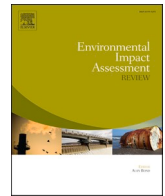


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## A call for strategic assessments of regional applications of solar radiation management: Exploring the challenges and opportunities from marine cloud brightening and albedo surface modification

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### ABSTRACT

Technological advancements offer the opportunity for interventions to reduce and potentially even counteract the impacts of climate change. However, advancements that can facilitate the adaptation of human and natural ecosystems to climate change, and possibly lessen the intensity and damaging impacts of extreme weather events, come with social, technical, and environmental challenges. These challenges are triggered by the complexity and uncertainty associated with their deployment in real-world settings. In this paper, we consider Solar Radiation Management interventions aiming to limit the heat absorbed by our planet's surface and trapped in its atmosphere, focusing on Marine Cloud Brightening and Albedo Surface Modification, particularly to protect ice surfaces, as examples of regional-scale interventions. Building on the need for more socially inclusive decision-making around these interventions, as highlighted by the Australian case study of the Great Barrier Reef's Reef Restoration and Adaptation Program, this paper proposes a policy framework with worldwide potential to assist with regional Solar Radiation Management. To this end, we suggest the use of Strategic Environmental Assessment, a United Nations recognised policy framework that is applied internationally to support environmentally sustainable strategic decision-making and planning. We consider Strategic Environmental Assessment's performance criteria in relation to Solar Radiation Management and discuss how these align with much-needed assistance in developing socially inclusive Solar Radiation Management interventions.

### 1. Introduction

Climate change impacts are threatening humanity and ecosystems globally, with increasingly dire warnings embodied in the scientific

literature which have provoked evocative statements from global leaders. The Secretary-General of the United Nations, Antonio Guterres, recently declared that "the era of global boiling has arrived" (UN, 2023), emphasizing the urgency of action. Scientific reports conclude that six of

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nine planetary boundaries—critical thresholds for maintaining Earth's stability—have already been transgressed (Richardson et al., 2023). As efforts to reduce greenhouse gas emissions struggle to keep pace with the rate of environmental change, there is an urgent need for innovative strategies to manage impacts and reduce risks associated with unavoidable climate change. It is in this context that geoengineering approaches have emerged as a set of potential interventions to complement traditional greenhouse gas mitigation efforts (Sovacool et al., 2022a).

Solar radiation management (SRM) and carbon dioxide removal (CDR) are two of the most prominent geoengineering approaches currently under development (The Royal Society, 2009). SRM refers to interventions that aim to reflect radiation back into the atmosphere and reduce the amount of solar radiation reaching the earth's surface (Keith, 2000), while CDR refers to interventions that aim to reduce the amount of carbon dioxide in the atmosphere (NASEM, 2018, 2021; Smith et al., 2023). SRM interventions, the focus of this paper, vary based on the technology proposed and the potential scale of application (local, regional, or global). Some technologies are applicable at multiple scales (e.g. surface albedo modification), while some are only applicable at global (e.g. stratospheric aerosol injection), regional or local scales (e.g. fogging). Deployment of geoengineering technologies raises a suite of complex environmental, technical, and social risk problems that require sophisticated management approaches (Sovacool et al., 2022a, 2022b). These challenges necessitate a robust framework for evaluating and managing the potential consequences of SRM deployment.

Strategic Environmental Assessment (SEA) provides such a framework, we argue in this manuscript, particularly for the assessment of SRM interventions at multiple scales. SEA is a decision support framework applied across strategic decision tiers that are routinely referred to as policies, plans and programs (PPPs) (Fischer, 2007). It is connected with assessments and implementation at a project level, frequently referred to as Environmental Impact Assessment (EIA); at times also labelled as Environmental and Social Impact Assessment – ESIA or Environmental, Social and Health Impact Assessment ESHIA). Whilst according to the Netherlands Commission on Environmental Assessment, EIA is presently applied, based on legislative requirements, in 187 of 195 countries formally recognised by the United Nations, similar requirements for SEA exist in just over 90 countries. However, most countries have some experiences with its application, based on, for example, demands by development banks and other international institutions (Annandale et al., 2021).

As an assessment procedure, SEA is applied to, and integrated with, the preparation of individual policies, plans, and programs. In this context, it works as a (1) science and an (2) art (Fischer, 2003; Retief et al., 2019), in that it aims to provide scientific and other evidence to decision makers on the potential environmental (and frequently, health and socio-economic) consequences of their PPP ideas, proactively introducing and assessing alternatives that may represent better solutions to aims, targets and problems; whilst accepting the political nature of decision making, attempting to steer it towards more sustainable and coherent outcomes (Kørnøv and Thissen, 2000). Importantly, SEA has the potential to deal with both climate change mitigation and adaptation (Jiricka-Pürner and Fischer, 2022). In this context, it can clarify possible win-win solutions and trade-offs, which is crucial given the prevalence of risk-risk trade-offs (Felgenhauer et al., 2022; Sovacool et al., 2023a). Usefully, SEA has also been applied at decision tiers across administrative and geographical boundaries and across multiple scales and sectors. It can help to clarify the complex relationship and different effects across those boundaries, thus supporting the search for optimised solutions (Fischer and González, 2021).

To date, SRM research and related public debates have primarily focused on applications at the planetary scale, with limited attention given to deployment at regional or local scales (Keith et al., 2014; Niemeier et al., 2013). Regional SRM applications can typically draw on a wider range of technologies than global scale interventions, depending on the target scale (Harrison, 2024). Examples of reducing impacts of

solar radiation at a regional scale include Marine Cloud Brightening (MCB), which involves the dispersal of aerosolized salt water to improve the reflectivity of low clouds in marine environment. SRM can also involve using reflective material (e.g., brighter paint coatings or mirrors) to cover surfaces and reduce impacts of solar radiation at a local scale. SEA supports interdisciplinary collaboration, stakeholder engagement, and the integration of local knowledge into decision-making, providing flexibility across different spatial and governance scales, which makes it an essential framework for managing risk and decision making for regional SRM (Fischer and González, 2021; McLaren and Corry, 2021).

SRM interventions can vary significantly in scale, from local initiatives targeting specific regions to global strategies with potential worldwide impacts. These different scales necessitate diverse governance frameworks to effectively manage associated risks and complexities. The application of SEA to SRM is particularly pertinent, as SEA processes must adapt to accommodate the various geographical scales and socio-political contexts inherent in SRM strategies. To effectively integrate SEA with regional applications of SRM, it is crucial to consider the concept of 'bounding' or the delineation of boundaries during impact assessments. This approach is well-articulated in the works of Beanlands and Duinker (1983), Conover et al. (1985), who emphasize the importance of defining several types of boundaries: physical bounds, socio-ecological bounds, jurisdictional bounds, and technical bounds. Each type of boundary provides a different lens through which to assess impacts. Physical Bounds refer to the specific geographic areas directly affected by SRM interventions. For example, an SRM initiative aimed at reducing solar radiation in the Great Barrier Reef region would have well-defined physical bounds limited to that marine area (Beanlands and Duinker, 1983). Socio-Ecological Bounds extend beyond the physical boundaries to include broader ecological systems and social dynamics. They consider how SRM interventions impact not just the immediate environment but also interconnected ecosystems and human communities (Conover et al., 1985). For instance, a regional SRM intervention could affect neighbouring regions through atmospheric changes, such as the spread of particulates or altered weather patterns. Jurisdictional Bounds relate to governance and regulatory responsibilities, which are particularly complex in regional and global contexts. For example, an SRM initiative in Europe would need to consider multiple national jurisdictions and their respective policies, making the governance process more intricate. Technical Bounds involve the limitations of current knowledge, technology, and the inherent uncertainties in predicting SRM outcomes. The application of the precautionary principle is often necessary in such scenarios to account for potential risks and unknowns associated with SRM technologies. Incorporating these boundary considerations into the SEA framework allows for a more nuanced assessment of SRM interventions, particularly when scaling up deployment from a local to a regional level. This approach ensures that the legitimacy of the governance process is maintained, as it involves essential inputs from regional stakeholders and communities and carefully considers the potential impacts on various scales.

To fill the gap in existing scholarship concerning smaller (regional, local) scale SRM applications, and to envision and identify regional governance needs, we explore SEA as a framework to support collaborative governance and interdisciplinary risk examination and management. SEA's flexibility across different spatial and governance scales and its support for interdisciplinary collaboration, stakeholder engagement, and integration of local knowledge into decision-making, make it a particularly useful framework for regional SRM (Fischer and González, 2021; McLaren and Corry, 2021).

For the purposes of this paper, we consider a 'region' as a geographically distinct area that can vary widely in scale, from localized regions such as the Great Barrier Reef which, stretching approximately 2000 km along the Australian coast, sits within a single nation state, to broader, more complex regional constructs like the European Union, which encompass multiple countries and diverse communities with

varying governance frameworks. The scale and scope of a region significantly impact stakeholder involvement, governance arrangements, and the socio-economic impacts of SRM interventions. By contrast, as ‘global scale’ we refer to phenomena or initiatives that transcend regional boundaries, involving multiple regions or the entire globe, often necessitating international cooperation and governance (Fawcett, 2016; Reynolds, 2019). For instance, while regional SRM initiatives might focus on localized climatic effects, global SRM efforts must account for widespread atmospheric changes, such as those observed with volcanic eruptions that have worldwide impacts.

We discuss the challenges posed by the complexity and uncertainty surrounding geoengineering projects at this scale, and how, until recently, socially inclusive approaches to engage communities in the design, management and assessment of these interventions have been absent, or performed in a perfunctory or ad hoc fashion. We argue that there is a need for an overarching policy framework to guide engagement with the broader community and relevant stakeholders to ensure that regional scale geoengineering interventions are socially sound, and risks (and the trade-offs between them) can be understood and managed in the most effective way. We explore opportunities for SEA to support achieving this (see, for example, the SEA protocol by the United Nations Economic Commission for Europe). SEA features and performance criteria are compared with the Oxford Principles, five high-level principles for research, development, and deployment of geoengineering technologies (Rayner et al., 2009), and with the risks associated with Solar Radiation Management interventions to define SEA’s potential to assist with regional/local SRM.

The remainder of this paper is organised as follows. The challenges and risks posed by regional-scale SRM are explored in the light of the five Oxford principles for geoengineering governance (Section 2). Section 3 then details emerging examples of SRM from around the world, with a focus on Marine Cloud Brightening under the Reef Restoration and Adaptation Program in the Australian Great Barrier Reef. Ways that SEA can serve to overcome these emergent challenges are explored in sections 4 and 5, followed by a conclusion section which also details areas for future research (Section 6).

## 2. The governance and engagement challenges of regional solar radiation management

The specific type of technology and scale of deployment of SRM interventions are important factors in determining the associated risks, opportunities, and potential impacts. Unfortunately, these examinations are reasonably limited. Theoretically, the adverse impacts of SRM at smaller scales also lends itself more readily to research and experimentation, for example in terms of regional variations in climate change impacts, with factors such as local topography, cloud cover, and vegetation cover significantly influencing the distribution of solar radiation (Srivastava et al., 2022; Sultan et al., 2014).

Studying SRM at regional and local scales can provide opportunities for interdisciplinary collaboration and the integration of local knowledge and perspectives (McLaren and Corry, 2021) to develop insights into the potential benefits, risks, and trade-offs associated with implementation in specific geographical areas and the required. Regional-scale SRM offers a more practical application given: the scale and scope of governance arrangements needed to underpin each intervention; the ability to monitor outcomes including potential adverse consequences; the involvement of stakeholders at different stages; and even the amount of material needing to be deployed (Conca, 2019; McKinnon, 2019).

Even though the focus of this paper is the regional scale, we acknowledge contributions that have been made in recent decades towards the definition of principles for guiding ‘good’ geoengineering governance. The ongoing debate on how to achieve responsible conduct in geoengineering research and deployment to ensure rigorously appropriate to the magnitude of its environmental and social

implications (Gupta et al., 2020; Jinnah et al., 2019; Tsonis and Kirwan, 2023) has stressed the need for a flexible set of norms and processes that fit the varied nature of geoengineering technologies, scales, and geographies of intervention. For example, the need of a ‘code of conduct’ is emerging as one of the possible ways forward (Hubert, 2020; Loomis et al., 2022), as well as the need for an international moratorium that builds on the inadequacy of current international political systems to manage inclusively and justly any global geoengineering intervention (Biermann et al., 2022).

As Heyward et al. (2017) highlight, some principles for managing global geoengineering have a narrow scope, focusing on field trial research. Examples include the Asilomar Principles (ASOC, 2010) and the Morrow Principles (Morrow et al., 2009). Some, such as the Jamieson’s Principles focus on technology deployment (Jamieson, 1996). Of a wider scope are the 5 Oxford Principles. Defined in the early 2000s by a group of academics, in conjunction with the UK House of Commons Select Committee on Science and Technology and a Royal Society Working Group, the 5 Oxford Principles considers early research to any deployment. The Oxford principles provide high-level guidance to frame geoengineering governance. The 5 principles are: 1) Geo-engineering is in the public interest and should be regulated as a public good; 2) there should be public participation in geo-engineering decision-making; 3) geo-engineering research should be transparent and available to the public; 4) risk assessments should be conducted by independent bodies, and be directed towards both the environmental and socio-economic impacts of research and deployment; and 5) the legal, social, and ethical implications of geo-engineering should be addressed before a project is undertaken or technology deployed (Heyward et al., 2017).

It is not clear how advancements in regional geoengineering research and governance fare against the Oxford principles. This is despite increasing government attention on climate interventions over the past decade, triggered by increasingly adverse weather events due to escalating climate change (e.g., EC, 2023; OSTP, 2023),

We adopt the Oxford principles in our reflection on SRM challenges and risks (e.g. geoengineering being ethically defensible) and Strategic Environmental Assessment. Further improving these principles is outside the scope of this paper however we acknowledge that the literature presents efforts aimed at improving them, such as the ‘Tollgate Principles’ for geoengineering governance (Gardiner and Fragnière, 2018).

Risks arising from novel technology-based solutions to SRM can be vastly different in nature and present highly complex pathways involving social, economic, and environmental dynamics. These inter-related risks have been categorized by social scientists working in the Australian Reef Restoration and Adaptation Program, an assisted ecosystem restoration and adaptation effort researching the feasibility of several interventions, among which is regional application of SRM for local adaptation to climate change (Lockie et al., 2024; Tollefson, 2021). In addition to the routinely characterized and assessed business and social risks, there are more uncertain, complex and ambiguous risks, spanning biocultural relationships, and risk perceptions which vary in how they materialise across space and time, which Lockie et al. (2024) identify as: business, social, biocultural, and vulnerability risk (Table 1).

Social vulnerability risks include exacerbating existing vulnerability drivers and missed opportunities to promote equity through deployment of climate interventions. For example, the distribution of benefits of SRM interventions could amplify vulnerability risks at different scales. Risk perceptions can amplify or attenuate other types of risk, both directly (e.g. through their impacts on peoples’ socioemotional well-being and on the perceived legitimacy of SRM applications) and indirectly (e.g. through their impacts on peoples’ behaviour). These risk categories are intertwined with the challenges of ensuring both ‘procedural fairness’, which pertains to public engagement and stakeholder involvement throughout the process, and sustainable and equitable outcomes, or ‘outcome fairness’ (Sovacool, 2021; Sovacool et al., 2022a;

**Table 1**  
Risk categories (adapted from Lockie et al., 2024).

Risk category	Description
Business risk	Threats to the legitimacy and acceptability of a program or intervention. They can arise early in the life of a program, and can come with distrust or lack of support in organizations or programs stemming from lack of transparency.
Social risk	Threats to social and economic wellbeing, culture, human rights, health and safety, such as employment opportunities and labour force dynamics that can have immediate consequences while also accruing over long-term horizons.
Biocultural risk	Threats to community wellbeing and First Nations peoples' rights to autonomy, to practice culture, and self-determination.
Vulnerability risk	Threat to community posed by the lack of access to resources that, combined with exposure to potential hazards, places populations "at risk" of failure to withstand those hazards.

Vella et al., 2021). These risks speak to the legitimacy of the governance process - in that if the people impacted by these technologies are not consulted (and it may not even be their government making decisions about them), a legitimacy deficit (or, democratic deficit, as in Reynolds, 2021) may arise. In the light of this renewed and enhanced focus on stakeholder and community engagement in geoengineering projects, we discuss how each Oxford principle (OP, illustrated in Table 2) can guide the development of a governance framework fit to tackle emerging challenges and risks of regional SRM.

*OP1: 'Regulation of regional geoengineering projects as public good'*

OP1 has suffered from limited advancements in legislative frameworks, leaving questions around clarity and how to make use of geoengineering in a way that is 'fair' and not prerogative of special interests, while considering the unfitness for strategic decision-making of current global governance (Biermann et al., 2022; Gupta et al., 2020; Keith, 2021; Winickoff et al., 2015). The increasing number of SRM interventions led by private entities has only exacerbated the risk of unregulated, unilateral, or self-interest uses of novel technology, a key threat to their procedural and outcome fairness (Tuana et al., 2012). Coupled with the lack of specifically designed regulations, this trend poses increasingly crucial challenges to the legitimacy and acceptability of these interventions (business risk).

*OP 2: 'Involving stakeholders and potentially interested and affected communities through mechanisms for public participation in geoengineering decision-making'*

OP2 can help addressing the flaws of geoengineering governance discussed so far. As critics argue, public engagement has often been lacking, both in terms of passive feedback and active involvement, in developing geoengineering interventions (Burns and Flegal, 2015; Macnaghten and Szerszynski, 2013; Stephens et al., 2022). The very same Oxford Principle (OP2) appears to indicate forms of public participation that can be interpreted as passive notification of intents, consultation, and acquisition of prior informed consent from third parties, rather than advocating for active public involvement and collaborative research and deployment.

*OP 3: 'increased transparency in disclosing research plans and publishing related results' and OP4: 'impacts of geoengineering research are managed by a body independent of those undertaking the research'*

While reforming regulations and governance arrangements require time and mobilization of large societal sectors, SRM project proponents

**Table 2**  
Oxford Principles (from Reynolds, 2019).

The Oxford Principles
1. Geoengineering to be regulated as a public good.
2. Public participation in geoengineering decision-making.
3. Disclosure of geoengineering research and open publication of results.
4. Independent assessment of impacts.
5. Governance before deployment.

can tackle the risks posed by these uncertainties with OP 3, and ensuring the consideration of OP4 (Rayner et al., 2009). Especially, though not exclusively when geoengineering is proposed by private entities, full disclosure on research, its results, and estimated impacts can reduce the perceived or real social, economic, cultural, biocultural, and vulnerability risks (Lockie et al., 2024). Clearly framing accountability and responsibility on research and unintended consequences of these projects has proven to be essential (Owen et al., 2012). These strategies could help to manage uncertainties due to spatial and temporal distance between interventions and manifestation of their effects in the real world, as well as clarifying the ethics of interventions. However, for assessment of impacts to be done by a body independent from the project proponent, guidelines and policy should be set in place to guarantee impartiality and avoid collusion. In the absence of robust governance and regulations (OP 1, 5), there is a risk that actions are entirely dependent on the good-will of project proponents. This is a key reason for why we advocate the use of Strategic Environmental Assessment (SEA).

*OP 5: 'the lack of the robust governance structures that are needed to develop and implement geoengineering interventions'*

Struggles in advancing regulation are a contributing cause of OP 5. When governance arrangements are undermined by insufficient allocation of roles and responsibilities, the complexity of the technologies and interventions at stake pose challenges and therefore business risks to project developers, in terms of stakeholder management, practicality, cost-effectiveness, and timeliness of interventions (Vella et al., 2021). Weak regulation and governance also exacerbate social distrust of scientific and management institutions, triggering potentially inaccurate perceptions of risks associated with geoengineering projects.

The Oxford Principles, which outline governance frameworks for geoengineering, provide a global perspective on the ethical and regulatory considerations for SRM. However, when applied to regional interventions, these principles must be adapted to account for the unique challenges posed by local governance, stakeholders, and socio-environmental dynamics. A few examples are presented below.

- The first principle, which states that geoengineering should be treated as a public good, applies differently at the regional scale. While SRM impacts at the global level require universal governance, regional interventions directly affect specific local communities. These communities must be considered key beneficiaries of SRM technologies, and local governance mechanisms must ensure that the public good is prioritized within the regional context.
- The second principle emphasizes the need for transparent and inclusive decision-making processes. In regional applications, this principle becomes just as important, as local stakeholders and communities may experience more direct and immediate impacts from SRM interventions. Ensuring that public participation is robust at the regional level aligns with this principle and helps mitigate governance challenges across multiple scales.
- Transparency, as outlined in the third principle, takes on a more complex form at the regional scale. Governance structures must ensure that local, regional, and national authorities coordinate effectively, maintaining transparency in decision-making and responsibility for outcomes.

Indeed, an insufficient degree of public participation can undermine

the quality, legitimacy, and acceptance of SRM interventions, leading to public scepticism and concerns about transparency and democratic decision-making (Conca, 2019; Jinnah and Nicholson, 2018; Lin and Hourdequin, 2022). Several projects and related studies have addressed public participation from a passive perspective, focusing on collecting information on public perceptions and community feedback on hypothetical or proposed SRM interventions (Braun et al., 2017; Delina, 2021). This is far from unique to the area of SRM, least of all given their principally hypothetical character at present. However, the fact that limited and delayed engagement with stakeholders and interested communities on potential SRM interventions has been the norm is problematic, given both the potential controversies evoked, and the ensuing absence of public debate about, and engagement with, the acceptability of these methods (Corner and Pidgeon, 2015; Merk et al., 2019; Sovacool et al., 2023b). Critics emphasize the need for meaningful and inclusive engagement that goes beyond tokenistic consultations and incorporates diverse perspectives, local knowledge, and values into decision-making processes (Corner et al., 2012; Stilgoe et al., 2020; Vella et al., 2021).

Frameworks for enhanced public participation in geoengineering have emerged in the professional literature and practice, including strategies for understanding public acceptance and public deliberation, models and frameworks for the governance of complex and uncertain risks, and public involvement in technology assessment. These frameworks could provide much-needed context for debates, negotiation, and expression of dissent around SRM interventions, enabling a transparent and proactive sharing of views and expectations held by different stakeholders and communities (). Challenges inherently faced, and posed, by public participation, such as power dynamics and exclusion of potentially interested groups could be then incorporated in democratic processes of engagement, collaborative learning, and co-design of desirable solutions (Fritz et al., 2024; Shackleton et al., 2023).

This underlines the need for engaging with the widest possible range of socially, culturally and economically diverse communities, recognising and accounting for these human dimensions of SRM way beyond the traditionally considered, environmental, and technical implications of such projects (Nicholson et al., 2017). Such a change in approach will require decision-makers and project proponents to shift their attitude towards public participation, away from simple communication of decisions to the public towards active involvement and collaborations, acknowledging that this shift will come with certain promises to the public (IAP2, n.d.).

Moving beyond tokenistic consultations and beyond the traditional focus on technical and environmental aspects of SRM will enable a more adequate understanding and distribution of the related social and economic risks and benefits, such as disruption of local livelihoods, and cultural and ethical disruptions. In practice, however, there is a lack of application of comprehensive assessments to ensure that SRM projects align with local values, respect cultural diversity, and contribute to sustainable development goals (Macnaghten and Szerszynski, 2013; Reynolds, 2019). Neglecting these considerations may contribute to unintended consequences and exacerbate existing social and economic inequalities (Gupta et al., 2020), including failure of these projects to move beyond inception and research. A look at recent real-world case studies of regional SRM projects confirms how little most projects have advanced to research and development stages, arguably because of the failure of national governance systems to operationalise and meet the Oxford principles, and move beyond them.

### 3. Lessons from real-world projects: The importance of socially inclusive decision-making

#### 3.1. An overview of real-world solar radiation management projects

Definitions of what may or may not constitute a ‘softer’ form of geoengineering have the tendency to be tweaked and extended, not

surprisingly to include favoured approaches or exclude those deemed to be potentially problematic (e.g.: Del Bello, 2018; Olson, 2012; Riederer, 2023). Befitting our focus on regional-scale activities and technologies already being trialled, we consider ongoing and recently concluded or halted SRM applications at the regional scale, examining the following options: marine cloud brightening (MCB); and ice-protection efforts for surface albedo modification (see Table 3).

Marine cloud brightening (MCB) entails the atomisation to small droplets of seawater, the salt constituent of which, when dispersed into the atmosphere, can theoretically increase the reflectivity of clouds under certain atmospheric conditions (Latham et al., 2012; Russell et al., 2013). MCB has been prominent in discussions of solar geoengineering from early on, though there have been limited efforts in the way of field trials (Low et al., 2022). An example of analogous activity, though different from MCB because of its oil-based instead of salt-based particles, is the Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE), a project taking place off the coast of southern California and led by researchers at University of California, San Diego. This project was oriented towards improving understanding of cloud-aerosol interactions and atmospheric science, by seeding low lying marine clouds using oil particles from a smoke generator (Modini et al., 2015; Sanchez et al., 2016). One subsequent and ongoing effort, more closely aligned with seawater MCB, the ‘Marine Cloud Brightening Project’ based at the University of Washington, is more explicitly framed in terms of geoengineering (Wood et al., n.d.; Wood et al., 2017).

So far, research on this project has consisted of laboratory experiments, modelling and simulation-focused research and the project is not known to have undertaken any outdoor field experimentation. Nonetheless, the intensifying impacts of the climate crisis have paved the way for mooted the prospective use of MCB in the Arctic (Anthony, 2022), along with attempts to outline possible governance strategies (Diamond et al., 2022).

Considering real-world regional SRM experiences, confronting the interlocking crises of climate change and coral bleaching on the Great Barrier Reef, researchers under the auspices of the Reef Restoration and Adaptation Program in Australia have undertaken the first in-field trials of MCB (Sovacool et al., 2023c). In Australia, regional application of MCB is being explored as a means to intervene during marine heatwaves to reduce coral bleaching (Harrison, 2024). The proposed intermittent, months-long duration deployment of MCB directly over a target ecosystem for conservation purposes is novel, with potential risks and benefits markedly different to previously proposals to use the technology at planetary climate altering scales. Hydrodynamic modelling has

**Table 3**  
Ongoing and recently concluded or halted applications of Marine Cloud Brightening or Surface Albedo Modification at a regional scale.

SRM project	Type of intervention	Geographical location	State of the project
Australian Reef Restoration and Adaptation Program (RRAP)	Marine Cloud Brightening (among others)	Great Barrier Reef, Australia	Ongoing
Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE)	Cloud-aerosol interactions (oil-based aerosols)	California, USA	Concluded
Marine Cloud Brightening Project	Marine Cloud Brightening	California, USA	In progress
Ice 911	Surface Albedo Modification	Minnesota and Alaska, USA	Concluded
Arctic Ice Project	Surface Albedo Modification	Norway and laboratory studies	In progress (Norway); Ongoing (laboratory)
Bright Ice Initiative	Surface Albedo Modification	Greenland and Himalayas	In preparation

indicated that MCB applied regionally over the marine park for several summer months could lower sea surface temperatures within the Great Barrier Reef lagoon sufficiently to significantly reduce the severity and extent of coral bleaching (Harrison, 2024). Ecosystem modelling has gone on to suggest that ongoing deployment of such an intervention could improve the trajectory of the coral reef ecosystem into the future, delaying the decline of the reef under a high emissions scenario or even preventing the decline under a low emissions scenario (Condie et al., 2021). This project in Australia has been conducting field testing of MCB technologies in the Great Barrier Reef Marine Park since 2020 (Harrison, 2024).

The other regional-level form of SRM corresponds to a pair of ice-protection efforts. These activities, applying “small hollow glass microspheres” to increase the reflective properties of ice and thereby work to slow down the loss of sea and/or glacier ice, are being undertaken by the Arctic Ice Project (Arctic Ice Project, n.d.) and the Bright Ice Initiative (Bright Ice Initiative, 2023a, 2023b). Some of the stated benefits of this approach are that microspheres, of the kind produced “by the trillions” by 3 M (where some of the senior scientists were first employed), are both inexpensive and their scaling-up manufacturing should be less of a problem (Riederer, 2023). Both initiatives have their origins in the Ice911 project, which conducted a series of small experiments on a private frozen pond in Minnesota starting in 2012, and then in 2017 an Arctic field trial on a pond in Utqiagvik, Alaska. Here, the first experiments indicated the potential ice-protection capabilities of the microspheres, the later experiment proved to be inconclusive after foxes chewed through the wiring of instrumentation (Riederer, 2023). Following on these activities, members of the working group diverged over whether to continue to focus on Arctic Sea ice (Arctic Ice Project) or instead shift towards glaciers (Bright Ice Initiative). To date, the Arctic Ice Project is holding off on active field trials (planned for Norway) while laboratory studies continue. The Bright Ice Initiative, meanwhile, is actively seeking permissions to test on the Greenland ice sheet and the Chhota Shigri Glacier, in the western Himalayas (Bright Ice Initiative, 2023a, 2023b) – possibly as early as summer 2024, though no information has been publicly released (Riederer, 2023).

### 3.2. A closer look: community engagement in the Australian Reef Restoration and Adaptation Program

The Australian Reef Restoration and Adaptation Program (RRAP) is unique as an example of regional attempts to assist ecosystems adapt to climate change, in that current research is focused on (McLeod et al., 2022):

- transdisciplinary research and development on coral reefs;
- interventions to enhance coral performance under climate change; and
- research into socio-cultural perspectives on reef restoration and assisted adaptation.

Socio-cultural perspectives and opportunities for collaboration with Reef communities are being explored by a dedicated RRAP research subprogram focused on Stakeholder and Traditional Owner Engagement, which brings together social scientists from academia and government research organizations (RRAP, n.d.). This is being achieved through a range of activities that include (RRAP, n.d.):

- national surveys of public perceptions;
- direct engagement with reef community members through one-on-one interviews;
- analysis of social risks and benefits;
- the establishment of community panels;
- the establishment of collaborative monitoring;
- the exploration of future partnerships; and

- an assessment framework for biocultural risks together with First Nation peoples;
- and a stakeholder advisory group; with
- and a dedicated monitoring, evaluation, and learning strategy to self-reflect on potential areas for improvement in future engagement with reef communities.

To address some of the engagement challenges for SRM outlined above, one approach trialled by RRAP researchers was to set up geographically-based community panels. Drawing on the participatory technology assessment panel model (Ely et al., 2011; Joss and Bellucci, 2002), panels created a space for community members to engage in a long-term and deep discussion with RRAP scientists about proposed novel reef interventions including SRM (e.g. marine cloud brightening) along with other technologies (e.g. enhancing coral resistance to warmer waters). The panels’ goal was to draw on diverse community perspectives and aspirations for the Reef and its management, so to inform and better position RRAP to respond to potential environmental, social, and technological challenges (Bohensky et al., 2021).

The first of these panels, the Townsville Community Panel on Novel Reef Interventions for the Great Barrier Reef, brought together 13 community members from the region. Over the course of a year, members engaged with scientists leading the focal interventions in interactive discussions across five one-day facilitated workshops and research site visits. The panel discussed a range of potential ecological, social, cultural, economic, and logistical risks or uncertainties associated with MCB such as changes in rainfall patterns, noise pollution, difficulty optimising and scaling up interventions, negative public perception, and ability to secure long-term funding commitment. Panel discussions identified strategies for mitigating risks, considering checkpoints for guiding decisions to proceed with research and development activities and potential deployment, and the associated range of stakeholders who could bring to the table local knowledge to increase understanding of risks as well as MCB’s potential benefits or opportunities.

As a pilot, the Townsville panel was designed to test and guide design principles for future structured engagements. The project team’s evaluation of the process indicated an increase in participants’ awareness and understanding of the technical aspects of interventions, the challenges and the uncertainties involved in research and development, and the ways in which intervention scientists work. In addition, the experience enhanced relationships between panel members and intervention scientists, with the latter gaining a better understanding of community members’ personal connections to, and aspirations for, the Reef, and motivations for seeking greater engagement in dialogues with scientists. Significantly, there was some ambiguity about the formal pathways by which the insights generated through the panel dialogue could influence research and development decisions. While partly a reflection of the early timing of the Townsville panel, the experience highlights the potential utility of an overarching framework to situate the community panel as one of a suite of engagement efforts to support the program’s broader goals.

The case of RRAP is indicative of good practice engagement with interested stakeholders and communities in SRM projects. However, these practices are an exception among the international SRM interventions discussed in this section. This could be due to several reasons (see Sovacool et al., 2023c):

- For example, Australia is a country that has embarked on national initiatives to reconcile its society with First Nation peoples (see the Closing the Gap national policy), for whom the Great Barrier Reef has immense livelihood and spiritual importance. While the livelihood and spiritual significance of natural resources are often emphasized, this can sometimes underplay the crucial importance of rights. The Reef 2050 Traditional Owner Implementation Plan, for example, illustrates the rising prominence of co-management strategies. It highlights how traditional owners are increasingly recognised as key

partners in the management and protection of the Great Barrier Reef, ensuring their rights are upheld alongside the ecological and cultural values of the region.

- Beyond its cultural and ecological value, the Reef is also contributing to Australian local and national economy with about \$6.4 billion a year (Great Barrier Reef Marine Park Authority, n.d.). While this can be a contributing reason as to why government project proponents of RRAP recognised the importance of engaging with reef communities to shape sustainable, feasible and accepted interventions, the main difference with other SRM projects is that such commitment did translate into actual efforts.

The proliferation of SRM projects in recent years and the foreseeable future, coupled with the cautionary tale of the many failed projects discussed above, warrant against the reliance on good-willed government and non-government private SRM proponents. When navigating the complexity of regulations linked to SRM interventions, RRAP offers interesting insights on the governance and regulations. Marine Cloud Brightening (MCB) trials in the Great Barrier Reef are currently being conducted under a research permit. In this way, small scale trials for research and development purposes can be undertaken, the learnings of which can then be integrated into the next phase of research trials. However, as the impacts of climate change worsen, and with bleaching predicted to become more common in the GBR, operationalising regional scale MCB on the Reef is being investigated further. Current research in RRAP is therefore exploring paths for how MCB could be regulated after the current 'research and development' phase is completed. This is a major challenge faced by SRM projects around the world due to the lack of real-world practice and of dedicated/suitable governance. In the case of RRAP, researchers have explored since the inception phase of this program how engagement with regulators can progress in time, facing the challenges posed by larger-scale deployment (Fidelman, 2019).

Among the challenges faced by international SRM projects targeting ecosystems protected by specific regulations is the need to consider how these regulations allow for interventions that may negatively impact ecologically valuable areas. However, it is quite rare that existing regulations have been designed in the context of novel technologies, and as such may not incorporate risk assessment that is suited to the unique uncertainty and risks posed by these interventions (Linkov et al., 2018). Research and close collaboration with regulators is therefore essential for projects based on novel interventions such as MCB, to prevent scenarios in which misalignment between regulations and proposed interventions result in the failure to implement the latter in real-world settings. This has historically been a challenge with non-conventional interventions, including more traditional restoration activities (e.g. Blue Carbon methodology) (Bell-James, 2022). Regulatory collaboration can help ensure that project goals are supported by policy, particularly when novel or conventional interventions benefit from public investment/funding.

On an international scale, the disconnect between policy and implementation has limited the effectiveness of many interventions aimed at ecosystem restoration and adaptation, which have often been implemented at reduced scales and therefore fallen short in achieving larger conservation objectives (Bell-James et al., 2023; Shumway et al., 2021). In the case of MCB in Australia, it is worth noting that RRAP was designed as a research and development program to develop and test novel interventions to be deployed in the future as part of a wider government-led effort to assist the GBR ecosystem, and not as a stand-alone development to implementation initiative. Considering the wide range of policy, social, cultural, economic, and environmental implications that characterize regional SRM interventions since their research and development phases, a strategic approach involving government and non-government regulators, stakeholders and the public emerges as necessary to provide for a more systematic way to identify project objectives, and ensure activities are considered more effectively in the

policy process as interventions transition to deployment. SEA as a policy framework can enable SRM project proponents and regulators to frame interventions with an eye to existing regulatory frameworks, ensuring that thorough assessment of risks and impacts associated with SRM are recognised while complying with legislation and regulations.

#### 4. Strategic environmental assessments as policy frameworks for inclusive and fair decision-making

##### 4.1. SEA: process, approaches, and framework

The term SEA first emerged in the late 1980s (Fischer, 1999). Initially, it was approached with regards to the application of a project EIA approach with a main focus being on the assessment of negative impacts of draft strategic initiatives. This approach revolves around a process which includes stages such as screening (deciding on whether an SEA is necessary), scoping (establishing what aspects, impacts and options should be included in assessment), analysis and evaluation of impacts and the drafting of an SEA report, consultation with statutory and non-statutory bodies and public participation (ideally during scoping and after a draft SEA report has been prepared), decision making (and in this context, taking the results of the SEA into account), monitoring and follow-up. However, as numerous studies have shown (see Fischer, 2004; Noble and Nwanekezie, 2017) the more strategic a particular action is, the less applicable EIA-based approaches tend to be (Partidário, 2021).

For example, a development vision for a country or region (which might lead to associated policy) will probably not follow a strict and structured administrative procedure, as its preparation is likely to be based on a discursive approach. Also, due to associated levels of uncertainty, impacts of different possible options will likely be dealt with in a qualitative way. Furthermore, in situations where those participating are genuinely open to different solutions to a problem (i.e. in the absence of any strong vested interests, which might well be the case with regards to SRM), round table approaches might be suitably applied (Fischer et al., 2010; González et al., 2019). Taking account of the various differences in the application of SEA, a range of approaches have been identified that are connected with particular situations of applications, as follows (following Fischer and González, 2021, p6):

1. SEA for supporting the development of (environmentally sustainable) visions for e.g. global, country wide, regional or local initiatives (representing the 'strategic approach' to SEA; see above).
2. SEA for supporting the drafting of policy (see e.g. OECD, 2020, or in the EU, territorial impact assessment; Fischer et al., 2015).
3. SEA for supporting the preparation of plans and programs with an EIA based process (Rehhausen et al., 2021).
4. SEA for supporting the creation of consensus of future action in situations where there is openness towards outcomes and acting strategies (see e.g. Arbter, 2005).
5. SEA for supporting answers to particular methodological questions that can be connected with particular assessment techniques, e.g. geographic information system-driven when identifying suitable development locations, or matrix-driven when pursuing an objectives-led approach to SEA (Hayes and Fischer, 2021).

Importantly, SEA is now frequently approached as a 'framework' (rather than just a process applied to an isolated vision, policy, plan or program; initially discussed by e.g. Fischer, 1999; Gosling, 1999; Jansson, 2000). A key element of the framework approach is that questions to be asked and alternatives to be considered are associated with decision tiers (e.g. visions, policies, plans and programs that are tiered with project environmental impact assessment, as in Fig. 1). In this context, SEA is frequently used to support the attainment of sustainable development goals (Morrison-Saunders et al., 2019).

The development of SEA internationally has been influenced in

	SEA	'Higher tiers' / 'Lower tiers'		EIA
		Policy	→ Plan → Programme → Project	
Decision making level				
Nature of action	Strategic, visionary, conceptual			Immediate, operational
Output	General			Detailed
Scale of impacts	Macroscopic, cumulative, unclear			Microscopic, localised
Timescale	Long to medium term			Medium to short term
Key data sources	Sustainable development strategies, state of the environment reports, vision			Field work sample analysis
Type of data	More qualitative			More quantitative
Alternatives	Area wide, political, regulative, technological, fiscal, economic			Specific locations, design, construction, operation
Rigour of analysis	More uncertainty			More rigour
Assessment benchmarks	Sustainability benchmarks (criteria and objectives)			Legal restrictions and best practice
Role of practitioner	Mediator for negotiations			Advocator of values and norms Technician, using stakeholder values
Public perception	More vague, distant			More reactive (NIMBY)

Fig. 1. The changing focus of SEA from lower tiers (EIA project level) to higher tiers (SEA policy level) (Fischer, 2007).

particular by the European SEA Directive (EU, 2001; applied in the 27 EU members states and also countries that want to join the EU) and the UNECE (Kiev) protocol on SEA to the Espoo Convention (United Nations Economic Commission for Europe, 2003). Both have influenced the development of SEA not just in other countries, but also in e.g. development banks. However, associated requirements revolve around an assessment process, as described above and are therefore more routinely applied at the plan and program tiers, but not much when approaching policies. Development of the latter has been influenced in particular by political scientists working on policy analysis (see Adelle and Weiland, 2012).

4.2. SEA alignment with principles for geoengineering governance

In order to establish how SEA can provide a robust policy framework to assist regional geoengineering interventions, the abovementioned UNECE protocol and SEA performance criteria developed by the International Association for Impact Assessment (IAIA, 2002) provide useful guidance. Below, we reflect upon the conceptual alignments between these SEA features and those of geoengineering governance discussed

Table 4  
Conceptual alignments between Oxford Principles and SEA features (adapted from Reynolds, 2019).

The Oxford Principles	SEA features
1. Geoengineering to be regulated as a public good.	Consideration of environmental and health concerns across a range of dimensions.
2. Public participation in geoengineering decision-making.	Involvement of affected public and stakeholders in decision-making.
3. Disclosure of geoengineering research and open publication of results.	Establishing clear, transparent and effective procedures for SEA.
4. Independent assessment of impacts.	Accountability and need of independent checks and verification, and allocation of responsibilities.
5. Governance before deployment.	Integrating environmental and health concerns into measures and instruments designed to further sustainable development.

earlier in Section 2, illustrated in Table 4.

Public participation, a key requirement for geoengineering governance under Oxford Principle (OP) 2, is highlighted as a key aspect for SEA in the UNECE protocol (objective 4) and is considered essential for SEA to perform, involving affected public and stakeholders in decision-making by explicitly and actively addressing their inputs and concerns. SEA routinely engages stakeholders and potentially impacted communities through various mechanisms, defined in SEA policy and legislation, including public notifications and processes for allowing public submissions of relevant information and requests that legally need to be considered by government and vision/policy/plan/program proponents. However, weak regulations and legislation can affect political willingness by vision/policy/plan/program proponents to commit to meaningful public participation, limiting it to its essentials instead of striving for inclusive and constructive approaches (Rega and Baldizzone, 2015). While good practice for stakeholder and community engagement in regional SRM is increasingly called for (e.g. the RRAP community panels discussed in section 3), questions loom on their actual application in practice when loose legislation allows SRM to proceed with minimal public involvement.

The participative nature of SEA enables clarity and transparency in related decision-making (UNECE objective c), aligning with another key requirement of geoengineering governance (OP 3). Even when successfully and meaningfully achieved, though, public participation itself does not necessarily bring transparency in all aspects of a plan/program development and in the assessment of its impacts. There is a need, in geoengineering projects, of arrangements that clearly regulate these interventions to achieve the public good (OP 1). This is a key aspect of SEA, as it aims to contribute to sustainable development (UNECE objective e) through consideration of environmental and health concerns across a range of dimensions that include biodiversity, human health, fauna, flora, soil, water, air, climatic factors, cultural heritage, and the interrelationship between them (EU Directive 42/2001, Annex I). Thoroughly assessing the impacts of proposed interventions, and the associated environmental and social risks, is another priority shared in the core values of geoengineering governance and SEA. For example, the UNECE protocol (objective b) highlights the focus on environmental and

human health aspects. For decision-making around geoengineering to achieve and ensure public good and the well-being of impacted stakeholders and communities, impacts of proposed interventions need to be assessed independently (OP 4). Once again, SEA provides a valuable framework, having among its performance criteria a strong focus on accountability and the need of: independent checks and verification; clear definition of responsibilities; and documentation and justification of how sustainability issues are considered in related decision-making (IAIA, 2002). For geoengineering governance to benefit from these aspects of SEA, regulators and governments need to explore the application of SEA frameworks, as codified in existing policy and legislation, eventually considering changes in regulations to introduce suitable SEA policy where not already present.

**5. A tiered SEA model to assist the development of regional and local SRM interventions**

As shown above, principles of SEA and for geoengineering governance align closely. However, meaningful application of SEA to SRM intervention programs depends on several conditions. While SEA around the world follows – or, should follow – the IAIA performance criteria for best-practice, its features vary depending on specific situation of application, as well as on impact assessment traditions, institutional settings, decision-making processes, policy, and legislation. It is not our goal, in this paper, to discuss how different SEA legislation and policy can fit regional SRM interventions. A follow-up paper, in development, will address this question. Rather, on the next pages we reflect on how different SEA approaches (as introduced in the previous section; see Fischer and González, 2021) can contribute towards SRM interventions. Here, the Australian Reef Restoration and Adaptation Program (RRAP)

will be mentioned as an example of successful SRM interventions, to illustrate how a tiered SEA approach can benefit similar programs around the world. The purpose of this section is not to provide recommendations specific for RRAP, though, as it is characterized by several different proposed interventions that require specific considerations and do not belong to SRM, such as coral enhancement and ocean-floor rubble stabilization.

Section 2 and 3 reflected on the challenges posed by the management of complex, large-scale SRM programs. A key aspect to consider in planning these programs, and therefore in establishing mechanisms for timing public participation and stakeholder engagement, is that they are often articulated in distinct temporal and functional phases. Due to the uncertainty and complexity that surrounds the often-untested technology to be deployed through these regional and local SRM interventions, and due to the volatile political environments surrounding them, it is not uncommon for these programs to require several years of preparation. An initial phase of ‘inception and design’ can be followed by ‘research and development’, with in-lab and real-world testing of these interventions at limited scales. The RRAP is among the very few programs in the world that are on track to complete both these phases, as it is now looking at a third phase, scheduled for 2025, that will explore preliminary deployment at scale of some of its interventions. It is worth noting that the MCB intervention is on a longer research and development trajectory, and not likely to be ready for deployment within the next phase. The example of RRAP shows how a tiered SEA approach, as discussed in section 3, is suited to assist governments and private project proponents of similar programs.

A due premise, considering the lessons from failed real-world experiments with regional SRM, is that *it is never too early* to engage with potentially interested and affected communities and stakeholders, as

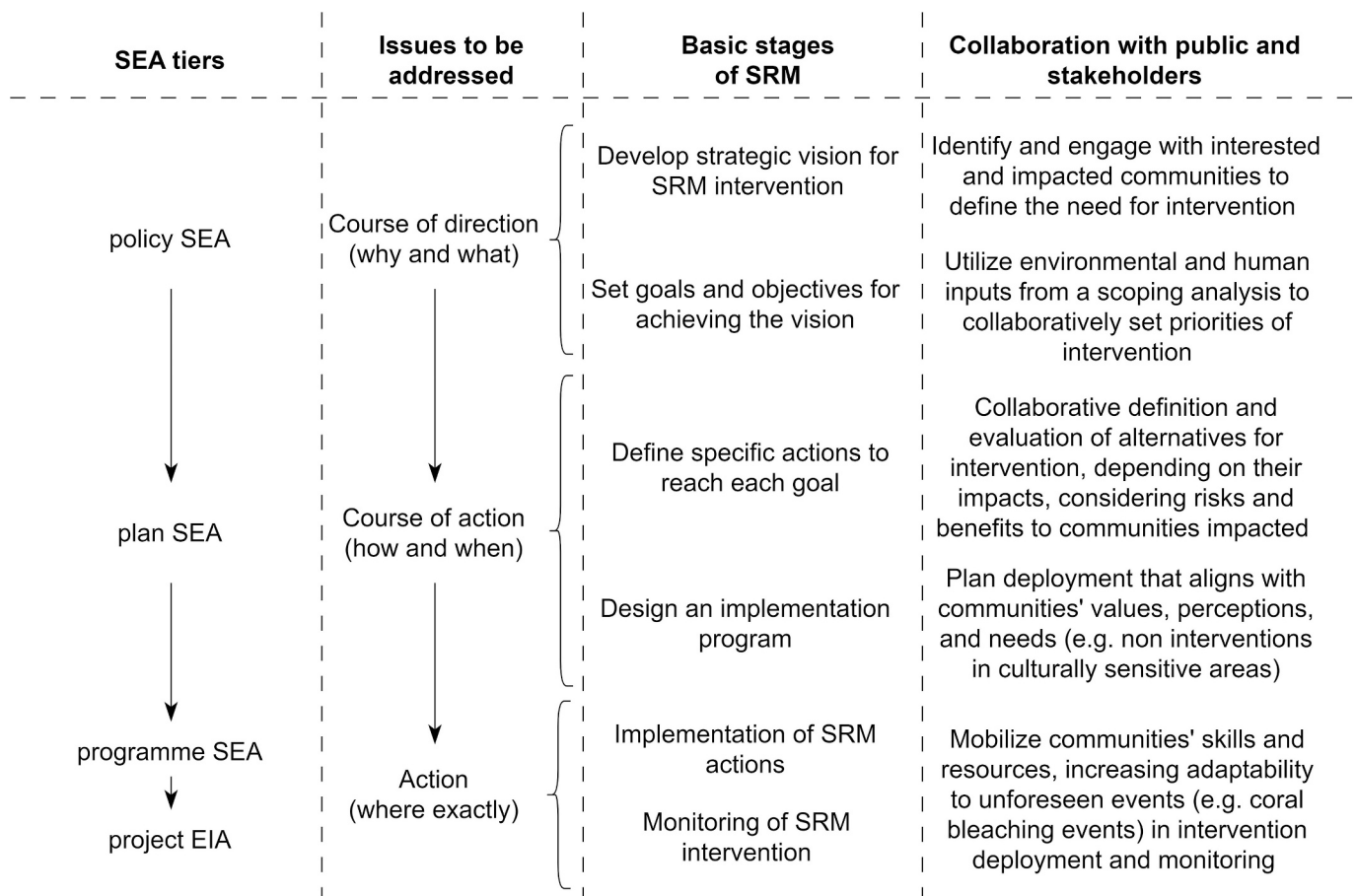


Fig. 2. A tiered model for SEA applicable to regional scale SRM interventions (adapted from Marshall & Fischer, 2006).

well as with the general public, thus accounting for the range of social risks highlighted by Lockie et al. (2024). Moving from this premise, in Fig. 2 we advance a tiered model for SEA applicable to regional scale SRM interventions, developed on the model for energy providers by Marshall and Fischer, 2006, p. 282).

Each type of SEA -Tier 1 (policy SEA), Tier 2 (plan SEA), and Tier 3 (program and project SEA)- has distinct implications and applications depending on the spatial scale at which SRM interventions are being considered. Policies (Tier 1 SEA) can provide governance frameworks adaptable to multiple spatial scales, influencing SRM strategies from a global to a regional context. Plans (Tier 2 SEA) often align with jurisdictional boundaries and are suited for regional-scale interventions, considering regional socio-ecological and governance dynamics. In contrast, programs and projects (Tier 3 SEA) are localized and directly address site-specific interventions where environmental impacts are most tangible. The relevance of different SEA types is particularly evident when considering spatial scale in SRM interventions. Regional applications, such as those targeting specific climatic zones, benefit from plan SEAs (Tier 2) that incorporate a structured evaluation of regional socio-ecological systems and governance frameworks. Localized interventions require program and project SEAs (Tier 3), focusing on precise risk assessments and management strategies tailored to the specific environmental and social dynamics of the location. By incorporating spatial considerations into SEA processes, governance frameworks for SRM can be more flexible and adaptive. This approach allows for the alignment of policy objectives with regional and local environmental and social conditions, ensuring that governance mechanisms are responsive to the unique challenges posed by SRM interventions at various scales. Each tier is detailed below.

### 5.1. Tier 1. Course of direction – from policy SEA

**Goal:** Co-develop a vision of regional SRM interventions that is shared by project proponents and potentially impacted communities

**Leading question:** Why is SRM intervention needed?

With public participation in mind, the most strategic aspect of SEA lies in the definition of the direction, or vision, that should guide every SRM intervention at the regional scale. Whether the proponent is a government, or a private entity, stakeholders' and public voices need to be heard before the intervention itself takes shape. This early step allows for stakeholders' and communities' vulnerabilities and perceptions to be recognised and actively considered in framing and assessing the potential problems that regional-scale SRM poses. SEA practice shows that, for example, government and non-government stakeholders can provide key inputs that influence the development of land use plans. This can be done at different levels of engagement, which can assume the features of mutual exchange of information and expectations (e.g. public feedback on project proponents' notifications to the public about initial intentions for SRM interventions). More collaborative approaches can also be adopted, acknowledging that prioritizing collaboration with specific community groups at the expense of openness to the general public may be a source of distrust and suspicion.

Collaboration through roundtables, seminars, workshops, or focus groups open to the public and/or publicly broadcasted is encouraged to enhance the quality of community engagement and increase community's sense of ownership of these interventions. These may be informed or complemented by survey research to map broader public perceptions and potential program risks (e.g. Taylor et al., 2019a, 2019b). The widest the public involvement in this process, the more likely it is to assume that the SRM project proponents will learn directly from the potentially impacted communities about social vulnerabilities and perceptions otherwise doomed to remain unknown to decision-makers, and consequently neglected. Though challenging, this early step of the process would allow for the early recognition of the governance, social, ontological, and epistemic challenges posed by regional SRM, paving the way to a shared vision around the 'why' and 'what' of potential

interventions.

**Goal:** Setting of goals and objectives to achieve the shared vision for SRM intervention.

**Leading question:** What will SRM need to achieve?

Building on a shared vision, sets of goals and objectives can be articulated, in order to define what the SRM intervention will specifically aim to achieve. When done collaboratively between a proponent and interested or potentially affected parties, this will produce shared understanding and subsequent joint up action that may increase a sense of ownership in the public and ensure intervention is undertaken with the necessary 'social license' to operate. Taking (again) the Australian RRAP as an example, due to its advancements over the past 5 years, it is worth noting that an initial 'concept feasibility' phase of the program, conducted in 2018–2020, produced foundational knowledge on feelings and opinions of communities living and operating in the Great Barrier Reef region.

While surveys and interviews highlighted widely-held views that intervening on the reef was necessary (due to coral bleaching events that have and still are threatening the very own survival of the reef ecosystem), they also detected general uncertainty around the types of interventions to be used in the RRAP (Taylor et al., 2019a, 2019b). Understandably, this uncertainty likely fuelled concerns associated with ecological and socio-economic risks of RRAP interventions. This early, though necessarily limited, engagement of regional communities, allowed RRAP to map the types of interventions that could be investigated further, accounting for communities' perceptions of them (e.g. acceptance of Marine Cloud Brightening on the reef). This step set the foundation for the second phase of RRAP, which began in 2021, focusing research and development on viable interventions. It is worth noting that this is where most of the SRM projects illustrated in section 3 have fallen short, namely by not adequately considering communities' sentiments and perceptions around potential problems – and therefore not coalescing efforts around socially accepted potential interventions.

### 5.2. Tier 2. Course of action – from plan SEA

**Goal:** Collaboratively plan the specific actions that are required to achieve the goals, and that account for the foreseeable risks and benefits for all parties involved.

**Leading question:** What needs to be done to shape the regional-scale SRM intervention and implement it in real-world settings?

When a course of *direction* has been set through the definition of goals and objectives, an SEA-assisted tiered framework would suggest defining the course of *action* through the identification/planning of specific actions to reach each goal. It is at this stage that the example of RRAP, though valid, reaches its limitations due to it being still at a stage of research and development of viable interventions.

Essential inputs coming from regional stakeholders and communities are helping RRAP by updating and improving the consideration of technical as well as social risks, contributing to an innovative risk assessment framework that incorporates the novel approach to social risk presented in Lockie et al. (2024). The detection and management of risks posed by interventions in the real world are key to plan specific actions. An important question is, for example, which among different potential interventions is best-suited to a certain geographical area with specific weather patterns, ecosystems, and social-cultural values. Ongoing RRAP activities, such as the panels presented in section 3, serve as a good-practice example of how communities can be engaged to collaboratively analyse the social, cultural, and economic risks and benefits associated with design interventions in specific contexts, and to provide input into aspects of the intervention design and deployment, some of which the scientists took into consideration. This definition of 'how' and 'when' to intervene in real-world settings implies not only planning specific actions, but also designing their implementation.

This stage of an SRM development and deployment process is among the ones that can benefit the most from SEA, this being the stage in

which alternatives of interventions are defined and articulated and expressed in implementable steps. Evaluation criteria to assess these alternatives, which should align and build on the risk framework preliminarily defined with inputs from interested and affected communities, as is the case of RRAP, need to be put in place at this stage of the process so as to provide the accountability and transparency embedded in SEA. Environmental, technical, social, cultural, and economic considerations need to be equally addressed to provide a thorough analysis and evaluation of impacts, in the spirit of SEA principles (IAIA, 2002) such as (1) integration (addressing the interrelationships of biophysical, social, and economic aspects) and (2) focus (providing meaningful information for planning and decision-making).

This part of a tiered SEA approach comes closest to current European Union SEA requirements, which is designed for plans and programs. It is worth noting that the consideration of potential SRM impacts could build on a thorough risk framework that includes the 12 dimensions of sustainable development detailed in the EU directive on SEA n.42/2001, Annex I: biodiversity, population, human health, fauna, flora, soil, water, air, climatic factors, material assets, cultural heritage including architectural and archaeological heritage, landscape and the interrelationship between the these factors.

The accurate estimation of SRM impacts is essential to provide reliable information to be processed collaboratively by decision-makers and the interested parties to evaluate alternative scenarios and co-designing solutions that are equally technically feasible and aligned with the needs of stakeholders and communities. This development of alternative scenarios of intervention, another key aspect of SEA, enables conversations, and where needed negotiations, to map different benefit and risk distributions characterizing each scenario. In the case of SRM, characterized by intrinsic complexity and a certain degree of uncertainty around potentially desirable but also unforeseen outcomes, mapping risk and benefits and their distribution can become an insurmountable obstacle for SRM continuation, if done poorly.

### 5.3. Tier 3. Action – from Program SEA and project EIA

*Goal: Implementation of SRM through partnerships and joint initiatives between project proponents and interested community groups.*

*Leading question: how can interested communities of livelihood stakeholders, governments, First Nation peoples and other community groups contribute to the implementation of SRM interventions, and to the monitoring of its impacts on human and environmental systems?*

As of today, SRM projects that have succeeded reaching the implementation stage of proposed interventions are quite rare. Due to smaller scales and the use of technology that resembles natural occurring phenomena, surface albedo modification at the local scale is the exception. When the scale of interventions moves beyond the well-defined boundaries represented, for example, by individual buildings or blocks, the increased uncertainty around these interventions inevitably triggers exponentially more impactful environmental, social, cultural and economic risks.

For SEA to assist, the criteria set for evaluation of proposed interventions in previous stages need to be considered when collecting and analysing data on SRM deployment. The data collection process is inherently connected to the last key aspect to consider when shaping SRM interventions: the monitoring of how these interventions keep impacting natural and human-made environments after interventions have happened. For example, will weather patterns be affected by certain types of Marine Cloud Brightening? Or, will differences be observed between long-term impacts of in-lab/small scale testing of surface albedo modification and real-world large-scale deployment? The case of RRAP suggests that rather than this being a last point to consider at the end of SRM interventions, this can rather be a starting point.

The more thorough the in-lab or small-scale testing will be, the less likely it is that unforeseen outcomes will present themselves when scaling up deployment at the regional scale. Once again, the Australian

RRAP may serve as an example for how to engage with stakeholders and community groups to enable them to contribute to SRM interventions. SRM interventions, such as MCB in RRAP, need to combine communities' input while building on solid science and technical expertise provided by researchers and experts involved in designing monitoring processes. To this end, the previously mentioned RRAP Collaborative Monitoring Project is being developed with members of the GBR community to collaboratively define best practices for monitoring how RRAP interventions will impact the marine ecosystem (e.g. coral reproduction, fish presence), whose survival is essential to stakeholders and communities depending on the GBR for their livelihood (e.g. tourism, fisheries, First Nation peoples). The difficulties in designing a specific monitoring program for a potential fogging event (MCB) highlighted how community is best involved when building, and providing constructive feedback, on technical aspects that need to be designed by the actual research groups that have access to data (e.g. sample sizes) that is critical to make informed monitoring decisions. This includes the efficacy of community-based monitoring programs to achieve the power and reliability to detect change in the features they are measuring.

The range of collaborations between project proponents and interested community groups can assume different features. For example, partnerships for scaling up interventions can bring additional skills and funding to enable wider and potentially more successful interventions. In the case of RRAP, researchers have been working (2021-ongoing) on establishing connections across Australian government, industry and community groups to investigate the potential for partnering on deployment of interventions at the regional scale, beyond the initial local-scale testing. These collaborations for implementation can assume different features to cover a wide array of much-needed support for regional scale SRM, such as material support by providing sea vessels (i. e. boats) to carry necessary MCB equipment. The value of the Great Barrier Reef for First Nation peoples warranted, since RRAP inception, the need to involve them in all aspects of the program, from the setting of its goals through to their involvement in its implementation (Taylor et al., 2019a, 2019b). Acknowledging the need to extend benefits to local communities, RRAP is setting itself as an example of good-practice in empowering a wide range of community groups and stakeholders by planning for a potential shift from a research-based program towards the constitution of a proper 'reef industry'.

### 5.4. Considering Physical, Socio-Ecological, Jurisdictional, and Technical Boundaries in tiered SEA for regional SRM

The concept of boundaries plays a crucial role in assessing the impacts of SRM interventions at different scales. These boundaries—physical, socio-ecological, jurisdictional, and technical—each interact with the distinct tiers of SEA, which are applied to policies, plans, and programs in regional SRM. We build on the contemporary summary by Morrison-Saunders (2023) to develop an understanding of how these boundaries affect SEA tiers, which allows for a more comprehensive and structured approach to evaluating SRM interventions.

**Physical Bounds:** At the project level (Tier 3), physical boundaries are defined by the geographic area directly affected by SRM activities. For instance, an intervention such as Marine Cloud Brightening (MCB) in the Great Barrier Reef (GBR) will focus on the marine environment, with direct effects on local ecosystems. At the planning level (Tier 2), physical bounds expand to consider how the intervention may affect interconnected areas, such as nearby marine ecosystems and atmospheric conditions beyond the immediate region. At the policy level (Tier 1), physical bounds are addressed more broadly, considering how the SRM intervention fits into the regional or national environmental strategy.

**Socio-Ecological Bounds:** Socio-ecological boundaries extend beyond the immediate physical effects of an SRM intervention. In Tier 3 SEA, socio-ecological bounds assess how local communities, economies, and ecosystems might be directly impacted by SRM technologies. For

example, the MCB trials in the GBR must consider the potential effects on local fisheries and tourism, as well as broader regional ecological dynamics. At Tier 2, socio-ecological bounds include broader impacts on interconnected ecosystems and social structures. For example, changes in local weather patterns might affect agricultural practices or livelihoods in surrounding areas. At Tier 1, socio-ecological bounds encompass national or international considerations, ensuring that the SRM intervention aligns with broader social and environmental sustainability goals.

**Jurisdictional Bounds:** Governance is a key factor in regional SRM, particularly in Tier 2 and Tier 1 SEAs. For example, at the project level (Tier 3), jurisdictional bounds are generally limited to the area under the control of specific local or regional authorities. For larger-scale regional interventions (Tier 2), multiple jurisdictions might need to collaborate, as SRM effects may cross regional or even national boundaries. At the policy level (Tier 1), jurisdictional considerations focus on ensuring that governance frameworks are aligned across regions and potentially with international standards, as seen in the complexities of governing the GBR, which involve multiple stakeholders and levels of government.

**Technical Bounds:** In Tier 3 SEAs, technical limitations are critical as interventions are trialled at smaller scales, where the risks and uncertainties are more manageable. In Tier 2, technical bounds are broadened to address uncertainties in scaling up interventions and potential unintended consequences. For example, the scalability of MCB is still under investigation, and the broader technical challenges of implementing SRM on a regional scale are still being assessed. At Tier 1, technical bounds guide long-term planning, ensuring that SRM policies are flexible and adaptive to evolving scientific knowledge and technological advancements.

Incorporating these boundary considerations into SEA will ensure that SRM interventions are comprehensively evaluated across all levels, from local projects to regional and national policies, allowing for a more adaptive and responsive governance structure that aligns with best governance for SRM, as well as with the specific features of SEA, discussed throughout this paper.

## 6. Conclusion and future directions

Regional application of Solar Radiation Management (SRM), in the form of Marine Cloud Brightening or Albedo Surface Modification for ice surfaces, comes with a range of challenges and risks. Literature and real-world applications of SRM at the regional scale outline how their potential impacts on environmental and human systems require engaging the public in decisions around the reasons, the ways, and the impacts associated with these interventions.

For instance, when interested and affected communities are not properly engaged, project proponents of SRM interventions lose opportunities to acquire consensus, accurately estimate risks and benefits associated with interventions, and support with deployment of interventions. The presence and consideration of suitable policy to support organization and public engagement within SRM interventions may provide frameworks to assist project proponents and prevent the complications faced by several real-world case studies discussed in this paper. In light of this, Strategic Environmental Assessment (SEA) emerges as a policy framework used internationally to assess environmental (and often social, as well as health) impacts of visions, policies, plans, and programs, and presents key features that align with 'good' geoenvironmental governance.

The adoption of a tiered SEA framework to regional-scale SRM interventions provides a potential approach for scientists, decision makers, stakeholders, rightsholders and communities to work through risk assessment and management options in a structured way and articulate decision-making through collaboration across the range of potentially impacted and interested communities. This aligns with practice emerging from the Australian Reef Restoration and Adaptation Program, a program that operates within the Great Barrier Reef Marine

Park and its longstanding and comprehensive regulatory framework that embeds a flexible risk-based approach to the approval processes for interventions like MCB. While this paper does not provide practical applicable guidelines for tackling regional SRM interventions, it presents an original reflection absent in the published literature on how an internationally used policy framework (Strategic Environmental Assessment - SEA) can assist decision-makers assessing environmental and human impacts of regional SRM interventions.

Future application of SEA frameworks to the development of regional SRM interventions has the potential to provide a policy tool that will assist project proponents (e.g. governments, privates, scientists), and regulators, as well as enable the public to actively contribute to shaping SRM interventions that are feasible, sustainable, and equitable. Follow-up papers, currently in preparation, will present how different institutional and SEA frameworks can practically be applied to the development and implementation of regional SRM interventions.

## Author statement

The authors declare that, to the best of their knowledge, this manuscript presents original research that is not being considered for publication by other journals.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Umberto Baresi reports financial support was provided by Great Barrier Reef Foundation. Umberto Baresi reports financial support was provided by Queensland University of Technology. Stewart Lockie reports financial support was provided by Great Barrier Reef Foundation. Annah Piggott-McKellar reports financial support was provided by Great Barrier Reef Foundation. Victoria Graham reports financial support was provided by Great Barrier Reef Foundation. Erin Bohensky reports financial support was provided by Great Barrier Reef Foundation. Nicole Shumway reports financial support was provided by Great Barrier Reef Foundation. Daniel Harrison reports financial support was provided by Great Barrier Reef Foundation. Rose Foster reports financial support was provided by Great Barrier Reef Foundation. Karen Vella reports financial support was provided by Great Barrier Reef Foundation. Zoran Ristovski reports financial support was provided by Great Barrier Reef Foundation. Chad Baum reports financial support was provided by European Union. Livia Fritz reports financial support was provided by European Union. Benjamin Sovacool reports financial support was provided by European Union. Some of the authors are working full-time or part-time in the Great Barrier Reef Reef Restoration and Adaptation Program', which is mentioned in the paper. These authors are based at universities and research centres that do not refer or report to the Great Barrier Reef Foundation, which is the entity that is funding the 'Reef Restoration and Adaptation Program'. These authors are: Baresi, U., Lockie, S., Piggott-McKellar, A., Graham, V., Bohensky, E., Shumway, N., Harrison, D.P., Foster, R., Vella, K., and Ristovski, Z. If there are other authors, they 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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## Data availability

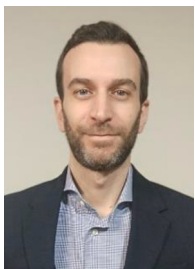
No data was used for the research described in the article.

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