerinke@uva.nl (M. Wewerinke-Singh), heleen@solargeoeng.org (H.M. Bruggink), dana.ruddigkeit@uba.de (D. Ruddigkeit), aarti.gupta@wur.nl (A. Gupta), v.mohan@uu.nl (V. Mohan), Jennie.Stephens@mu.ie (J.C. Stephens), Stacy.VanDeveer@umb.edu (S.D. VanDeveer), sean.low@wur.nl (S. Low), wolfgang.cramer@imbe.fr (W. Cramer).

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acidification unabated; changes to stratospheric ozone; a sharp rebound in warming if deployment stopped abruptly (termination shock); weaker political will to cut emissions; and geopolitical conflict (pp. 9–11). The Intergovernmental Panel on Climate Change has likewise found that SRM would introduce "a widespread range of new risks to people and ecosystems, which are not well understood" (IPCC, 2022, p. 19).

These positions also align very well with those taken by more than 600 academics advocating for an international non-use agreement on solar geoengineering (SGNUA, 2022). Non-use, according to this initiative, would require a commitment by States not to develop or deploy SRM: with no public funding for its development, no outdoor experiments, no patents, no deployment of technologies developed by third parties and no support for its institutionalisation as a policy option in international fora, while atmospheric and climate research as such remains unrestricted (Biermann et al., 2022, p. 5). This Perspective argues that precaution, as international law articulates it, requires exactly that.

Yet the UNEP working paper's conclusions do not consistently follow from its own evidence. Having documented why SRM cannot presently be considered viable, it nonetheless leaves the door open to future use and frames expanded research — including outdoor experimentation — as the appropriate response to the very risks it identifies. Sections 2 to 5 show how it reproduces each of the four misconceptions; Section 6 considers what giving effect to its own conclusion would require.

2. "More research" as the answer to problems research cannot solve

The working paper's central move is a *non sequitur*. It identifies risks that are, on its own account, profound and in part irreducible — termination shock, geopolitical instability, uneven regional impacts, and committed multi-generational dependency (UNEP, 2026, pp. 8–11) — and then prescribes more modelling and field research as the response. But it concedes in the same breath that the models are idealised (p. 4) and that small-scale field studies are "inherently limited in scope" and cannot resolve uncertainties in global-scale climate responses (p. 8). Better models and more experiments cannot dissolve what are not, at root, knowledge gaps. The decisive risks of SRM are social, political and intergenerational: they concern who would control a planetary thermostat, on whose behalf, and with what recourse for those harmed. Finer parameterisation of aerosol microphysics does not touch on these political questions (Stephens et al., 2023; Corry et al., 2024; Möller and Young, 2026).

Nor can such research be separated from the politics it is meant to inform. The working paper itself acknowledges that "confidence in simulated physical responses does not imply confidence in social license, institutional capacity or legitimacy" (p. 7), and that risk is "also political, psychological and normative" (p. 8). Choices of scenarios, of risks to compare and of whose knowledge counts are value judgements, and authoritative assessments have steered the field rather than merely describing it (Gupta and Möller, 2019), recasting equity as a question for more science (Flegal and Gupta, 2018).

This is also where the working paper's treatment of equity falls short. It rightly notes the concentration of research in the Global North and calls for "reciprocal capacity sharing, regionally-led research and full recognition of diverse knowledge systems" (UNEP, 2026, p. 18). But capacity sharing in research is not the same as decision-making power over whether the technology is developed at all, and the working paper does not confront that distinction. The deeper point, which the non-use literature has also emphasised (e.g. Gupta et al., 2024; VanDeveer et al., 2024; Bruggink et al., 2026), is that "solar geoengineering at planetary scale is not governable in a globally inclusive and just manner within the current international political system" (Biermann et al., 2022, p. 1). Deployment would require continuing global decisions on where, how intensely and for how long to cool, with risks falling unevenly; no existing institution has the legitimacy and authority to take such decisions for all, while the low cost of some techniques would let a few States act alone or in small coalitions (pp. 2–4). More research cannot make an ungovernable technology governable. It risks instead entrenching the research momentum and funding architectures that — as the working paper itself warns — narrow future choices and legitimise deployment pathways (UNEP, 2026, p. 17; see also Stephens et al., 2021; Surprise et al., 2025). This is the risk of lock-in that the working paper flags but does not allow to discipline its own recommendations.

Furthermore, greater care must be taken when applying the 'research' label. It is imperative to safeguard the right to freedom of scientific research and to protect the integrity of institutions dedicated to research and knowledge production against subversion. While legitimate research warrants protection, speculative and risky endeavours should not be legitimised under the guise of 'research'. Legitimate research, in this sense, is inquiry aimed at understanding rather than at developing a deployable technology: atmospheric and climate science, laboratory and modelling studies of Earth system processes, and social, ethical and legal research on SRM. Treating development as research amounts to a strategy of 'learning by doing' on a pathway to potential deployment, constituting 'post-caution' rather than pre-caution.

International law already draws such lines. Parties to the London Convention and Protocol agreed that ocean fertilisation activities "other than legitimate scientific research should not be allowed", judging legitimacy by criteria that include adding to scientific knowledge and freedom from economic interests (LC/LP, 2008, paras. 7–8; 2010). The Antarctic regime prohibits "[a]ny activity relating to mineral resources, other than scientific research", and subjects research itself to prior environmental impact assessment (Madrid Protocol, 1991, arts. 7–8). Prohibition and research are therefore not alternatives. A non-use agreement follows the same logic, restricting the activities that turn inquiry into capability, above all outdoor experiments, which, as the working paper records, blur the boundary between research and operational capability, risk normalising deployment, and cannot resolve uncertainties about global-scale climate responses (UNEP, 2026, pp. 4, 8). Limited, regulated experiments would add little missing knowledge while advancing the pathway that precaution counsels against.

3. The precautionary principle is a constraint, not a licence

The working paper's most consequential error is legal. Instead of treating precaution as a constraint, it asserts that there is "a growing consensus that precaution does not mean inaction, but rather demands careful, inclusive and globally coordinated oversight" and that "precaution does not mean paralysis" (UNEP, 2026, pp. 16, 18). This inverts the principle – an error with significant legal consequences. As with any legal principle, not all questions about its operation have been answered (Peel, 2021), but its core is clear: where there are "threats of serious or irreversible damage", scientific uncertainty is no reason to postpone preventive measures (Rio Declaration, 1992, Principle 15; UNFCCC, 1992, art. 3 (3); ICJ, 2025, para. 293). Precaution thus operates as a constraint on activities that may cause serious or irreversible harm under conditions of scientific uncertainty; it is not a warrant to generate that harm in order to study it.

The confusion has a recognisable structure. The precautionary principle does not itself need to be "balanced" against competing considerations; instead, it structures and disciplines the balancing exercise. Applying it involves, at a minimum, two steps: a scientific assessment of impacts, probabilities and uncertainties, followed by a decision-making phase in which the costs and benefits of action and inaction are weighed against the objective of reducing risk to an acceptable level (European Commission, 2000). Where serious and unacceptable risks remain after that process, the principle justifies prohibition even absent full scientific proof. What it does not authorise is the pitting of one speculative risk against another — the "risk–risk" framing now common in the SRM debate (Davies and Vinders, 2025; McLaren, 2025) — so as to license experimentation on the grounds that unmitigated warming is itself

dangerous. The dangers of warming are real, but they are an argument for the mitigation the working paper rightly prioritises, rather than the justification for a second planetary-scale intervention whose known risks are grave and unevenly distributed, and whose full effects could be known only by deploying it.

This reading is now firmly anchored in international jurisprudence. In its 2024 Advisory Opinion, the International Tribunal for the Law of the Sea held, as its Seabed Disputes Chamber had in 2011, that the precautionary approach is "an integral part of the general obligation of due diligence", which requires States to account for the risks of activities under their jurisdiction or control even where evidence of the probability and severity of harm is insufficient (ITLOS Seabed Disputes Chamber, 2011, para. 131; ITLOS, 2024, paras. 213, 242). Endorsing that conclusion, the International Court of Justice, in its Advisory Opinion of 23 July 2025, confirmed the "precautionary approach or principle" as a guiding principle across the law most directly relevant to climate change, informing the interpretation of treaty obligations and forming part of the due diligence that the customary duty of prevention requires of every State (ICJ, 2025, paras. 161, 172, 178, 180, 294, 409). A guiding principle that shapes a binding obligation has binding consequences: precaution guides due diligence, and due diligence binds (see Wewerinke-Singh and Viñuales, 2026). The Court's dual phrasing, as Judge Charlesworth noted, "does not affect the principle's scope or legal application"; as she also observed, prevention focuses on risk and precaution on uncertainty, and the two "operate on a continuum and complement each other" (Charlesworth, 2025, paras. 2, 4). The Inter-American Court of Human Rights, in Advisory Opinion OC-32/25, went further still: it held that prevention is supplemented by the precautionary principle, and recognised the prohibition of conduct capable of irreversibly damaging the "vital equilibrium of the common ecosystem" as a peremptory norm of international law (IACtHR, 2025, paras. 228–229 and operative para. 8, adopted by four votes to three). Together, these opinions show why the inversion has legal consequences: a State that followed the working paper's reading would consider itself diligent while pursuing the very conduct that precaution, as part of due diligence, restrains. None of this jurisprudence is engaged by the working paper, which cites the ICJ's opinion once, in passing, and the other opinions not at all (UNEP, 2026, p. 2).

The implication for SRM is decisive. Precaution ordinarily restrains an activity until evidence shows its risks to be acceptable. For SRM, such evidence cannot be obtained safely. On the working paper's own account, the decisive uncertainties cannot be resolved by models or small-scale studies (UNEP, 2026, pp. 4, 8–9), and stratospheric intervention cannot be tested without implementation at full scale, sustained long enough for its signal to emerge from natural variability (Robock et al., 2010). Any programme capable of showing that SRM is acceptably safe would therefore impose the very risks it was meant to assess, so the condition for lifting the restraint can never be met without breaching it. SRM is thus held at both ends of the prevention–precaution continuum: its known harm pathways engage the duty of prevention now, while its irreducible uncertainties keep it within precaution's grip. Framing precaution as a permission slip for outdoor experimentation is unsupportable in light of this jurisprudence.

The climate treaties point the same way. The objective of the UNFCCC is to stabilise greenhouse gas concentrations at a level that prevents dangerous anthropogenic interference with the climate system — to be achieved, the Convention adds, within a time-frame that allows ecosystems to adapt naturally, ensures that food production is not threatened, and enables economic development to proceed sustainably (UNFCCC, 1992, art. 2). Those conditions mark out the interests the treaty protects, and they are the very interests SRM would put under strain: disrupted regional climates and ecosystems, threatened food production (UNEP, 2026, pp. 9–10; Proctor et al., 2018), and — were sustained intervention interrupted — change too rapid to allow adaptation (Trisos et al., 2018). Within the Convention's scheme, moreover, climate action means addressing emissions by sources and removals by sinks (UNFCCC, 1992, art. 4 (1) (b)); SRM does neither, leaving concentrations rising and ocean acidification unmitigated (UNEP, 2026, pp. 2, 10). A treaty concluded to prevent dangerous anthropogenic interference with the climate system cannot coherently be read to authorise a further deliberate interference of that character — whether offered as a substitute for the emission reductions it mandates or as their supposed complement.

SRM is increasingly cast as a 'last resort' against overshooting 1.5°C and modelled as a means of 'shaving' the peak of a temporary exceedance (UNEP, 2026, pp. 1, 7). That framing treats the temperature limit as a variable to be managed, and has co-evolved with technological promises in ways that enabled prevarication on mitigation (McLaren and Markusson, 2020). The law points elsewhere. Reading decisions of the Conference of the Parties serving as the Meeting of the Parties (CMA), the Paris Agreement's governing body, as subsequent agreements on the treaty's interpretation, the International Court of Justice identified 1.5°C as the Agreement's primary temperature goal and held that parties must exercise stringent due diligence to make their nationally determined contributions, taken together, capable of achieving "the temperature goal of limiting global warming to 1.5°C" (Paris Agreement, 2015, art. 2 (1) (a); ICJ, 2025, paras. 224, 245–246). In terms that the CMA has adopted from the IPCC, and on which the Court relied, limiting warming to 1.5°C refers to pathways with no or limited overshoot; pathways with a high overshoot do not limit warming to 1.5°C but return to it later (CMA, 2023, paras. 26–27; ICJ, 2025, para. 243; IPCC, 2023, Box SPM.1). A high overshoot is therefore not a way of meeting the goal but a failure to meet it, and SRM deployed to manage one would compound that failure with a second planetary intervention.

The permissive reading of precaution that runs through parts of the working paper must therefore be rejected. Insistence on more research and field experimentation is not precautionary. Instead, if applied to a planetary-scale, partly irreversible and ungovernable intervention, the precautionary principle points in one direction: non-use.

4. Non-use is the outcome of expanded deliberation, not its suppression

A recurring rhetorical move in the working paper is to distinguish those "calling for strengthened governance" from those who "wish to silence discourse", and to characterise advocates of restrictive governance as implicitly silencing debate and discourse (UNEP, 2026, p. 16). This is not a neutral empirical observation; it mischaracterises and delegitimises a considered legal and political position calling for restricting a dangerous activity. Academics advocating for non-use of SRM, for example, have not silenced discourse; to the contrary, they have enlivened it, as the widening range of actors and rationales in the debate attests (Bruggink et al., 2026).

Opposition to SRM does not seek to foreclose inquiry. Instead, it actively engages in and broadens discourse and debates on SRM. While expanding the space for debate and discourse, it calls for restricting risky and unjust practices and systems. This non-use position builds on two decades of research and deliberation across the natural and social sciences, law and global governance (e.g. Robock, 2008; Szerszynski et al., 2013; Biermann and Möller, 2019; Stephens and Surprise, 2020) — recently including the case for a non-use agreement (Biermann et al., 2022), the comparative legal analysis of how such a regime could be designed (Gupta et al., 2024), and the assessment of its political feasibility (VanDeveer et al., 2024). This position is also reflected in the decisions of States: the African Ministerial Conference on the Environment has called for a non-use agreement and reaffirmed its "unequivocal rejection of stratospheric aerosol injection and other forms of solar geoengineering" (AMCEN, 2023, decision 19/5, para. 15; 2025a, para. 6; 2025b, paras. 35, 45); Mexico announced that it would prohibit solar geoengineering experiments on its territory (SEMARNAT, 2023; Carabajal et al., 2025); at the sixth UN Environment Assembly, African States, supported by Fiji, Vanuatu and other Global South States, resisted

a resolution on SRM that was eventually withdrawn (Biermann and Gupta, 2024); and at the 2024 Conference of the Parties to the Convention on Biological Diversity, Pacific Island States pressed for stronger protection as the *de facto* moratorium on climate-related geoengineering was reaffirmed (CBD, 2008, 2010, 2024; Chandrasekhar et al., 2024).

To recast this body of considered judgement as censorship is both factually wrong and rhetorically corrosive. It is also in tension with the working paper's own, more careful acknowledgement elsewhere that effective governance must rest on legal, ethical and scientific grounds (UNEP, 2026, p. 16) — standards that restrictive-governance positions meet. The distinctions between inquiry and development drawn in Section 2, which the working paper's own evidence supports, are precisely what its "silencing discourse" framing of opposition to SRM obscures.

International human rights law itself draws the distinction on which the non-use position rests. The right to science — recognised in Article 27 of the Universal Declaration of Human Rights and codified in Article 15 of the International Covenant on Economic, Social and Cultural Rights — protects both the freedom indispensable for scientific research and the right of everyone to share in scientific advancement and its benefits (UDHR, 1948; ICESCR, 1966). It is not, however, a licence to develop and deploy whatever technology inquiry makes possible. The UN Committee on Economic, Social and Cultural Rights has clarified that the right to science incorporates the precautionary principle discussed above, which demands action to avoid unacceptable harm even without full scientific certainty, including harm that is "threatening to human life or health", "serious and effectively irreversible", "inequitable to present or future generations" or "imposed without adequate consideration of the human rights of those affected" (CESCR, 2020, para. 56). The Committee has been equally clear that, while limitations on the freedom of research itself are narrowly circumscribed, precaution applies more broadly to the use and application of scientific outcomes — and that States must align their policies with the best available evidence and protect the public against scientific disinformation (paras. 52, 57). Judged against this framework, a non-use agreement does not curtail the right to science; it gives effect to it. It preserves the inquiry, deliberation and access to reliable knowledge that the right protects, while restricting a development pathway whose acknowledged risks meet the Committee's definition of unacceptable harm almost to the letter.

5. Participation is not consent, and consultation is not governance

The working paper repeatedly invokes "inclusive governance", "inclusive participation" and "inclusive deliberation" as the answer to SRM's equity problems (UNEP, 2026, pp. 5, 11, 15, 17–18). Inclusion matters. But the working paper avoids acknowledging the significant difference between participation and the power to decide — and this avoidance carries a precise legal cost.

These terms are distinct, and each is contested: participation concerns who takes part, deliberation how options are weighed, inclusion who is admitted and on whose terms. In research-centred governance, all three tend to operate within a frame in which research proceeds: affected groups may shape how SRM is studied, not whether it is pursued, which closes down rather than opens up the choice at stake (Stirling, 2008). The human rights framework gives deliberation a different task: in controversial cases, participation and transparency serve to enable society "to decide whether or not the risks are acceptable" (CESCR, 2020, para. 57). Deliberation that cannot end in refusal is consultation by another name. Geopolitical fragmentation, strained multilateralism and misinformation sharpen the point, as the globally coordinated governance that SRM models assume recedes (Corry et al., 2024; Möller and Young, 2026; UNEP, 2026, p. 12).

It matters in law — and the normative and ethical considerations underpinning it — that the communities most exposed to outdoor experimentation and to any future SRM deployment are overwhelmingly those least represented in decision-making arenas (UNEP, 2026, pp. 14–15; Dove et al., 2026). The principle of free, prior and informed consent — codified in the UN Declaration on the Rights of Indigenous Peoples and affirmed by the Inter-American Court in the climate context (UNDRIP, 2007, arts. 19, 32 (2); IACtHR, 2025, paras. 608–610) — cannot be approximated by "transparent, internationally supervised research" (UNEP, 2026, p. 14). When the Saami Council objected in 2021 to a planned balloon test flight from Kiruna, Sweden, it sought not a role in the experiment but its cancellation; the project was later abandoned (Saami Council, 2021; Salata Institute, 2024). Consultation that informs but does not bind is not consent; and consent over a discrete project is not collective governance of a planetary intervention, whose harms, such as a failed monsoon, would be hard to attribute and harder to remedy (UNEP, 2026, p. 9).

The UN Human Rights Council Advisory Committee has already concluded that new technologies intended for climate protection can interfere with the enjoyment of human rights and pose physical, political and social risks to frontline communities, including Indigenous Peoples (HRC Advisory Committee, 2023, paras. 55, 66). Against that background, a regime that offers the exposed a seat at a consultative table while reserving decision-making to a few capable States and their funders is not "inclusive governance"; it is incompatible with States' positive obligations under international human rights law. The Inter-American Court has now recognised a peremptory (jus cogens) prohibition on massive and irreversible environmental harm (IACtHR, 2025, para. 294 and operative para. 8) — a prohibition that squarely engages a technology designed to alter the entire climate system, with acknowledged potential for irreversible and inequitably distributed effects.

6. Operationalising UNEP's own conclusion

The working paper's own finding is that SRM is not currently a viable climate response. The task now is to give that finding effect. Calling for broad consultation and improved modelling is not a substitute for taking a clear decision or stance; and the decision on which the evidence, the precautionary principle and the human rights framework converge is restriction, not facilitation. What is needed is not a global research programme but a global agreement restricting the development of solar geoengineering technologies.

Such an agreement is neither unprecedented nor utopian. International law already offers a rich repertoire of prohibitory and restrictive regimes from which States could draw (Gupta et al., 2024) — among them the Environmental Modification Convention (ENMOD, 1976), the Anti-Personnel Mine Ban Convention (APMBC, 1997), the Montreal Protocol's control of ozone-depleting substances (Montreal Protocol , 1987), the Basel Convention's restrictions on hazardous-waste movements (Basel Convention, 1989), the London Protocol's reverse-list approach (London, 1996, art. 4.1.1), and the ocean fertilisation and Antarctic mining restrictions discussed in Section 2. Furthermore, restrictions on development and use of biological and chemical weapons in the Biological and Chemical Weapons Conventions (BWC, 1972; CWC, 1993) neither silenced discourse nor impeded decades of progress in the biological and chemical sciences or technologies. More broadly, the legal principle of systemic integration means that any future SRM regime would in any event need to account for existing legal obligations and the customary no-harm rule (ICJ, 1996, para. 29) — a body of law that, as prior research shows, is far better suited to constraining this technology than to enabling it (Gupta et al., 2024; Ruddigkeit et al., 2025).

Each of the five measures for securing 'non-use' of SRM as set out in Section 1 gives precaution operational form, particularly where the development pathways are hardest to reverse. Withholding public funding and patents prevents the accumulation of investments, institutions and commercial interests that press towards use (UNEP, 2026,

pp. 3, 13; Surprise et al., 2025). Banning outdoor experiments keeps inquiry from becoming intervention. Refusing to deploy technologies developed by others closes a route to unilateral action, and objecting to the institutionalisation of SRM as a policy option prevents a speculative technology from hardening into an expectation (Oomen, 2024; see also McKinnon, 2019).

Governments in Africa and the Pacific have already shown the way (UNEP, 2026, p. 13). It is within UNEP's mandate, and consistent with its own conclusion, to support rather than dilute that leadership. A UNEP working paper should not be used to justify research budgets and activities that its own analysis does not warrant; nor should recurring misconceptions advanced by SRM's proponents be allowed to shape its assessments and recommendations. UNEP should operationalise its first key finding (p. 18) — and help move the international community from a posture of open-ended exploration to one of principled non-use.

CRediT authorship contribution statement

Margaretha Wewerinke-Singh: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Heleen M. Bruggink:** Writing – review & editing, Formal analysis, Conceptualization. **Dana Ruddigkeit:** Writing – review & editing, Writing – original draft, Formal analysis. **Aarti Gupta:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Varun Mohan:** Writing – review & editing, Validation, Formal analysis. **Jennie C. Stephens:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Stacy D. VanDeveer:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Sean Low:** Writing – review & editing, Validation, Conceptualization. **Wolfgang Cramer:** Writing – review & editing, Validation, Methodology, Formal analysis.

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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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