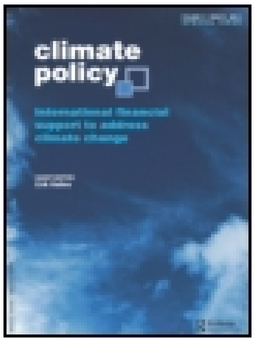

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OUTLOOK ARTICLE

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Governing geoengineering research for the Great Barrier Reef

Jan McDonald [a], Jeffrey McGee [b], Kerryn Brent [a] and Wil Burns[c]

[a]School of Law and Centre for Marine Socioecology, University of Tasmania, Hobart, Tasmania, Australia; [b]School of Law, Institute for Marine and Antarctic Studies and Centre for Marine Socioecology, University of Tasmania, Hobart, Tasmania, Australia; [c]School of International Services at American University, Washington, DC, USA

ABSTRACT
Coral reefs are highly vulnerable to the impacts of rising marine temperatures and marine heatwaves. Mitigating dangerous climate change is essential and urgent, but many reef systems are already suffering on current levels of warming. Geoengineering options are worth exploring to protect the Great Barrier Reef (GBR) from extreme warming conditions, but we contend that they require strong governance and public consultation from the outset. Australian governments are currently funding feasibility testing of three geoengineering proposals for the GBR. Each proposal involves manipulating ocean or atmospheric conditions to lower water temperatures and thereby reduce the threat of mass coral bleaching events. Innovative strategies to protect the GBR and field testing of these is essential, but current laws do not guarantee robust governance for field testing of these technologies. Nor do they provide the foundation for a more coherent national policy on climate intervention technologies more generally. Responsible governance frameworks, including detailed risk assessment and early public consultation, are necessary for geoengineering research to build legitimacy and promote scientific progress.

Key policy insights

- Marine heatwaves pose a serious threat to coral reefs, including Australia's iconic Great Barrier Reef.
- Australian governments have recognized the threats of warming waters, and are funding research of geoengineering options for the Great Barrier Reef.
- The limited earlier field testing of geoengineering demonstrates the need for specific governance to manage risks, build legitimacy and maintain public support.
- Australia requires a framework to govern geoengineering research and development before deployment of such technologies.

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Introduction

There is clear evidence that coral reef health is declining worldwide due to current levels of ocean warming and acidification (Anthony et al., 2011; Hughes, Kerry, et al., 2017; Hughes, Barnes, et al., 2017; NASEM, 2018). Stabilizing global temperatures by achieving net zero CO_2 emissions is therefore the highest long-term priority for protecting these sensitive ecosystems from the impacts of climate change (Hughes, Kerry, et al., 2017). However, with dramatic bleaching events occurring even on current levels of warming, restoring reef systems, enhancing their resilience, and expanding available adaptation options are now essential parallel strategies (Australian Government and Queensland Government, 2018; NASEM, 2018).

Australia is the steward of the Great Barrier Reef (GBR), the world's largest reef system and a World Heritage Site. Following two massive coral bleaching events in 2016 and 2017 (Hughes, Kerry, et al., 2017; Hughes, Barnes, et al., 2017), Australian governments and researchers are considering dramatic interventions to save the reef.

CONTACT Jan McDonald jan.mcdonald@utas.edu.au School of Law and Centre for Marine Socioecology, University of Tasmania, Private 89, Hobart TAS 7002, Australia

Some of these proposed interventions are aimed at improving reef recovery following bleaching events. These include stabilizing reef rubble to promote coral regeneration and various forms of coral 'farming' techniques to boost coral abundance in damaged reefs. Other proposed interventions seek to protect the reef – or at least some parts of it – from future warming, in the hope that global action to reduce CO_2 emissions is ramped up fast enough to avoid exceeding critical thresholds.

The Australian national government and Queensland state government are funding feasibility studies of three proposals to manipulate regional ocean or atmospheric conditions or to lower water temperatures and thereby reduce the threat of further bleaching events (Advance Queensland, 2018; Frydenberg and Entsch, 2017; Reef and Rainforest Research Centre 2017) (Figure 1). Two are forms of shading to reduce exposure to warmer air temperatures – one using marine surface techniques; the other aimed at increasing atmospheric shade. The first proposal involves applying a biodegradable reflective surface polymer film of calcium carbonate to the water in select locations on the GBR to reflect a portion of incoming solar radiation back to space and thereby lower sea surface temperatures. This 'floating sunshield' proposal could be deployed locally during marine heatwaves to reduce heat stress on corals (Barrier Reef Foundation, 2018; NASEM, 2018). Very small-scale outdoor experimentation of the polymer sunscreen occurred in early 2019, under a research permit issued by the Great Barrier Reef Marine Park Authority, with research results yet to be published. The second proposal is marine cloud brightening (MCB), which would involve spraying microscopic salt particles into low-lying marine clouds to increase their reflectivity and reduce the amount of solar radiation energy that warms the waters of the GBR (Harrison, 2018; Latham, Kleypas, Hauser, Parkes, & Gadian, 2013; SIMS, n.d.). This approach is in early feasibility stages as the required technology has yet to be developed, so is still some years from field testing. The third proposal is cool water mixing, which would involve mixing warm shallow water with cooler water drawn from a depth of 10–30 metres. This technique is intended to overcome the stratification of the water column on very hot days, which prevents natural mixing of warmer shallow and cooler deeper water. At this stage, the water mixing proposal is targeting one specific small-scale site – Moore Reef. Moore Reef has significant economic value for reef tourism by virtue of high visitation that is facilitated by the mooring of two large day-trip pontoons. It is also located in close proximity to deep water (Long, 2018).

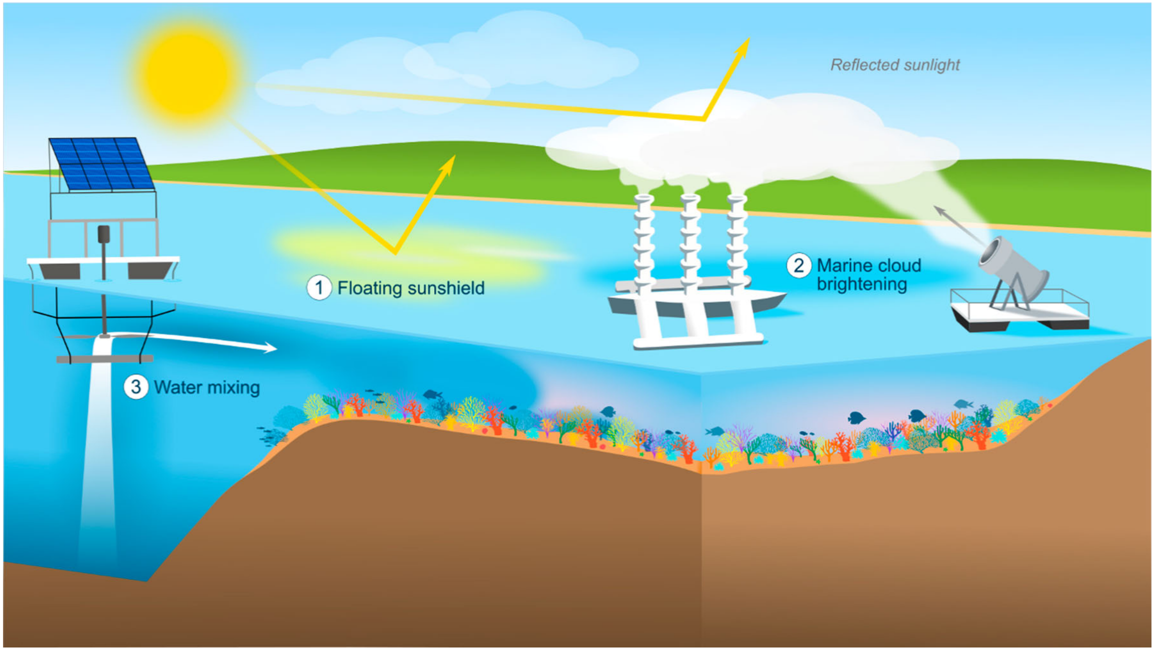

Figure 1. Funding has been awarded for feasibility studies of three geoengineering technologies to protect the reef: (1) a 'floating sunshield' of reflective surface film made of calcium carbonate to reflect sunlight and lower water temperatures; (2) marine cloud brightening; and (3) water mixing.

While it was originally planned for 2018, the schedule for water mixing field tests awaits further data collection and refinement of the technology. It should be noted that none of these techniques is likely to be helpful when the marine heatwave is due to transport of warmer water from other regions.

Given their developmental status, there is limited peer-reviewed literature on these technologies (NASEM, 2018). The polymer film and water mixing technologies are intended to operate only at a small spatial scale, but the MCB has potential use at larger spatial scales, and hence wider implications.

The article argues that innovative strategies to protect the GBR and field testing of these are essential, but current laws do not guarantee robust governance for field testing of these technologies. Robust public analysis of potential adverse environmental effects both from testing and from the implications of wider deployment should be incorporated into the earliest stages of feasibility testing. This is broadly desirable, but is especially important for an asset like the GBR, the economic, recreational, spiritual and cultural value of which is nationally and internationally high. Management of this vast area is already subject to a high degree of contestation and complex multi-scale governance arrangements involving conservation, tourism, recreational and commercial fishing, extractive industries, and research constituencies (Morrison, 2017). This contestation is reflected in the print and social media criticism that some of the proposals have already received, even in their stages of feasibility assessment.

For technologies aimed at protecting the GBR by manipulating ocean and weather conditions to succeed in the long term, stakeholders need to feel engaged in decision-making, and confident that potential risks are being rigorously evaluated and managed, alongside the risks to the Reef of *not* taking action. The World Heritage status of the GBR and the potential for transboundary environmental and social impacts of large-scale MCB on Australia's Northern neighbours also underscores the need for international consultation and cooperation. Moreover, establishing robust early governance is also important as these activities could set a precedent for future climate intervention initiatives nationally or regionally, or been seen to 'lock in' larger-scale deployment (Parker, 2014). Good governance from the outset will create strong norms that can be adapted to larger scale geoengineering R&D on the GBR and elsewhere, and minimize the risk of such experiments leading to 'geoengineering by stealth'.

Our argument proceeds as follows. Following this introduction, we examine the nature of the GBR research proposals and assess whether they meet current definitions of geoengineering. This is important, because international law and research guidelines potentially govern such activities. We then examine the application of the rules of international law to the proposed research activities, highlighting the partial coverage of such rules and the need for robust domestic laws. The operation of national and state-based laws is then considered for each proposal, with a particular focus on the governance of research activities on the GBR and the operation of national environmental impact assessment laws. The case is then made for a robust national framework governing geoengineering research more broadly, before briefly considering the content of such a framework. We conclude that research into how best to protect the GBR from coral bleaching events is critically important, but that the implications of such research requires a wider national conversation.

The data for this research is drawn from a range of sources. The domestic and international legal analysis was undertaken using traditional legal doctrinal techniques. Information about the proposals themselves was sourced from the limited academic literature, publicly-available sources, including project websites, government media releases and news media coverage. A search of the Great Barrier Reef Marine Park Authority's database of approved research licences yielded further details of the polymer film experiment and revealed that research permits had not yet been issued in respect of other activities. The authors also contacted each research team by phone or email to confirm the status of each project.

Are these proposals really for 'geoengineering' research?

Neither the proponents nor funding agencies have referred to these three proposals for the GBR as 'geoengineering research'. Instead, they are described as research for 'the protection, regeneration and recovery of GBR coral populations' (Advance Queensland, 2018) or 'environmental interventions' (NASEM, 2018). Geoengineering is not a technical term, but is widely understood to refer to 'deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change.' (Royal Society, 2009). It broadly comprises two major groups of technologies: those associated with mitigiating climate change by removing carbon dioxide from the atmosphere (carbon dioxide removal – CDR) and those aimed at cooling the planet by reflecting a portion of sunlight back into space (solar radiation management, or SRM) (Parsons & Keith, 2013). Both the floating sunscreen and MCB are forms of SRM – both are aimed at reflecting thermal energy away from the reef. Water mixing is neither CDR not SRM, but it is a manipulation of local conditions to counteract climate change. It also has features in common with a CDR technology known as marine upwelling, which brings nutrient-rich deep waters to the surface to increase primary production for higher carbon sequestration.

The current proposals for floating sunscreens and water mixing technologies are only intended to apply at a small-scale, so in this respect they are not 'large-scale manipulations' as contemplated by the Royal Society definition, but full deployment of MCB across an area the size of the reef (2000 km long) in the long term could result in large-scale manipulation of the planetary environment.

As small-scale variants of recognized geoengineering approaches (National Research Council, 2015; Oschlies, Pahlow, Yool, & Matear, 2010) the proposals may have potentially far-reaching implications for geoengineering research and deployment, well beyond the GBR, across both CDR and SRM technologies. For example, the application of a floating sunshield will involve adding substances to the waters of a site listed for its outstanding universal values under the World Heritage Convention. The polymer is biodegradable and not expected to cause any adverse impacts. However, permitting the addition of substances to Australian waters for environmental purposes raises some of the same environmental concerns as ocean iron fertilization, an earlier geoengineering proposal, which aims to remove carbon dioxide from the atmosphere and store it in the deep ocean (Brent et al. 2018; McGee, Brent, & Burns, 2018).

Of the three proposals, MCB has the greatest potential for transboundary climatic effect. To be sure, there is a difference between approving a local or regional-scale marine cloud brightening experiment, with minimal lasting impacts, and larger solar radiation management (SRM) techniques like stratospheric aerosol injection (SAI). But both carry the risk of potential transboundary impacts, either in areas beyond national jurisdiction (such as the high seas) or to the marine and/or land jurisdiction of nearby countries.

The need for early domestic governance

Attempts to govern geoengineering under international law underscore the importance of accurate classification of these proposals and the need for robust domestic governance. Relevant international law is complex, ambiguous and partial in its coverage. It derives from the combined operation of rules of customary international law, and international treaties relating to matters such as biodiversity conservation, marine pollution, and the law of the sea.

The UN Convention on Biological Diversity (CBD) contains no binding obligations in respect of geoengineering, but has explicitly addressed the issue in two non-binding decisions. It passed a non-binding decision in 2010 that invited all countries to prohibit geoengineering activities that could adversely affect biodiversity, at least until there is adequate science to justify proceeding (Brent et al. 2018; McGee et al., 2018; UNEP, 2010). In 2016, this was supplemented by another non-binding decision acknowledging the need for further research into the risks of geoengineering (UNEP, 2016). While non-binding, these decisions are usefully read in conjunction with the CBD's substantive obligations to protect biodiversity *in situ*. The above proposals to protect the GBR are all aimed at furthering this obligation to conserve the Reef's unique and globally-important biodiversity. Provided they do more good than harm, the activities therefore should not fall foul of the CBD. Robust domestic governance arrangements are needed to ensure that this will be the case.

The London Protocol on Dumping of Waste at Sea adopted an amendment in 2013 that provides a framework to prohibit marine 'geoengineering' subject to limited exceptions, such as legitimate scientific research (IMO, 2013). However, this amendment has yet to come into effect and would not in any event apply to the marine sunscreen, water mixing or MCB, because the only technology currently covered by this prohibition is ocean fertilization. (Scott, 2018). This leaves such activities to be regulated solely by the operative binding obligations of the London Protocol itself. This Protocol aims to protect the marine environment from 'all sources of pollution', but its rules only apply to marine geoengineering that involves *placing matter into the ocean* (Reynolds, 2018; Scott, 2018). The London Protocol may prohibit marine sunscreen research/deployment (as it places matter into the ocean), if it is likely to harm the marine environment. But these rules will not apply to MCB or water mixing, as they do not involve placing matter into the ocean (Scott, 2018). Australia was one of three countries to propose the 2013 amendment and should therefore be expected to act in accordance with its spirit, regardless of whether the amendment has become binding international law. To date, however, Australia has taken no steps to amend national law to give effect to the restriction on ocean fertilization. Based on current national sea dumping law (and its definition of the term 'dumping'), application of the marine sunscreen is either completely prohibited, or falls outside the scope of the regime altogether (Brent, McDonald, McGee, & Gogarty, 2018). Resolution of this unusual position will depend on the Federal Minister for Environment's own interpretation of the language of the London Protocol.

The UN Convention on the Law of the Sea (UNCLOS) enables marine scientific research within a party's EEZ, provided it causes no harm to the marine environment (Reynolds, 2018). The rules of customary international law and UNCLOS require nations to conduct a transboundary environmental impact assessment and consult with neighbouring countries (Brent, 2017) if an activity poses a risk of significant harm to the territory of another state or to the marine environment. The northern end of the GBR is close to Papua New Guinea (PNG), and Australia has an obligation to prevent geoengineering activities from causing significant harm to the territory of PNG and other neighbours. It is up to the proponent country to determine if this threshold is met on a project-by-project basis (Brent, 2017). While MCB is clearly intended to improve protection of the GBR, the impacts on other areas is not yet known and will depend on the location and extent of field-testing. Ultimately, the risks may be very low, but international law requires that clear processes be put in place at a domestic level in order to make this determination. Rigorous national impact assessment protocols can minimize the risks of unintended environmental impacts. As discussed below, they can also help raise public awareness and cultivate public trust, which early experience with geoengineering trials suggests is essential.

Current governance of GBR activities

Strong national frameworks are therefore needed to operationalize international legal obligations. However, Australia currently has no national law or policy governing geoengineering or SRM, or even on how such activities might fit within national climate response strategy. The announcements of funding for the feasibility studies contained no special governance arrangements for either the three 'geoengineering' proposals, or coral abundance research. In the absence of an explicit general law or policy on geoengineering, or the governance of these feasibility tests specifically, they will be overseen by existing environmental law and research oversight arrangements. Australia's environmental laws neither exempt nor explicitly provide for geoengineering research activities; there is an implicit assumption that current laws and policies are fit-for-purpose to coordinate and manage the risks of these geoengineering proposals. This assumption deserves further scrutiny.

Research regulation in the Great Barrier Reef Marine Park

The GBR enjoys special protections in Australian law, yet the operation of these and other environmental laws produces some inconsistent outcomes in relation to the three proposals for GBR intervention. The national management agency for the reef – the Great Barrier Reef Marine Park Authority (GBRMPA) – has specific legislation, regulations, policies, strategies and approvals systems for research activities conducted in the Marine Park (Commonwealth of Australia, 1974, 1983; GBRMPA, 2014, 2017a, 2017b, 2017c), which it administers in conjunction with the national parks agency of the State of Queensland. A detailed reading of these documents suggests that, at the very least, they require modification to accommodate these new forms of experimentation.

The framework for governing activities in the marine park is based on a comprehensive zoning plan, with specified activities either prohibited, permitted as of right or permissible in each zone. No permit is required for accredited instititutions to conduct 'limited impact' research in most zones. As noted, GBRMPA has already granted a research permit for very small field tests of the polymer film sun shading, and those tests were conducted in early 2019. The definition of, and guidelines for, 'limited impact' research suggest that both MCB and water mixing would require a permit issued jointly by the GBRMPA and the Queensland

Government. The water mixing activity will take place within the 'Great Barrier Reef Marine National Park' Zone. A permit for research activities in this zone may only be granted if the research: (1) is a priority for the management of the Marine Park, meaning it addresses one of the questions in the Science Strategy; *and* (2) it cannot reasonably be conducted elsewhere (GBRMPA, 2017a, para 85). If these criteria are applied to the current water mixing proposal, a strict interpretation suggests that a permit should be refused. This is because the GBRMPA Science Strategy identifies the impacts of climate change as a key priority, but exploring mechanisms to boost the resilience of reef ecosystems to coral bleaching is not a listed research priority (GBRMPA, 2014). It is striking that actually developing feasible responses to the risks of coral bleaching currently does not feature in the list. The over-arching strategic plan for the GBR – the *Reef 2050 Long-Term Sustainability Plan* was expanded in 2018 in response to the two mass bleaching events. A key action is now to 'protect and restore ecosystem health: develop technologies to facilitate recovery of degraded reefs, and to build increased resilience under forward climate scenarios'. The Register of Detailed Knowledge Needs in the GBRMPA Science Strategy is intended to be adaptable, so an update would be highly desirable to reflect these new management priorities, technologies and research goals. Whether due to this constraint, or because the water mixing project was not considered 'research', it appears that the project is currently being conducted as a management intervention for climate change adaptation, not a research activity. Other direct intervention activities are being undertaken to protect turtle nesting beaches at Raine Island in the far north of the GBR, so there is a precedent for such a blurring of research and what might be regarded as adaptive management or climate change adaptation activities.

The governance of MCB is less clear, in part because it is at such an early stage. To form marine clouds that travel over the reef, the activity of spraying fine salt particles into the air may well occur beyond the boundary of the Great Barrier Reef Marine Park. If this is the case, the Act's permit requirements do not apply and the GBRMPA has no role in regulating these activities, leaving them to be assessed under national or Queensland state environmental laws. If a permit is required, it is again not clear that one could be granted on the criteria outlined above, given the current list of research priorities for the Reef. At the very least, it appears likely that the project will need to comply with permitting requirements to conduct atmospheric surveys to better understand cloud – aerosol relationships and the atmospheric and meteorological conditions over the reef.

Research permits issued under the GBR's framework will also be subject to the GBR's Cumulative Impact Management Policy (Australian Government and Queensland Government, 2018; Great Barrier Reef Marine Park Authority, 2018). This policy was introduced in 2018 and its contribution to improved decision-making is yet to be tested. It may be relevant in assessing interactions between multiple reef protection proposals, but it does not speak to concerns about setting a precedent for other geoengineering activities more broadly.

Environmental impact assessment of significant activities

Beyond the GBR-specific legal framework, Australia's national environmental law requires Ministerial approval and environmental impact assessment (EIA) for activities with the potential for significant environmental impacts on important national environmental assets. The GBR is listed as one of these 'matters of national environmental significance' (Commonwealth of Australia, 1999). Twenty years of experience has yielded substantial evidence that these EIA laws perform poorly in a range of ways (Godden, Peel, & McDonald, 2018; Macintosh, 2010) and specifically in respect of decision-making for the GBR (Brodie, 2014; Grech et al., 2013; Sheaves et al., 2016). There are many reasons for this. In practice, application of these rules is highly discretionary, so the proposals may not even be subject to impact assessment and associated public consultation. The Federal Environment Minister first assesses whether the impacts of a proposed activity on the environment would meet the threshold test of 'significance' (Commonwealth of Australia, 1999, sections 12, 18, 23, 24B, s75). Australia's main EIA law provides little guidance on how the Minister should make this assessment. If the Minister decides the impacts are not significant, no national-level assessment is required beyond what the GBR arrangements dictate.

Even where proposals are subject to some form of national EIA, in the past the process has resulted in approval of 98% of applications across Australia (Macintosh, Roberts, & Constable, 2017). An EIA is also project-specific, which means the Minister generally need not consider whether approving one geoengineering research activity will inadvertently set a precedent for future actions in Australia.

Two other key deficiencies of EIA laws deserve mention. First, EIA processes are premised on an assumption that sufficient scientific information is available upfront to enable decision-makers to make informed decisions. Conditions attaching to approvals seldom contain strong adaptive management conditions, such as a requirement to halt activities when specified thresholds of unacceptable impacts are reached, or indicators of impacts are detected (although such a condition is included in the research permit for the polymer sunscreen). Historically, environmental protection conditions have been relaxed when they have proved impossible or prohibitively expensive to comply with (McGrath, 2008). As these proposals are for research activities whose specific aim is to assess feasibility, this may be less problematic. But the risks of path dependency or 'lock in' from substantial research investment should be explicitly addressed in any research approvals protocol. Finally, as the current management of the water mixing project suggests, the Great Barrier Reef Marine Park Authority is likely to be a proponent or co-proponent for some of these activities, raising questions about the capacity for truly independent assessment of risks.

These deficiencies are not unique in their application to geoengineering in general or these GBR proposals in particular. Many of the concerns relating to these proposals could be addressed through incremental improvements to, or clarification of, existing laws. We would welcome a commitment to subjecting field tests – especially of MCB – to rigorous independent, public impact assessment under existing laws would certainly. Experience with even modest proposals to field test SRM techniques elsewhere demonstrates the risks of leaving public engagement too late in the process (Corner, Pidgeon, & Parkhill, 2012; Parsons & Keith, 2013). Early public consultation builds trust and legitimacy, identifies differing perceptions of risk between the public, experts and regulators, and recognizes that even small research projects have implications for broader-scale deployment (Burns & Flegal, 2015; Corner et al., 2012; House of Commons Science and Technology Committee, 2010; Parsons & Keith, 2013).

In 2012, modest field testing for the UK Stratospheric Particle Injection for Climate Engineering (SPICE) project was abandoned in part over public concerns about the project. These concerns were described at the time as 'a perfect example of the problems that will persist until geoengineers grasp the nettle of regulation and oversight' (Nature Editorial, 2012). The lesson for Australian governments from this UK experience is that geoengineering governance, including public consultation, 'needs to be working before the experiments begin, rather than racing to catch up' (Nature Editorial, 2012). Learning from the SPICE experience, it is noteworthy that the Scopex project underway at Harvard University has had a strong emphasis on governance and public engagement from the outset. This project is likely to become the world's first SAI field test, with a modest testing of equipment to inject a small quantity of calcium carbonate into the stratosphere above New Mexico in 2019 (Keutsch Research Group, 2018).

The case for a national geoengineering governance framework

Beyond specific processes for GBR activities, there are four key reasons why we see significant benefit in the Australian government developing a specific governance framework for geoengineering technologies generally, but in particular solar radiation management, to manage future R&D of such technologies. First, the risks of transboundary impacts of SRM justify having a process in place that expressly contemplates wider regional engagement. Second, the assessment of risk for future geoengineering is quite different from conventional project-based EIA. The 'benefit' of geoengineering will be the avoidance of some of the catastrophic environmental, economic and social impacts of climate change. But geoengineering has its own significant environmental and social risks or perceived impacts. This 'risk-risk scenario' (Parker, 2014) may ultimately militate in favour of undertaking such activities. Third, new technologies may have unanticipated effects, demanding new forms of governance that focus on building our capacity to anticipate and respond, rather than predict and condition (Foely, Guston & Sarewitz 2018). Finally, in the absence of a coherent overarching national climate policy, it is important for the national government to articulate expressly where it sees SRM and other climate interventions fitting within Australia's overall suite of climate response strategies.

The GBR geoengineering proposals considered here are all at an early stage, so it is not too late to develop a responsible national governance framework on geoengineering, in parallel with the current feasibility studies of these specific proposals. An extensive research programme is being developed under the Reef 2050 programme of action on climate-proofing the GBR. This research is being coordinated by a multi-party 'Reef Restoration and Adaptation Program', which is expected to develop governance arrangements, including for MCB. This development is welcome to the extent that it can reduce contestation of reef MCB testing, but does not address the implications of such R&D beyond the GBR.

Design principles for a governance regime

A national framework for solar radiation geoengineering should build on existing Australian laws and institutions, with tailored environmental impact and risk assessment processes and strong public consultation requirements to build legitimacy and public confidence (Burns & Flegal, 2015; Corner et al., 2012; House of Commons Science and Technology Committee, 2010).

The aim is not to stifle this critical research or impose a de facto moratorium on out-of-laboratory testing (*cf* Parsons 2014). Rather, with current emissions trajectories showing a growing need for SRM and CDR geoengineering options, governance frameworks should aim to facilitate small-scale field tests, while also managing risks and building legitimacy and public confidence (Nicholson, Jinnah, & Gillespie, 2018; Parsons & Keith, 2013).

The *Oxford Principles for Geoengineering Research* (House of Commons Science and Technology Committee, 2010) and the *Asilomar Principles* (Asilomar Conference, 2010) enjoy broad support internationally, and are therefore a good starting point for the design of governance frameworks. These Principles, along with the more detailed prescriptions of the *Code of Conduct for Responsible Geoengineering Research* (Hubert, 2017), emphasize the importance of transparency and public access to information. Ideally this should include processes for engendering public support for outdoor testing, calibrated to the scale and risks of the proposed action and the importance of the asset to be protected (House of Commons Science and Technology Committee, 2010; Parsons & Keith, 2013). We do not underestimate the challenges this poses. Nor we do not propose the conferral of powers of veto over any group or individual (Horton et al., 2018). What is needed is a far more sophisticated process of engagement with commercial, scientific and conservation publics, as well as the wider community, than is typically undertaken in a conventional research ethics or EIA process.

Processes for independent evaluation of the environmental and socio-economic impacts of geoengineering research are also required to inform decision-makers. Parsons and Keith (2013) suggest a tiered approach that permits small-scale, low-risk geoengineering research activities with minimal additional requirements but imposes a moratorium on large-scale activities. This, they say, would: help frame 'a social bargain that lets research proceed'; ensure that public debate is informed by science; and contribute to 'international norms of cooperation and transparency' (Nicholson et al., 2018; Parsons & Keith, 2013). The stringency of requirements should then be scaled up as tests expand their geographical range and/or intensity (Parsons & Keith, 2013).

In some cases, even small-scale field tests may require some form of public oversight. This is especially important when public funds are given to private entities for research and development of technologies that might later be deployed on a commercial basis. This is not to suggest that we expect these technologies to be financially profitable (Reynolds, Contreras, & Sarnoff, 2017). Rather, it seems possible, if not likely, that government agencies would tender and contract out the delivery of preferred technologies, such that the developers of those technologies might profit from them. The announcement of the funding for the MCB and sunscreen projects discussed here expressly contemplated that proponents would retain intellectual property rights over their technologies. The university-based developers of the MCB technology have already taken out a patent over that technology (SIMS n.d.). At the very least, we suggest that contractual arrangements for research funding should clarify how any resulting intellectual property rights will be allocated so as to safeguard public access to the benefits of the research, as the Oxford Principles contemplate.

There will doubtless be features of each geoengineering technology that require special arrangements – identifying critical indicators of ecological health, determining thresholds of unacceptable impact or risk appetite, and articulating other preconditions or guiding principles would also be desirable. Our intention here is not to articulate what that governance framework should exactly look like. Instead we seek to highlight the importance of having one, or at the very least having a conversation about having one.

Conclusions

Given the impact of coral bleaching in 2016 and 2017, a suite of policy options is urgently needed to protect the GBR from severe climate change impacts. With extensive coral bleaching already occurring at less than 1.5°C warming, the Reef will be placed under more stress, even if the Paris Agreement's target of 1.5-2°C warming is achieved. Geoengineering options need to be explored now for the GBR, and indeed for other climate-sensitive ecosystems. Australia is one of the first countries to openly entertain research into such options, albeit without using the term geoengineering, or solar radiation management. This research should be facilitated, but its potential risks should also be carefully identified, evaluated, and managed. This demands transparency about research proposals, deep and early engagement with scientific, commercial and conservation stakeholders in the Reef, robust independent risk assessment, and agile adaptive approvals regimes.

Australia is a wealthy country with a strong commitment to international environmental treaties and a long history of state and national environmental legislation and associated governance tools. It is well placed to govern the challenges of emerging climate intervention technologies, but needs to do so before field testing begins. With the prospect of similar impacts on unique ecosystems around the world it is likely that other countries will follow. As a test case, the world should be watching how Australia governs these first steps towards geoengineering the GBR.

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Notes on contributors

McDonald led the conceptualization, writing of original draft, review and editing.

McGee and ***Brent*** made equal contributions to conceptualization, writing, review and editing.

Burns contributed to review and editing.

ORCID

Jan McDonald http://orcid.org/0000-0002-7953-1458
Jeffrey McGee http://orcid.org/0000-0002-2093-5896
Kerryn Brent http://orcid.org/0000-0003-0983-2906

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