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Taking it outside: Exploring social opposition to 21 early-stage experiments in radical climate interventions

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ABSTRACT

Large-scale and highly experimental interventions are being considered as strategies to address climate change. These include carbon dioxide removal approaches that are becoming a key pillar of post-Paris assessment and governance, as well as the more controversial suite of solar geoengineering methods. In this paper, we ask: Who defends and opposes these experiments, and why? After screening 44 early-stage experiments, we conduct a qualitative comparative analysis of 21 of them in five areas: ocean fertilization, marine cloud brightening, stratospheric aerosol injection, ice protection, and enhanced weathering. We develop a common framework of analysis, treating experiments as sites in which the risks and appropriate governance of early-stage science and technology are envisioned and disputed among scientists and other social groups. Our contribution is to map and explain the key issues of contention (why), actors (who), and tactics (how) that have shaped opposition across these linked fields of experimentation and technological development, from the 1990s till today. In doing so, we build upon and connect past studies on particular climate experiments and develop insights relevant to governance outlooks perceptions, discourses, and intents surrounding immature but potentially crucial climate technologies.

1. Introduction

A series of deliberate, large-scale and highly experimental interventions are being considered as strategies to address climate change. These include carbon removal (or negative emissions) approaches that are becoming a key pillar of post-Paris assessment and governance, as well as the more controversial suite of solar geoengineering (sunlight reflecting methods, or solar radiation management). In this paper, we focus on the most radical and early-stage climate interventions in terms of technological readiness levels (TRLs) and social acceptance, and which remain at a handful of small-scale experiments. Early-stage experiments pose minor physical and environmental impacts - yet many have been met with substantial and ongoing opposition. Contestation over these experiments raises questions concerning how scientific assessment is conducted, and public consent sought, within the charged politics of geoengineering as well as climate governance.

Climate geoengineering, or 'deliberate, large scale interventions in the global climate', is the original umbrella concept for carbon removal and solar geoengineering. Shepherd et al. [1] provide a landmark assessment report; Keith [2] and Oomen and Meiske [3] trace a history that stretches into Cold War-era environmental interventions. The term's invocation still shapes how experiments are designed and opposed. More recently, carbon removal and solar geoengineering have become separately assessed [4,5]. Carbon removal is becoming normalized as an expanding range of 'nature-based' and technological approaches, where incoming practitioners often eschew the controversial geoengineering label or emphasize the 'naturalness' of their intervention technique [6–8]. Researchers have been more open to retaining the specific phrasing of 'solar' geoengineering for sunlight-reflecting methods. But opposition led by key environmental non-governmental organizations (ENGOs) still invokes critiques of the underlying rationales for geoengineering.

In this paper, we ask: Who defends and opposes early-stage experiments for radical climate interventions, and why? The significance of this inquiry belies the current stage of small-scale experiments in fringe corners of climate technology development. We expose how academics, technologists, societal groups, and ENGOs contest conceptions of co-benefits and risks for society and industry on potentially game-changing climate strategies, through the design and governance of foundational experiments.

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After screening an initial 44 prospective experiments, we conduct a deeper qualitative comparative analysis of 21 experiments in five low-TRL carbon removal and solar geoengineering approaches: ocean fertilization, marine cloud brightening, stratospheric aerosol injection, ice protection, and enhanced weathering. Beyond breadth of technology, we aim for a long arc: the past 30 years, from the 1990s and the birth of the 'geoengineering' label, till the present day.

In Section 2, we develop a common framework of analysis, treating experiments as sites in which the risks and appropriate governance of early-stage science and technology are envisioned and disputed among scientists and other social groups (e.g. [9]). Section 3 clusters experiments separately by technology; Section 4 derives generalizable insights. Our unprecedented scope allows us to highlight the common issues (why), actors (who), and tactics (how) that have shaped experiment design and opposition across these linked fields of technological development, and may continue to do so in the future (similar to [10]).

We orient our inquiry from 'controversy studies' within the wider discipline of science and technology studies, where contestation provides an opportunity to examine politics hidden in technical and technocratic assessment [10–16]. Controversies over scientific processes or new technologies with challenging societal implications offer focal sites where actors can contest their direction of travel - creating communities, terms of reference, and practices that extend beyond science into policy, civil society, media, national government, and international governance. Controversy becomes about 'how the certification of knowledge matters to the resolution of broad social struggles' [15].

In doing so, we build upon and connect past studies on particular solar geoengineering or carbon removal experiments [9,17,18], or reviews within technology types (e.g. [19] on ocean fertilization; [20] on solar geoengineering), to experiments currently unfolding. We develop insights relevant to governance outlooks that draw upon prospective [21], stalled [22], or ongoing experiments [23], and to the emerging literatures of technological perceptions, discourses, and intents surrounding radical climate experiments and their governance [24–27].

2. Research design

We deploy a qualitative comparative analysis (QCA), treating cases (e.g. an experiment) as a combination of factors (e.g. issues, actors, tactics) that contribute to a certain outcome (e.g. opposition and controversy) [28–30]. Following QCA guidance, we generalize modestly, drawing insights between the technological fields examined as part of the study [29,31]. In this, we follow recent work conducted on socio-technical transitions [32].

We draw attention to more unproven prospective interventions, and concentrate our analysis on carbon removal and solar geoengineering approaches between TRL 3–5 (see Fig. 1): ocean fertilization, marine cloud brightening, stratospheric aerosol injection, ice protection, and

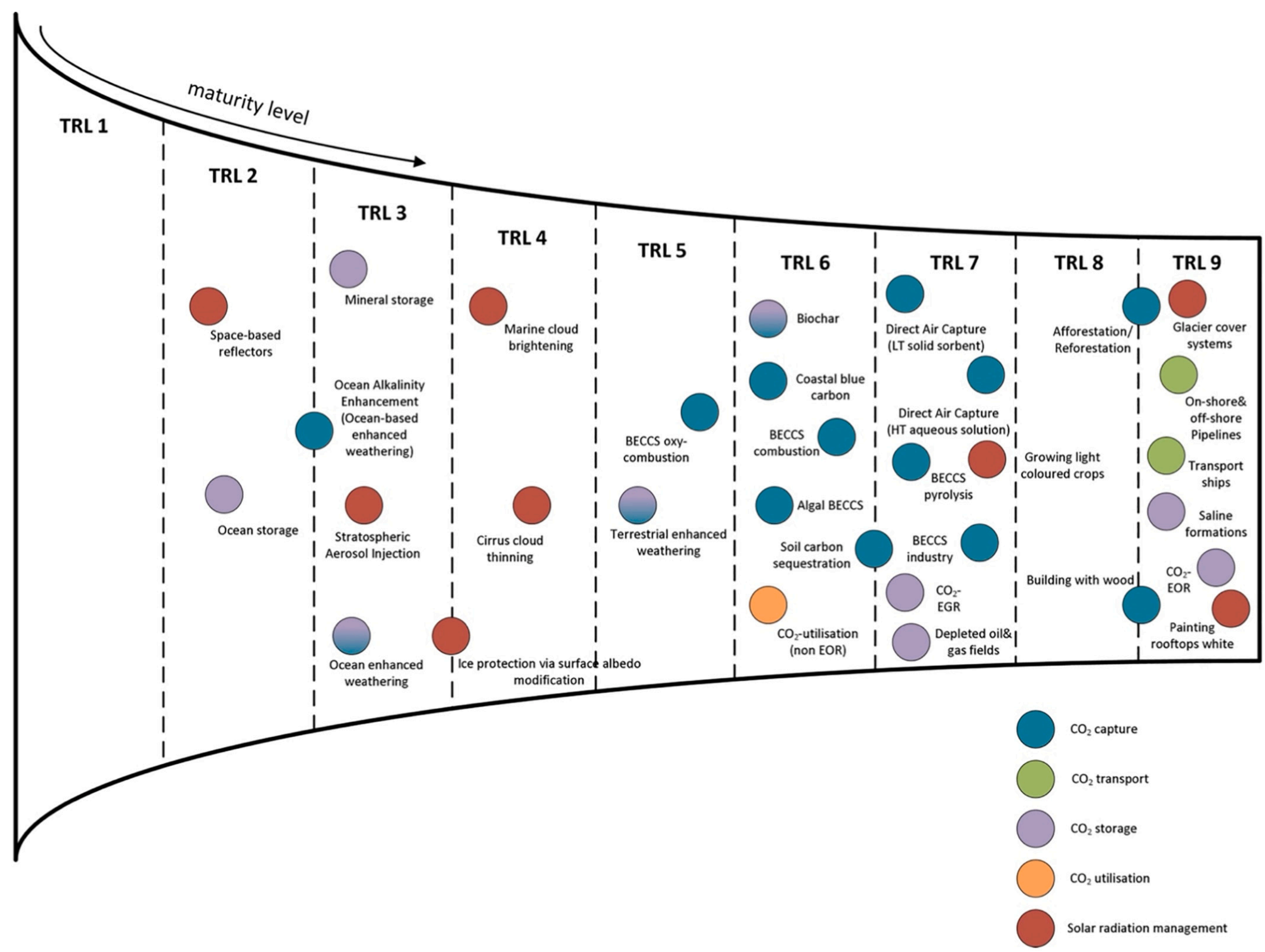


Fig. 1. Classifying climate interventions by Technological Readiness Level.
Source: Authors and Benjamin Mitterrutzner, based on qualitative discussions and unpublished data from the International Institute of Applied Systems Analysis as well as ETH Zurich. These are part of a large European Research Council project, GeoEngineering and NegatIve Emissions pathways in Europe (GENIE).

enhanced weathering. TRLs are a widely-used framework for systematically measuring and managing technologies over different parts of the journey from invention to maturity [33]. Nine TRLs are often identified in order to track the status of development progression (below); we focus on approaches within TRLs 3–5 to highlight contestation during the development or experimental stages beyond proof-of-concept, but prior to demonstration.

1. Initial idea: basic principles have been defined
2. Application formulated: concept and application of solution have been formulated
3. Concept needs validation: solution needs to be prototyped and applied
4. Early prototype: prototype proven in test conditions
5. Large prototype: components proven in conditions to be deployed
6. Full prototype at scale: prototype proven at scale in conditions to be deployed
7. Pre-commercial demonstration: solution working in expected conditions
8. First-of-a-kind commercial: commercial demonstration, full-scale deployment in final form
9. Commercial operation in relevant environment: solution is commercially available, needs evolutionary improvement to stay competitive

TRLs, used simplistically, can reify techno-economic biases. However, the framework is increasingly used and expanded as a springboard to investigate the social dimensions of new or experimental technologies, especially in the context of climate change mitigation or decarbonization [34–36]. With an eye to these extensions, we retain the use of TRLs for two reasons. Firstly, the TRL framework has been extensively applied to emerging energy and climate technologies [37–43]. Secondly, this paper exists as part of a large European Research Council project, GeoEngineering and NegatIve Emissions pathways in Europe (GENIE), where the TRL framework is more widely used (see also Fig. 1).

After screening 44 experiments or projects with planned experiments within these technological clusters undertaken or announced from 1990 to 2020/2021 (Annex 1), we select 21 as in-depth case studies. Our choice of case studies is guided by several criteria. We focus on (planned) experiments that have been confronted by visible controversy and contestation. However, from the vantage point of 2022, we also look at experiments which raised no significant controversy at the time, but with hindsight have become more controversial, have clearly influenced the design and contestation of experiments, or continue to embody interesting dynamics for future experiments.

Our QCA framework of analysis for all cases comprises four elements. First, we examined the initial experiment design and governance, highlighting the initial actors (e.g. principle investigators), risks envisioned (e.g. environmental or social implications), and governance practices intended to explore and mitigate risk (e.g. impact assessment, stakeholder engagement). Second, we examined (where relevant) the emergence of controversy and opposition to the experiment: highlighting new actors, different risks envisioned (often in contrast to those emphasized by experiment designers), and oppositional practices intended to shut down the experiment. Third, we analyzed if and how experiment designers reacted to controversy, modifying their governance practices to engage with oppositional concerns – we were interested in whether new experiment governance took place or was able to navigate or defuse controversy. Fourth, we concluded with each case's implications for future assessment and political debate. Where controversy did not occur, we focused on the first element. It is important to note that because of space constraints, we cannot detail every case study according to this four-step framework. Rather, we present our data and analysis in the following manner.

The following Section 3 describes and analyses the experiments by technology, creating five comparative summaries of how these experiment clusters and social opposition – or lack thereof – have unfolded over time. These summaries are necessarily abbreviated, but highlight key motivating issues and tactics of social contestation. Section 4 then builds on these summaries by deriving generalizable insights across all experiments and technologies.

3. Summaries of climate intervention experiments by technology

In this section, we summarize the five broad clusters of radical experiments investigated in the paper: ocean fertilization (Section 3.1), marine cloud brightening (Section 3.2), stratospheric aerosol injection (Section 3.3), ice protection (Section 3.4), and enhanced weathering (Section 3.5).

3.1. Ocean fertilization

Ocean fertilization – the release of iron or other nutrients to seed phytoplankton blooms that sequester carbon – has had the longest run of experiments and the most varied career in framing of intent. Our QCA examined four ocean fertilization experiments in depth (Table 1): Planktos (2007, which we label *OF1*), Climos (2008–2009, *OF2*), Lohafex (2009, *OF3*), and the Haida Salmon Restoration Corporation (2012, *OF4*).

Experimentation represents three overlapping phases. The first two phases are summarized by Strong et al. [19]. Beginning in 1993, scientific institutions first sought to establish the processes of phytoplankton's 'biological pump'. Over the 2000s, ocean fertilization as a scientific endeavor was paired with a second stream of for-profit enterprises that sought to commercialize ocean fertilization though carbon credits. A smaller number of commercial enterprises were conducting trials, but with little remaining documentation and of unclear value [19]. All appeared to pass without concerted opposition, though in a period of rising debate. Established scientific networks viewed commercial ocean fertilization with wariness, but the debate grew in visibility due to mutual exchange between the two streams [19].

In 2007, Planktos (*OF1*) – a for-profit enterprise built around American entrepreneur Russ George – announced a plan to seed an unprecedented area of 10,000 km^2 near Ecuador's Galapagos Islands [44]. The prospect of commercially-driven, large-scale ocean fertilization was made more pressing by George's reputation as a maverick

Table 1
Ocean fertilization case studies.

Case abbreviation	Full name of experiment or project (if applicable)	Project leads or host	Year and location
OF1	Planktos II (a prior experiment, Planktos I, had taken place in 2003)	Planktos, led by Russ George	2007; Near the Galapagos Islands
OF2	Climos	Climos, led by Dan Whaley and Margaret Leinen	Planned for 2008–2009, but not conducted.
OF3	Lohafex	Alfred Wegener Institute, Germany, led by Victor Smetacek, and CSIR-National Institute of Oceanography, India, led by Syed Wajih Naqvi	2009; Southern Ocean
OF4	Haida Salmon Restoration Corporation	Haida Salmon Restoration Corporation, led by Russ George and John Disney; founded by the Old Massett Village Council of Haida Gwaii	2012; Northwest Pacific Ocean

within both scientific and entrepreneurial circles – he sold his own carbon offsets, and openly celebrated his efforts as pushing ‘useful ocean research [beyond] the exclusive domain of the richest researchers’ [45]. Planktos' plans catalyzed widespread scientific and ENGO protest [46,47] that would lead to the experiment's premature cancellation [19]. The efforts contributed to the emergence of an evolving ENGO network who would continue to protest ocean fertilization as local socio-ecological disruption as well as a slippery slope to large-scale marine geoengineering, whose members would become active in experiments beyond ocean fertilization. In turn, protests spurred the Convention on Biological Diversity (CBD) and London Convention and Protocol (LC/LP) to develop guidelines on ocean fertilization experimentation and ‘marine geoengineering’ – which have also come to influence experiments and their opposition within and beyond ocean fertilization [19].

Climos (*OF2*), a concurrent for-profit enterprise, also had experiments planned – but these were never carried out in the aftermath of the Planktos episode [19]. Nevertheless, Climos is significant for posing a different operations model: aiming to integrate the practices of established scientific, business, and policy networks. Climos established a Code of Conduct emphasizing marine protection, rigorous credit accounting, and transparency [48], alongside publications exploring science-business relations [49], and developed carbon credits [50] intended to meet demands for third party verification, additionality, and 100-yr permanence. Climos' efforts did not prove sufficient to overcome ENGO opposition and scientific mistrust [51]. It closed in 2011, citing ‘the failure of governments to maintain economic signals that can support market-based solutions’ [52].

The 2009 Lohafex experiment (*OF3*) was the point at which ocean fertilization became scientifically challenged and commercial interest began to ebb. A project that has come to be seen as the capstone of around 12 experiments conducted by established scientific networks between 1993 and 2005 (Annex 1; summaries can be also found in [19,53]), Lohafex found that when taking a wider web of marine ecology into account, most carbon was only temporarily sequestered [54]. Project communications, attuned to political and commercial contexts, expressed clear doubt on ocean fertilization's sequestration potential [55] – a conclusion ensuring that commercial activities could not endure [19].

But Lohafex also had ripple effects in experimental governance, as a high-profile case of science diplomacy between Germany and India [56]. Oppositional ENGOs leveraged this visibility, targeting the experiment with a solidifying strategy: challenging a ‘host’ country's reputation (here, Germany as host to the Alfred Wegener Institute, a principal institution) based on violation of international guidelines in the making since Planktos' 2007 activities. In turn, this challenge exposed definitional politics over ‘legitimate research’, scale, and location, which differed between the Convention on Biological Diversity and the London Convention and Protocol [56]. The overseeing German ministries agreed to momentarily halt Lohafex, while seeking several independent rulings on its environmental impact and international legal guidelines. In defense, Lohafex's team framed the experiment within the Convention on Biological Diversity's strictures [57], and further defended the experiment via institutional communications and appeals to a politically-neutral, scientific ethos. The project's press releases emphasized scientific grounding, separation from commercial and political intent, willing compliance with the independent assessment, and that Germany's credibility in international science and environmental governance remained unsullied [54,58,59]. The independent rulings found in the experiment's favor [57], and weeks later, the resumed experiment had acquired its data.

Yet, both scientific and commercial efforts continued in a dampened third phase of activity that extends into the present. The benchmark example was the *Haida Salmon Restoration Corporation* or HSRC (*OF4*), led once again by Russ George. The indigenous Haida of Canada's Pacific coast were then faced with decreasing salmon runs (a cultural and economic mainstay), and George helped convince one of their communities to borrow $2.5 million (CAD) to found the HSRC, which would deploy ocean fertilization to seed phytoplankton blooms and increase salmon stocks. Meanwhile, George (incorrectly) promised that the carbon sequestered could be sold via carbon credits, recouping the initial investment [17,60]. HSRC scaffolded the experiment's design and governance with Haida mythology, socio-economic policies around ecosystems restoration and services, and community governance [60,61]. The loan was approved by a community vote, and the local Village Council approved three research permits [17]. In the summer of 2012, the experiment was conducted in international waters, 400 km west of Haida Gwaii.

It was only retroactively that the ETC Group and allied ENGOs contacted news media to describe the event as a violation of international guidelines [17]. Researchers in a parallel debate on solar geoengineering experimentation, themselves fighting for legitimacy (*SAI3*), denounced HSRC's ‘rogue science’ [17]. Scientific commentators recalled Planktos, arguing that George had duped an indigenous community with the promise of carbon credits [61,62]. Haida communities and authorities were taken by surprise, with the episode exposing fear of connection to geoengineering, and re-opening questioning about the project's relative prioritization of salmon restoration or carbon credits, cultural appropriation of Haida stewardship, and jurisdictions between Haida authorities [17,60,61]. In 2013, the Haida removed George from his position [63], and the HSRC was dissolved. Still, the episode raised uneasy questions about the convergence between non-traditional research, and indigenous and local knowledge – George's brand of ‘citizen science’ was easy to deride as ‘rogue science’, but it was more fraught to dismiss the experiment's co-development with Haida culture, economy, and self-government [17,60,61]. Moreover, ocean fertilization experiments and ‘marine’ geoengineering were connected via a wider framing of ‘climate’ geoengineering to planned experiments on solar geoengineering, entrenching further discussion on the unclear legal ‘patchwork’ surrounding small-scale research.

HSRC also ushered in a new phase for framing ocean fertilization. Non-established scientific and entrepreneurial networks continue in a small cluster of initiatives. Oceanos (a research organization) and the Ocean Nourishment Corporation (a private company) explicitly reject geoengineering and give light treatment to carbon removal and carbon crediting, while emphasizing local developmental co-benefits through ‘ocean seeding’ [64], ‘nourishment’, and ‘restoration’ [65]. Both claim frameworks for designing, conducting, and governing field trials [66], of which no documentation exists. The Ocean Nourishment Corporation has applied for patents in aspects of the ocean fertilization process [67]. There is a lingering implication of commercialization-by-stealth [68]. This, in turn, reflects two trends. Hybrid initiatives marrying entrepreneurial and technical innovation are expanding across (marine) carbon removal development and field-work [69], from the Ocean Visions Alliance, to more technology-specific Running Tide (macro-algae sequestration) and Project Vesta (enhanced weathering, *EWO2*), and even marine cloud brightening (*MCB2*). Some of these efforts lean into being labelled as nature-based, local ecosystems restoration and management, and possessing co-benefits for local actors or industry.

Meanwhile, scientific efforts may be reviving – Cambridge's Sir David King is proposing a new method for ocean fertilization, with experiments planned for 2022 [70]. The London Convention and Protocol, through its advisory body, also continues to map new marine geoengineering approaches and to deliberate on experimentation bounds [18,71].

3.2. Marine cloud brightening

Marine cloud brightening (MCB) posits that clouds can be seeded with salt particles (via spraying seawater), reflecting sunlight over vulnerable locales [72]. It has risen to greater prominence through the climate geoengineering debate, as part of solar geoengineering [1] - but had been considered in scientific circles as early as ocean fertilization

[73]. Marine cloud brightening builds on an analogous anthropogenic activity: in this case, sunlight-reflecting ‘ship tracks’ created by the particulate matter emitted as part of shipping pollution.

Our QCA considered three MCB experiments (Table 2): E-PEACE (2011, which we labelled *MCB1*), the MCB Project (ongoing, *MCB2*), and the Great Barrier Reef project (ongoing, *MCB3*). Indeed, the physics of clouds are subject to many uncertainties. As such, MCB is viewed as a more uncertain and regional kind of solar geoengineering, compared to the planetary schemes posed by stratospheric aerosol injections (SAI) (see Section 3.3). It has received far less study in earth system modelling and in political risk assessment. However, it still commands attention - featuring both in landmark reports from the US National Academies [5,74], as well as the London Convention and Protocol scientific advisory body examining ‘marine geoengineering’ [71].

E-PEACE (MCB1) investigators did not initially describe the project as a field demonstration for marine cloud brightening or geoengineering, and it is unclear if they envisaged it as such. Rather, the project was described as atmospheric science, referencing work on cloud-aerosol interactions [75]. Unengaged by ENGO opponents, E-PEACE was completed in July 2011, off the coast of Monterrey, California. But afterward, scientists engaged in solar geoengineering research pointed out that E-PEACE researchers had (deliberately or implicitly) avoided ENGO opposition and more stringent governance because they did not explicitly connect the experiment with geoengineering [20]. Indeed, with no physical difference at small scales between basic science (cloud-aerosol interactions) and precursor stages of geoengineering, scientists could self-label as either or both – and it was not clear which choice could avoid or invite controversy. However, demands for E-PEACE's transparency of intent had different motives. Some observers severely mistrusted the potentials of solar geoengineering while others sought to conduct their own experiments [20] – mirroring intra-scientific conversations in ocean fertilization. E-PEACE's investigators acknowledged implications for marine cloud brightening and geoengineering thereafter [76,77].

The more recent Marine Cloud Brightening Project or MCBP (*MCB2*), unlike E-PEACE, explicitly references solar geoengineering and climate geoengineering [78–80]. Originally called The Silver Lining Project, it branched in two parts. The first is the MCBP, a formalized scientific project led at the University of Washington [78]. The second - and MCBP's partner in policy support and communications - is the NGO Silver Lining. Silver Lining is an advocacy organization for solar geoengineering built around Kelly Wanser (a former Silicon Valley executive), which has become significant for its innovation- and philanthropy-facing activities, a polished public profile (comparable with Project Vesta, *EWO2*), and for controlling the funding that supports a great deal of solar geoengineering modelling research [81]. MCBP has meanwhile maintained a three-stage plan for experimentation [82], but even its most preliminary phase remains suspended due to insufficient funding. Opposing ENGOs have nevertheless mentioned MCBP in the context of an experiment that has more recently gone ahead [83].

Table 2
Marine cloud brightening case studies.

Case abbreviation	Full name of experiment or project (if applicable)	Project leads or host	Year and location
MCB1	E-PEACE - Eastern Pacific Emitted Aerosol Cloud Experiment	University of California San Diego, led by Lynn Russell	2011; Monterrey, California, USA
MCB2	Marine Cloud Brightening Project	University of Washington, led by Robert Wood and Tom Ackerman (part of a wider consortium)	Delayed since 2018; Monterrey, California, USA
MCB3	Marine Cloud Brightening for the Great Barrier Reef	Southern Cross University, led by Daniel Harrison (now part of the Reef Restoration and Adaptation Programme)	2020; Great Barrier Reef, Australia

The *Marine Cloud Brightening for the Great Barrier Reef* or MCB-GBR[1] project (*MCB3*), like E-PEACE, is significant for having been completed its first phase (in 2020, off the Queensland coast of Australia) while avoiding ENGO opposition, and making no allusions to climate geoengineering. But there, the comparisons end. The stated objective has rather been to investigate MCB's capacity to forestall coral bleaching of the Great Barrier Reef as a measure for ecosystems protection and recovery, and as part of a larger system of such efforts [84–86]. Unlike E-PEACE, the Australian experiment's governance relied on more than academic procedures – principal investigators complied with all domestic environmental laws [18], and acquired the consent of the area's indigenous custodian [84].

More significantly, MCB-GBR has incorporated into the $150 m (AUD) funded Reef Restoration and Adaptation Program (RRAP) [84]. RRAP - an ambitious partnership between the Australian government, CSIRO (Australia's national research agency), the Great Barrier Reef Marine Park Authority, and several marine institutes and universities - investigates a system of interventions that would shade, stabilize, and seed coral reefs [23,87], representing the emergence of a discourse regarding such interventions as restoration and resilience of (iconic) ecosystems, alongside benefits for science, and time-buying for “viable long term solutions” [18,85]. Future trials [84,88], alongside regulatory assessments and stakeholder engagements [89], are being planned over the next 10 years.

Belatedly, ENGOs led by the ETC Group responded with references to geoengineering and violation of international guidelines [83]. But the main controversy was intra-scientific. E-PEACE (*MCB1*) was invoked – that researchers could avoid scrutiny by steering clear of contentious framings around solar geoengineering [90]. Moreover, the project highlighted another dimension of jurisdictional issues. Many tests have raised demand for novel governance mechanisms or referenced international guidelines. MCB-GBR, however, would operate within national territory with legal and governmental consent [18], raising the question if different domestic contexts might provide clearer or murkier governance landscapes.

3.3. Stratospheric aerosol injection

The most commonly proposed deployment scheme for stratospheric aerosol injection (SAI) proposes to maintain a layer of reflective particles in the upper atmosphere with modified aircraft [91]. Our QCA covers three projects (Table 3): Yuri Izrael's field experiment (2008, *SAI1*), SPICE (2012, *SAI2*), and SCoPEx (2021, *SAI3*). Unlike marine cloud brightening, since reflective particles would spread across the upper atmosphere, SAI's cooling effects would be planetary in scope - but depending on the dimensions and location of deployment, with uneven regional effects [92]. Stratospheric aerosol injection is thought to possess low implementation costs coupled with high leverage on global temperatures, as well as the largest uncertainties in geopolitics and public consent [93]. As a result, stratospheric aerosol injection is sometimes viewed as having the clearest links to the concept and inchoate risks of geoengineering. The most attention in assessment has been devoted to this approach [5,74,92], and the most scientific and ENGO opposition as well [94,95].

These associations have extended into the planning of and opposition to stratospheric aerosol injection experiments - which, regardless of initial small scale and ‘exit ramps’ posed (e.g. [74]), connect to the end-

[1] The project does not appear to have been given an acronym by its scientific investigators.

Table 3
Stratospheric aerosol injection case studies.

Case abbreviation	Full name of experiment or project (if applicable)	Project leads or host	Year and location
SAI1	Yuri Izrael's Field Experiment on Studying Solar Radiation Passing through Aerosol Layers	Roshydromet and Russian Academy of Sciences, led by Yuri Izrael	2008; Saratov, Russia
SAI2	SPICE 'Test bed'- Stratospheric Particle Injection for Climate Engineering	Bristol University, led by Matthew Watson (part of a wider consortium)	Suspended 2012; Norwich, UK
SAI3	SCoPEx - Stratospheric Controlled Perturbation Experiment	Harvard University, led by Frank Keutsch and David Keith	Suspended 2021; Kiruna, Sweden

vision of a high-leverage planetary sunshade [27,96]. This has also made the approach more difficult to describe in 'natural' or 'local' terms sometimes deployed in carbon removal or marine cloud brightening conversations.[2] These factors ensure that stratospheric aerosol injection experimentation has operated in the least permissive environment in terms of ENGO and scientific attention.

In 2009, Russian scientists published a paper claiming the first outdoor study (*SAI1*) of stratospheric aerosol injection [97], which had passed without visible notice from ENGOs. This small-scale test (sulphate aerosols injected at 50 m and 200 m from a pair of army vehicles) was led by (the now late) Yuri Izrael – a scientist of high standing in the IPCC, who nevertheless questioned anthropogenic climate change and lobbied Putin to consider solar geoengineering [20]. Izrael's experiment's deliberate association with solar geoengineering was unprecedented in 2008. However, researchers into stratospheric aerosol injection outside of Russia swiftly disassociated themselves, delegitimizing it as a contribution to legitimate scientific inquiry – where it remains only sporadically mentioned as a cautionary tale in political studies [20,98]. Izrael's experiment also serves as an early 'dark mirror' of the scenario posed more recently by Australian marine cloud brightening trials (*MCB3*): an experiment held within national jurisdiction, and with (tacit) support of government authorities. This made the Russian test concerning to external observers, where intransparency and the overt geoengineering connection became easy to conflate with projections of the Russian state's geopolitical goals [20].

The 2012 UK-based SPICE 'test-bed' (*SAI2*) occurred during a period of charged debate over both carbon removal and solar geoengineering (E-PEACE, *MCB1* and HSRC, *OF4* also took place during this time). The test has an uncommon legacy: its failure to be conducted is sometimes recalled as a success for its governance. Part of a wider-ranging research consortium, the test-bed proposed to test the mechanics of an eventual delivery system via a small-scale version: an 18 m long balloon spraying water 1 km in the air. The progress of the test-bed was coupled to a comparatively extensive governance framework: a 'stage gate' review. SPICE investigators would have to pass five technical and societal criteria for the test-bed to proceed, judged by a multidisciplinary panel [22,101]. SPICE personnel conducted a multi-dimensional assessment, an environmental impact assessment, and stakeholder engagements. Some in the team welcomed the process as a needed grappling with normative and political implications of science; others implied that it could feel tedious or unnecessary [20,22]. But project leaders called the test off before it was fully vetted by the stage gate panel. ENGOs led by the ETC Group take credit, having driven negative public and media attention [102], including a letter to the UK government claiming violation of international guidelines [103]. The SPICE team maintain that they had suspended the test of their own accord, due to a late discovery that project personnel had applied for a patent on a component of the delivery mechanism, raising a conflict of interest [104,105].

SPICE's most interesting implication is posed by the test-bed's governance. Technology governance practitioners used SPICE as the foundational case in developing the 'responsible research and innovation (RRI)' framework [22], which has since been widely referenced in solar geoengineering and carbon removal [106]. In this sense, the real trial was not of the delivery system, or even of stratospheric aerosol injection experimentation - but of RRI as a framework for societal appraisal. RRI practitioners recall the cancellation as a healthy reflection of principles surfaced by the stage-gate [9,107]. But it is less clear whether the bulk of technical researchers in solar geoengineering consider the RRI framework help or hindrance [106].

Debate over the proper shape of experimental governance and societal appraisal have carried over into *SCoPEx* (SAI3) – a test long contested by ENGOs [108] as inextricable from David Keith, a leading scientific figure and vocal advocate in solar geoengineering [2,109]. As part of a finalized project plan that has seen many iterations, the experiment (a 'platform test' of a small-scale delivery mechanism, with no material release) was to take place in Kiruna, northern Sweden, in the traditional lands of the indigenous Saami. SCoPEx investigators saw the risks as technical and environmental, both argued to be negligible [110]. The contrast with the society-facing orientation of SPICE's governance (*SAI2*) is clear. Still, SCoPEx sought to provide a (alternative) template for experimental governance [111], instigating the formation of an independent Advisory Committee, which in turn initiated a series of legal, engineering, financial and societal reviews that would precede the test. As part of the reviews, the Advisory Committee recommended societal engagements that the project team contested as too restrictive.[3]

Before the experiment (or engagements of any scope) took place, controversy emerged. In February 2021, a first letter was sent to the Swedish ministries for environment, research, and enterprise and the Swedish Space Corporation by domestic and international ENGOs (including the ETC Group). This letter challenged Sweden's commitments in light of the incoming Stockholm +50 Conference in 2022, and referenced violation of international guidelines, geoengineering, and the UN Declaration on Rights of Indigenous Peoples [112]. A second open letter was sent to the SCoPEx Advisory Committee from the Saami Council, stressing that a small-scale test 'cannot be treated in isolation to ScoPEx's overall intentions' towards solar geoengineering [114]. Besides this global element, the letter invoked local concern: no agreements had been sought or reached with Saami and Swedish governments or societal groups. The SCoPex team agreed to suspend the test, and later announced that it was 'working with science engagement specialists in Sweden and seeking a host for engagement' [115]. The Advisory Committee also released a call for new members, emphasizing diversity and marginalized communities, and with language targeted towards (what they may see as) disruptive ENGO tactics [116]. The Saami Council has maintained its opposition, beginning a petition in June 2021 to shut the project down [117].

Comparison between SCoPEx and the SPICE stage-gate (*SAI2*) is unavoidable. The SCoPEx team favored clearer physical and technical thresholds for safe experimentation, and a focus on local dimensions in stakeholder engagement; the SPICE team engaged with uncertain societal prospections due to the demands of their stage-gate panel. As it

[2] This is not to say that such efforts do not exist. Corner et al. [99] notes efforts connecting stratospheric aerosol injection with 'natural' phenomena (e.g. volcanoes). Optimized modelling work also contains efforts to demonstrate regional variation and tailoring, which are critiqued in McLaren [100].

[3] The SCoPEx team saw the Advisory Committee's recommendations - calling for comprehensively engaging with the future implications of SCoPEx for wider politics - as restrictive and vague (again, recall the stage gate of SPICE, *SAI2*). A middle ground was found, calling for citizen engagements in the area of operation, solicited by an independent engagement group, on two aspects: local concerns, and ideal research governance (SCoPEx Advisory Committee [113]).

turned out, the SPICE panel had a point: it is not the (negligible and localized) physical risks that continues to concern opponents of small-scale tests, but “a slippery slope towards normalization and deployment” [112].

3.4. Ice protection

Ice protection is gaining more attention due to growing appreciation of the collapse of glaciers and ice sheets - ranging from the relatively small and local scale, e.g., in mountain ranges such as the Alps, to the continental scale in Antarctica and Greenland. Our QCA captures one case (Table 4): the Arctic Ice project (*IP1*).

We note that high-TRL glacier cover systems already encompass diverse efforts to mimic the reflectivity of snow and protect glaciers from melting [118–120]. Funding comes from commercial sources such as ski resorts, which means they tend to be clustered in high-prestige locations such as the Alps. Representing a low-tech, low-cost – if not low-effort – solution, such systems employ rolled-out ‘geotextile tarpaulins’ that reflect sunlight [118]. These lo-fi, localized solutions do not necessarily demand or benefit from further research, and have not yet been treated as controversial forms of climate intervention. For now, they represent cases of (partly) commercially motivated and funded protection of glacier ecosystems with recreational and touristic interest.

The Arctic Ice Project (*IP1*) represents a more immature technology – developing ‘hollow glass microspheres as a means for small, controlled and localized … surface albedo modification’ [121]. The project has been conducting or planning field experiments in Alaska (USA), Minnesota (USA), Manitoba (Canada), and Svalbard (Norway) [122]. The work in the USA has been well underway since 2017 [123]. But COVID-19 severely curtailed the expansion of field research to Manitoba and Norway, and there are few updates on progress [124]. But beyond a limited briefing from Geoengineering Monitor [123], critical ENGOs have not engaged.

Moreover, the project reflects more recent trends in framing: it explicitly rejects geoengineering, preferring ‘climate intervention’ as ‘action intended to improve the climate situation’ [121]. In doing so, it frames ‘ice restoration’ as part of wider innovations into ‘climate restoration’, that might ‘buy up to fifteen more years for our global economies to decarbonize’ and offers ‘a credible and timely path to significantly reduce climate-related losses’ [121]. The project also avoids the impression of non-establishment science - emphasizing collaborations with Canadian and Norwegian scientific institutions. At the same time, the project is reliant upon philanthropy, and appeals to innovation-focused actors through a vision to ‘continually develop the technology funnel for improved methods of ice restoration’ [122,124]. While current efforts at glacier protection are not seen to be problematic, forthcoming efforts at a larger scale could land them more firmly on the radar of ENGOs.

3.5. Enhanced weathering

Enhanced weathering strives to accelerate natural processes of weathering, wherein calcium- and magnesium-rich silicate rocks (e.g. basalt and lime) bind and remove CO2 in the atmosphere as they break down over time. Enhanced weathering is becoming more prominent for its stated potential to store carbon, at a relatively low cost, on the magnitude of 2.9 to 8.5 billion tonnes per year by 2100 [125–131]. Despite featuring in landmark reports [4], significant uncertainty remains on the effectiveness and permanence of sequestration, given the lack of field-scale evidence.

Our QCA captured ten experiments (Table 5), categorized in following sub-sections by spatial application: terrestrial environments such as croplands and rangelands (the Guelph wollastonite trials, *EWT1*; LC3M, *EWT2*; Working Lands Innovation Center, *EWT3*; and Project Carbdown, *EWT4*), coastal and marine environments (One Tree Reef, *EWO1*; Project Vesta, *EWO2*; OceanNETs, *EWO3*; and GGREW, *EWO4*), and the mining sector (FPX Nickel Corporation trials, *EWM1*; and CarbonVault™, *EWM2*).

In comparison to other technological clusters, very few enhanced weathering initiatives have been subject to visible, high-profile critique. Field trials center on the prominent rationale of co-benefits for regional ecosystems, agriculture, or industry, and how this may motivate acceptance and adoption among relevant stakeholders. But attention to governance and public acceptance varies significantly. The majority of

Table 4
Ice protection case studies.

Case abbreviation	Full name of experiment or project (if applicable)	Project leads or host	Year and location
IP1	Arctic Ice Project (formerly Ice911 Research)	Arctic Ice Project, led by Tom Light and Leslie Field	Since 2017 in Alaska and Minnesota, USA; planned for Manitoba, Canada and Svalbard, Norway

Table 5
Enhanced weathering case studies.

Case abbreviation	Full name of experiment or project (if applicable)	Project leads or host	Year and location
EWT1	Guelph wollastonite trials	Guelph University, led by Yi Wai Chiang and Rafael M. Santos	2015–2018 (and ongoing); southern Ontario, Canada
EWT2	Leverhulme Centre for Climate Change Mitigation (LC3M)	Leverhulme Centre for Climate Change Mitigation, University of Sheffield	Since 2018; Illinois, United States, north Queensland, Australia and Malaysian Borneo
EWT3	Working Lands Innovation Center	Working Lands Innovation Center, UC Davis (with Cornell College of Agriculture and Life Sciences), led by Benjamin Houlton and Whendee Silver	Since 2019; multiple sites across California and one site in New York
EWT4	Project CarbDown	Project CarbDown	Since 2020; across EU (i.e. Greece, Germany, Netherlands)
EWO1	One Tree Reef	Carnegie Institution for Science, led by Ken Caldeira	2014; Great Barrier Reef, Australia
EWO2	Project Vesta	Project Vesta	Underway after being delayed to late 2021; undisclosed coves in the Caribbean
EWO3	OceanNETs	GEOMAR Helmholtz Centre for Ocean Research Kiel, led by Judith Meyer and David Keller	Underway since 2021; Canary Islands
EWO4	GGREW	University of Oxford, Cardiff University, University of Southampton, University of Cambridge	Suspended in 2020 (due to COVID); Gulf of Eliat, Israel and Great Barrier Reef, Australia
EWM1	FPX Nickel Corporation	FPX Nickel Corporation	Since 2019; Decar Nickel District and Vancouver, Canada
EWM2	CarbonVault™	De Beers Group	Since 2020; Venetia mine in South Africa and Gaucho Kué in Canada

trials are positioned as scientific or technical processes, and lack of public outreach and engagement could in the future create space for criticisms on the harmful impacts on (poor) communities and local environments, high energy and water usage, or to generally label such efforts as greenwashing or camouflage [132–135]. Other trials display concerted and early attempts at stakeholder outreach (*EWT3*, *EWO3*), while others contain explicit orientation towards innovation-based, commercial actors and demands for funding and technical support (*EWT4*, *EWO2*).

3.5.1. Terrestrial enhanced weathering

Running from 2015 to 2018, the Guelph wollastonite trials (*EWT1*) were undertaken by agricultural scientists at the University of Guelph in partnership with the mining operation Canadian Wollastonite, to develop a large-scale carbon-sequestering option for regional farmers and fertilizer producers [136,137]. Despite being the only large-scale commercial field trials completed to date, the Guelph trials do not refer to enhanced weathering or geoengineering, but to agronomic research, novel ways to support farming business models, and new partnerships with regional industries and rural communities. Governance and public acceptability of the trials themselves are not emphasized – rather, the pitch of local co-benefits is central.

By contrast, the Leverhulme Centre for Climate Change Mitigation (LC3M; *EWT2*) explicitly orients itself towards the 'grand challenge' of climate change mitigation, with enhanced weathering in agricultural soils framed as a 'strategic 'negative emissions technology'' and 'climate geoengineering method under natural conditions' [138]. Ongoing since 2018, LC3M assumes the mantle of the first high-profile project on enhanced weathering in the world [131]. LC3M's trials are conducted in three agricultural ecosystems: sugarcane plantations in Queensland, Australia (James Cook University, 2020); palm oil plantations in Borneo, Malaysia; and a large mixed-crop agro-ecosystem in Illinois, United States [139]. Local partners have been integrated into trials. Couplings to agriculture and local economies are prominent, with envisioned co-benefits in higher production yields, crop protection from pests and diseases, less need for expensive fertilizers and pesticides, and improved water quality. LC3M understands risks as agricultural and environmental impacts, e.g., management of toxic leaching from mine tailings. There is an implicit market-based governance approach, with relevant actors informed of potential risks and action taken to ensure that supply chains are well-managed. Conversely, LC3M has stressed public engagement, undertaken within a separate project strand by researchers from the social sciences – key concerns identified include development of enhanced weathering taking too long to be a solution to climate change, potential effects on ocean ecologies, and the failure to address the root cause of climate change [134,135]. At present, however, LC3M has generated little explicit controversy.

The Working Lands Innovation Center (WLIC; *EWT3*) has been conducting experiments in California since 2019 and New York since 2021 [140]. The trials combine enhanced weathering, biochar, and organic compost 'in real live settings across a variety of cropping systems (corn, alfalfa, tomatoes, almonds), rangelands (coastal and interior), soils, and climates' [140–142]. Benjamin Houlton, the project leader, promotes WLIC as 'the largest enhanced weathering demonstration experiment on real farms in the world' [143]. Similar to other terrestrial enhanced weathering trials, WLIC emphasizes the potential for agronomic and agricultural co-benefits. Wedded to these, however, is an atypically earlier focus on public, policy, and stakeholder outreach: an 'Enhanced weathering protocol' as a template for researchers and practitioners, as well as plans to conduct cost-benefit analysis, commercialization assessments, and farmer surveys to explore possible barriers [142,144,145]. WLIC presents itself as a 'multi-stakeholder consortium' with researchers, state agencies, the mining and timber industry, farmers and ranchers, agricultural extension services, small business development, and indigenous communities [146,147]. In addition to one trial being conducted on agricultural lands belonging to the Pauma Band of Luiseño Indians, the project asked the Intertribal Agriculture Council to review the WLIC proposal early on and has emphasized its aims of integrating traditional ecological knowledge and engaging 'communities that had not previously been engaged in this type of work' [145]. For now, WLIC is under the radar of the public and ENGOs, with no comments or criticisms identified.

Project Carbdown (EWT4) is the only terrestrial EW project in continental Europe, with trials underway in Germany, Greece, and the Netherlands [148–150]. Similar to LC3M (*EWT2*), effectiveness is trialed with different mixtures of rock dust (sometimes paired with biochar, as in *EWT3*) and variation across ecosystems, local farming practices, and with an eye towards attaining co-benefits. Selling of carbon credits is a comparatively prominent objective of Project Carbdown – resulting in university-industry partnerships for improving monitoring capabilities, such as with the investment firm Carbon Drawdown Initiative, the IT infrastructure-monitoring firm Paessler AG, and field-service management software firm Fieldcode. As a result, a 'smart monitoring concept' that can be employed in fields, along with a small, low-cost 'Sugar Cone Device' claimed to enable real-time monitoring of carbon removal, are proposed as stand-ins for governance in a more traditional sense.

3.5.2. Ocean and marine-based enhanced weathering

In marine environments, there is a strong overlap with ocean alkalinity enhancement (for consistency, this paper's case-study abbreviations use 'EWO' for 'enhanced weathering, ocean'), where mining-sourced materials are added to oceans or on beaches, leaving the mechanical action of waves to (further) facilitate weathering processes [151–156]. Accordingly, we treat these approaches as a sub-set of enhanced weathering that differs primarily in locale.

In 2014, *One Tree Reef (EWO1)* was the first experiment to isolate the effect of acidification in a natural reef environment, taking place on the eponymous atoll in the Great Barrier Reef. Though illustrating how ocean alkalinization could alter seawater chemistry and counteract ocean acidification, such activities were neither envisioned nor subsequently described as 'geoengineering', but rather as basic science interested in understanding CO2 emission impacts on coral reefs. As such, this research attracted little attention from opponents of (marine) geoengineering – as with E-PEACE (*SAI1*) and early ocean-fertilization experiments. Key actors included researchers from the United States and Israel while, notably, the participation of Ken Caldeira and Katharine L. Ricke suggests cross-fertilization with other geoengineering research.

Project Vesta (EWO2) is one of the most high-profile projects within coastal or marine environments [157,158], intended to examine the carbon-sequestration potential of olivine-rich rocks added to a beach ecosystem. Crucially, Project Vesta sees itself at the vanguard of coastal enhanced weathering and as an innovation and governance blueprint for future projects – similar to WLIC (*EWT3*) for terrestrial activities. Co-benefits like beach nourishment and coastal development are highlighted alongside climate mitigation; activities ostensibly assume a multi-faceted understanding of risk as environmental, health-related, technical, and logistical, and with governance evolving according to a multi-stage 'project roadmap'. Project Vesta's set-up moreover trumpets an 'open source' approach, whereby any scientist in the field can contribute to the experimental design and analysis, with all data and methods promised to be made freely available.

Unlike other EW initiatives, Project Vesta is a non-profit, founded 'on Earth Day' in 2019 by San Francisco-based think tank Climitigation. Its ethos and approach reflects a geographic proximity to Silicon Valley, devoting substantial attention to self-promotion aimed at the public and innovation-oriented funders. Its homepage [160] sets slogans such as 'Wave goodbye to excess CO2' and 'Nature, accelerated' against glossy natural landscapes. Partnerships and strategic investments are central, with Project Vesta representing one of the first 'high potential' projects on carbon removal (pre)purchased by the online-payments platform Stripe [161], along with funding from Carbon Drawdown Initiative (who also provide support for Project Carbdown, [162]), Additional Ventures [163], and crowdfunding.

Unusually for an enhanced-weathering project, Project Vesta has been criticized by scientists and ENGOs, notably as a 'geohack' [157] that may have an adverse impact on ocean ecologies and does not necessarily address the root issue of climate change. Geoengineering Monitor [132] also opted to highlight the involvement of Eric Matzner, co-founder of Project Vesta and self-described 'biohacker' and 'brain entrepreneur'. Furthermore, the media and other researchers have raised concerns regarding Project Vesta 'overselling the potential or discounting the difficulties of its approach' [158]. In response, Executive Director Tom Green suggested the project aimed 'to fill in some of the scientific blanks and demonstrate it can be done for $10 a ton' [158]. Project Vesta's ostensible reaction to criticism is to promote the potential of enhanced weathering as a low-cost climate solution (with trials framed as scientific research) against the threat of climate change, while also obviating the need to consider other risks and concerns or to undertake stakeholder outreach as projects such as OceanNETs (*EWO3*) have done.

OceanNETs (*EWO3*) is an ocean-centered research project that launched its experiment off of the Canary Islands in late 2021. With Project Vesta (*EWO2*), OceanNETs represents the first wave of field trials in ocean-based enhanced weathering. The distinguishing characteristic of OceanNETs, among enhanced weathering trials, is its approach to stakeholder outreach and public engagement. Promoting its use of a transdisciplinary approach focusing on economic, political, legal, and social issues, it emphasizes a need for 'tight dialogue with stakeholders' and engaging in 'two-way communication' [164–166]. It remains to be seen whether this approach proves useful, but use of diverse techniques to integrate the perspectives of stakeholders and the public – cross-country surveys, interviews, lab experiments, and deliberative workshops in the Canary Islands and Norway – is a notable innovation. With regard to risks, explicit reference is made to issues of social and political acceptance, affordability, and societal impacts (e.g., food security, human safety), to be coupled with a comparative assessment provided to society and policymakers.

The Greenhouse Gas Removal by Enhanced Weathering (*GGREW*) project (EWO4), led by a multi-university UK consortium, aimed to assess biological responses to enhanced weathering and to explore its technological, economic, environmental, and social feasibility in marine and terrestrial environments [167,168]. Planned activities would have included a first-ever field trial in a 'controlled reef environment' (offshore in Australia and Israel) and to assess the viability of enhanced weathering with mining waste materials (in South Africa). In the end, field trials were downgraded to laboratory experiments in Oxford and Israel. Still, GGREW attracted scrutiny from ENGOs. One of the only references to GGREW activities in Israel and Australia comes from Geoengineering Monitor [132], which argued that the effects on biochemical processes and the marine food chain are unknown, and insinuated that one of the project leaders, Tim Kruger, tried to market ocean alkalinity enhancement with lime 'since 2008' and that his company Cquestrate received early-stage funding from Shell. Although trials never went ahead, critiques raise questions about the sufficiency of the project's governance focus on cost-benefit analysis and life-cycle assessment.

3.5.3. *Mining-sector enhanced weathering*

To explore trials in the mining sector, we distinguish between those activities undertaken in open-air settings (where mine tailings are processed to sequester carbon) versus more closed techniques, often coupled with carbon capture and storage or direct air capture, which are focused less on delivering long-term sequestration than providing a feedstock for industrial activities – often referred to as "carbon mineralization" or "mineral carbonation". We limit our discussion to cases that are still at trial stage, take place in the open air, do not provide feedstock for industrial processes, and are similar to efforts that mechanically or biologically foster an accelerated version of natural weathering processes.

The FPX Nickel Corporation trials (*EWM1*) are undertaken by a publicly traded mining firm (FPX Nickel Corporation) in collaboration with university researchers (from the University of British Columbia). Ongoing since 2019, the stated aim is for FPX Nickel to mitigate its climate impact – and retain its social license – by developing the 'world's first large-scale, carbon-neutral nickel operation' [169,170]. Like other enhanced weathering trials, the potential for co-benefits is featured, though in a more mining-specific fashion: including the possibility to stabilize tailing pilings and reduce the amount of dust generated on mining sites [171]. At present, there is no clear opposition to such research – though it has been name-checked in a recent information sheet put out by Geoengineering Monitor [132]. One key future implication is whether publicly traded firms in the mining sector, accountable to shareholders and under increasing pressure to reduce their climate impacts, might look more at enhanced weathering as a way to deal with mine tailings, generate positive press, retain their social license to operate, and pursue competitive advantage over international competitors.

CarbonVault™ (*EWM2*) is a field trial ongoing since 2020, funded by the mining conglomerate DeBeers Group, at open-air mining sites within South Africa and Canada [172–174]. Four types of enhancement are considered: physical, biological, chemical, and flue gas injection [175]. Similar to FPX Nickel (*EWM1*), explicit co-benefits include the potential to stabilize waste tailings and reduce the amount of dust generated on mining sites [171]. Framed as a project – together with academic partners from Canada and Australia – to capture and store carbon and pave the way for 'carbon-neutral mining operations' around the world, CarbonVault strives to develop 'hybrid' forms of enhanced weathering to improve its effectiveness. While no discernible opposition is apparent, the desire to explore an intersection between biotechnology and enhanced weathering [175] seems ripe for controversy. Future reactions to CarbonVault thus bear watching, to observe the effectiveness of 'hybrid' approaches and if such efforts attract strong backlash. The presence of an internationally recognized firm in DeBeers Group – notorious in certain circles – is also noteworthy for how this might affect public discourse.

4. Strategies, framing, and stakeholder involvement across technologies

The section above treated controversy as the result of contestations over what issues, actors, expertise, practices, and rules should hold sway over an experiment's or technology's development. In this section, we highlight common themes that have motivated the emergence of controversy and opposition across all the experiments in this study, and as they are evolving over time. This section also discusses other qualitatively salient aspects of the cases including unconventional science, indigenous knowledge and sovereignty, innovation, and jurisprudence. We summarize these cross-experiment insights in Table 6. Furthermore,

Table 6
Strategies, framing and stakeholder involvement across technologies.

Section	Generalizable themes
4.1 Oppositional strategies led by key ENGOs	• Modular strategy for contesting experiments: Slippery slope towards global-scale climate interventions; Local harms; Lack of consent; Reference to a UN 'moratorium'; Pressure 'hosting' governments • Currently most applied by an environmental NGO network • Many critical scientists advance similar concerns, but do not employ the same tactics
4.2 Strategies supporting experimentation, and societal appraisal	• Conventional-scientistic defense of experiments: Thresholds and 'safe zones'; University-/expert-based reviews; Need to separate basic science from political and commercial intent • Societal appraisal (e.g. Responsible Research and Innovation) becoming a key motif of governance • 'Societal appraisal' contested: e.g. Open-ended towards risk conceptions, critically-oriented 'slow science' vs. instrumental engagement on more bounded conceptions of risk
4.3 The framing of basic science or co-benefits, and 'camouflage'	• Outside of stratospheric aerosol experiments, experimenters deemphasize the term 'geoengineering' • Framings include: early-stage basic science, co-benefits with local economy, and eco-restoration and protection • Is this 'camouflage'?
4.4 Citizen, indigenous, and entrepreneurial involvement	• New actors and their agendas, concerns, and practices becoming prominent in experimentation: citizen science, indigenous actors (as a proxy for deeply localized actors and knowledge), and entrepreneurs, innovation, and industry
4.5 Rules of jurisdiction and jurisprudence	• Different bodies of norms and law stipulate different rules for 'legitimate' experimentation • Possibility for jurisdiction-shopping • What are latent or emergent bodies of regulation?

we show in Fig. 2 a combined timeline of all technology clusters with selected case studies.

4.1. Oppositional strategies led by key ENGOs

A key driver of opposition is an evolving alliance of ENGOs operating across solar geoengineering and carbon removal technologies, often independent of the specific type of experiment, location, or technology. Opposition has in the last decade been spearheaded by the ETC Group, the Heinrich Böll Foundation, the Center for International Environmental Law (CIEL), and the website Geoengineering Monitor. These marshal the attention and efforts of a much larger ecosystem of ENGOs who are less directly involved – but many of whom have a history of opposing research or experiments into climate intervention or geoengineering since the earliest days of ocean fertilization. These ENGOs are motivated – as are many scientists and other observers – by concerns that all such approaches present incentives for delaying decarbonization (or 'mitigation deterrence', see [176]), entrench inequities between heavy emitters and the least-developed and vulnerable polities, and reflect a deeply illusory techno-optimism over the management of complex natural systems (e.g. [177]).

A strategy for opposing experiments has reached a modular form which can be imported for understanding and contesting new technologies and experiments. A first key rationale and argument invokes both the global and local dimensions of harm, highlighting experiments as a slippery-slope towards geoengineering or as techno-fixes or 'geohacks' for the carbon economy and its politics, coupled with more localized issues of consent and socio-environmental impact. Another emphasizes reference to the Convention on Biological Diversity's 2010 voluntary guidance on restricting 'climate geoengineering' activities outside of small-scale scientific activities (for exact language, see [178]) - which the ETC Group and its allies describe as a UN-backed moratorium [95,177]. Opponents pressure the government in whose territory the experiment takes place, or to whose country the experiment's leading institutions belong – targeting their reputation in global governance and their alleged violation of international guidelines (usually, the 'moratorium' posed by [178]). These arguments in turn enroll an increasing array of actors, from other ENGOs, social groups (e.g. indigenous peoples), and media outlets, to surprised governments seeking to avoid controversy (e.g. Canada in *OF4*, Germany in *OF3*, and Sweden in *SAI3*), to bureaucrats and delegates at the international conventions at which rulings on solar geoengineering and carbon removal research are being developed (e.g. the Convention on Biological Diversity and London Convention and Protocol).

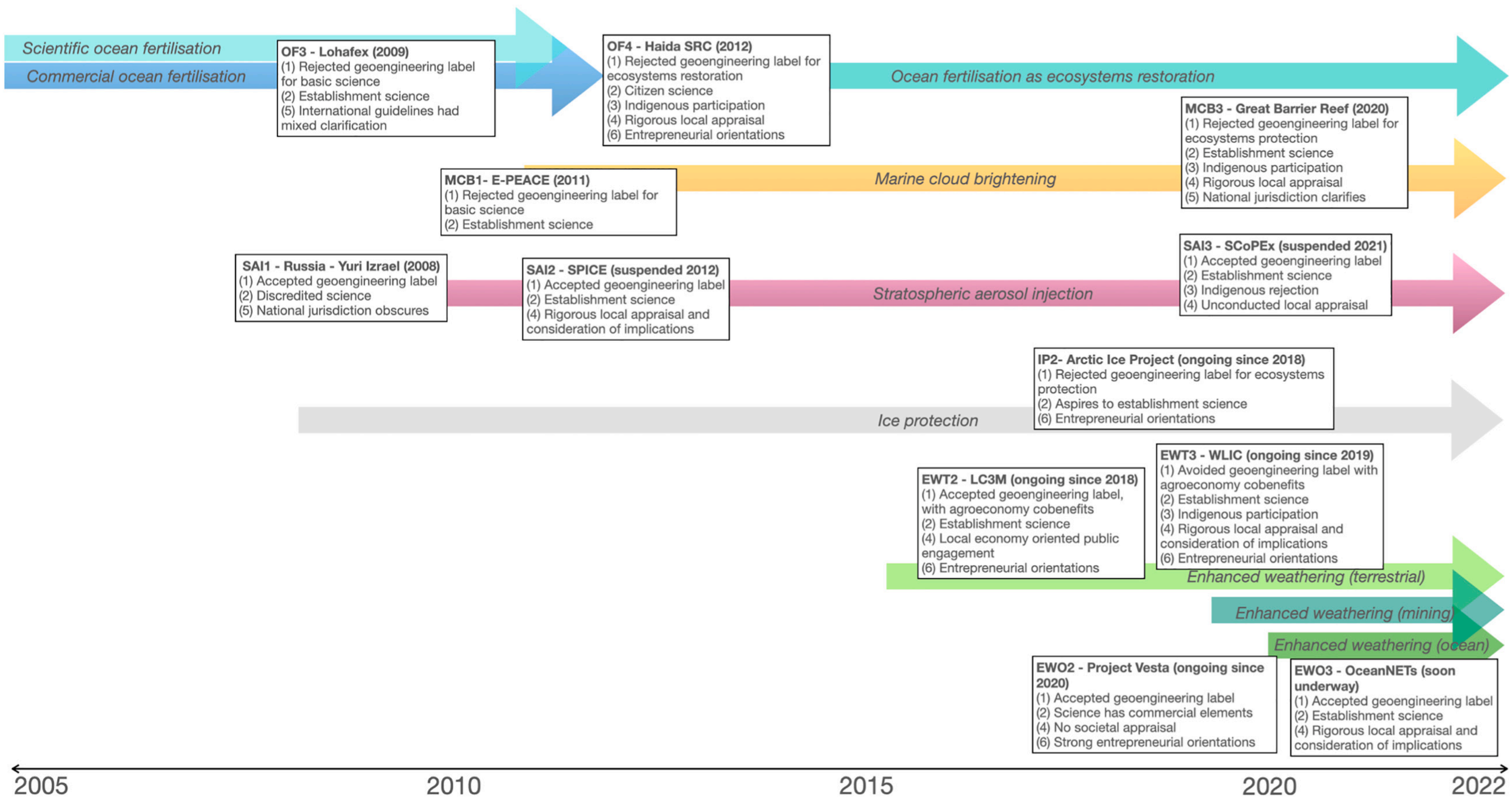
Controversy arises most visibly when these tactics and arguments are applied, even if their application remains selective. Moreover, the greatest visibility is generated when ENGOs apply pressure – rather than scientific networks, who maintain many of the same critiques, but not the same tactics. Ocean fertilization and solar geoengineering appear to have been strongly targeted so far; enhanced weathering has not. These hallmark efforts force experiment planners and other actors – governments, international regimes – to react directly, as well as grapple with the geoengineering label, a theme we return to in Section 4.3 on camouflage.

4.2. Strategies supporting experimentation, and societal appraisal

The arguments and governance procedures employed by experiment planners are also coalescing over time. A conventional-scientistic framing emphasizes the small scale of current experiments, determining *de minimis* impact thresholds for being allowed to conduct them (larger-scale terrestrial enhanced weathering activities appear to be the exception here, e.g. *EWT1–4*), university-based review procedures (*MCB1*, *EWO1*), and the separation of technical scientific work from political and commercial contexts via independent advisory panels, assessments and reviews, and institutional communications that include websites and public-facing briefs (*OF2*, *OF3*, *SAI3*, *EWO2*). Deliberately or implicitly, and regardless of the technology or approach tested, these efforts frame experiments as assessments that neutrally inform rather than purposefully shape decision-making, and bound the risks as technical and localized rather than socio-political and potentially far-reaching. As such, they are more facilitative representations of experimental work.

Unlike the oppositional ENGOs who clearly foreground their shared purposes (Section 4.1), the motives of experiment planners across case studies are varied and difficult to aggregate. Scientific researchers may hold a resilient conception of their work as explorative assessment that does not prescribe political action, while similarly rejecting the need for stronger oversight. They may also be well aware of the political or commercial implications, and instrumentally deploy arguments and procedures that minimize the need for scrutiny or seek to create a more favorable reception. It can be very difficult to distinguish one from the other.

In recent cases, facilitative framing efforts are more clearly pre-emptive, evolving alongside and anticipating critique (for example, in *SAI3*, see [109,179] for supportive arguments). Moreover, the justifications behind experiments are shifting as well, from emphases on technical assessment to clearer couplings with decision-making or commercial activities – posing new rationales for critics to scrutinize, and incentives for planners to forestall controversy. Justification for stratospheric aerosol injection fieldwork contains the strongest policy-oriented argumentation and is incorporated as such into an influential



Key
(1) Was the geoengineering label accepted or rejected? (section 4.1, 4.2, 4.3)
(2) Established or unconventional science networks? (section 4.2, 4.4)
(3) Were indigenous stakeholders involved? (section 4.4)
(4) Degree of societal (non-technical) appraisal (section 4.2)
(5) What jurisdiction and jurisprudence became relevant? (section 4.5)
(6) Were entrepreneurial actors involved? (section 4.4)

Fig. 2. Themes from selected case studies across technologies and time.

report by the US National Academies of Science ([74] for a critique, see [96]). Defenses of experimentation as scientific or technical have also been expanded by innovation-facing actors, historically in ocean fertilization, and increasingly in enhanced weathering (see Section 4.4, particularly Project Vesta, *EWO2*).

To engage with the concerns that motivate critique, research networks grounded in public engagement and critical social sciences emphasize the need for additional forms of societal appraisal – often referring to frameworks for governance of emerging technologies [22,180–183]. Practitioners of these frameworks often focus on the societal implications of science and innovation, and to reflect this, call for the inclusion of new kinds of expertise, stakeholder types, and rules of scientific conduct. Societal appraisal reflects efforts to forestall controversy by creating assessment, innovation, and decision-making that are more attuned to a wide range of demands and concerns. Still, the role and necessity of such frameworks are not settled in carbon removal and solar geoengineering experimentation. Experiment designers and opponents appeal to different understandings of what a safe and legitimate experiment is, and call for or ignore societal appraisal processes accordingly.

A key example is the responsible research and innovation (RRI) framework proposed by Stilgoe et al. [22], building on the 'stage-gate' review process of the SPICE test-bed (*SAI2*). The rationales for societal appraisal mirror oppositional arguments: firstly, that even technical, small-scale, and early-stage activities need to gain the input and consent of local stakeholders; secondly, that planners must anticipate rather than elide the potentially far-reaching political implications of their work. This is a direct response to the physical thresholds and allowed zones sought by some researchers that are more facilitative towards experiments (compare [179] to [22,27]).

SPICE (*SAI2*), LC3M (*EWT2*), WLIC (*EWT3*) and OceanNETs (*EWO3*) have adopted RRI-flavoured protocols, with OceanNETs providing an open-ended invitation via its Stakeholder Reference Group form for interested parties to consult and take part and WLIC collaborating with actual farmers, ranchers, and tribes, whose lands serve as the sites of trials. But there is no consensus around either the need for or shape of this mode of societal appraisal, with planners appealing to different understandings of the technical value and wider risks of experiments to shape their engagements with stakeholders. Many past and planned experiments focus on mitigating technical or environmental impacts, and are limited to institutional reviews, or engineering or impact assessments.

Other experiments challenge the RRI template: in comparison to the SPICE stage gate (*SAI2*), the SCoPEx team (*SAI3*) deemed grappling with future political implications too vague and restrictive, instead asking for concrete, instrumental questions to guide public engagement. Indeed, many scientists behind the scenes regard SPICE's review process as overly burdensome (*SAI2*). What is more, for all their efforts, the SPICE team did not appear to be successful in addressing ENGO concerns. Other initiatives, such as MCB experimentation over the Great Barrier Reef (*MCB3*) or Project Vesta (*EWO2*), have subsequently developed their own stakeholder engagement plans – though fewer details are available. But these operate under different governance jurisdictions and have so far avoided the geoengineering label, not to mention being largely overlooked by ENGOs – a comparison on effective societal appraisal is thus hard to make. And arguably the most in-depth and tailored engagement with local populations and authorities was conducted by the Haida Salmon Restoration Corporation (*OF4*), which ultimately had a mixed record: winning the local license it deemed relevant, but at the expense of a loss of reputation and credibility in the global context.

Stakeholder engagement is therefore becoming a motif of experimental governance, but it is unclear how many experiments favor open-ended appraisal and 'slow science' [9], perhaps with the clear and obvious exception of OceanNETs (*EWO3*). Emerging engagement processes may be robust; they may also disguise more instrumental forms of acceptance research or traditional scientific communication. RRI-informed societal appraisal certainly appears to motivate its own practitioners more so than the bulk of actors in science and industry [106]. For some of the more commercially inclined projects, engagement is an ad hoc solution that skirts the edges of stakeholder outreach (e.g. the 'smart monitoring concept' of Project Carbdown, *EWT4*).

4.3. The framing of basic science or co-benefits and 'camouflage'

Another theme from our QCA surrounds efforts to contest the geoengineering label. For research advocates, experiments may connect eventually to a large-scale or even planetary enterprise, but experiments themselves do not 'geoengineer' – they develop knowledge that fills in scientific blanks, reduces costs, and enables us to mitigate climate change (see quote by Tom Green of Project Vesta, *EWO2*), or informs whether upscaling could or should be done in the future (e.g. *OF3* and *SAI3*).

Self-labeling as 'geoengineering' therefore remains a key choice in framing experiments. The original framing of all solar geoengineering and carbon removal approaches as forms of deliberate and large-scale interventions [1] is breaking up as carbon removal has become normalized over solar geoengineering in post-Paris assessment, and as more regional- or local-scale approaches more firmly based in technological carbon removal or ecosystems management are coming to the fore. However, advocates of research into ocean fertilization and stratospheric aerosol injection still find it difficult to shake the label of marine or solar geoengineering. Moreover, there are terrestrial carbon removal approaches where implementation at large scale would make the geoengineering label accurate. The 'splitting' and 'lumping' of the umbrella term is far from settled.

Still, it is not only the technical accuracy of geoengineering that is relevant, but the term's association with the large-scale manipulation of the (human) environment, and its function as a shorthand for supposed time-buying strategies that permit the continued exploitation of fossil fuels. In earlier ocean fertilization and marine cloud brightening experiments, basic science – the biological pump of phytoplankton, or cloud dynamics – was a typical framing. Today, experiments outside of stratospheric aerosol injections are increasingly framed around coupling and co-benefits, with this being especially true for those on enhanced weathering. Ocean fertilization experiments – through framings of 'ocean nourishment' and 'ocean seeding' – now lean into restoring marine ecosystems and fisheries, and quietly maintaining the possibility for carbon sequestration and crediting [68]. In solar geoengineering work, marine cloud brightening experimentation in the Great Barrier Reef (*MCB3*) is integrated within a broad range of equally novel adaptive and resilience measures [184]; the Arctic Ice Project frames itself similarly (*IP1*). None of these projects mention marine or climate geoengineering.

Emerging enhanced weathering projects have tended to avoid the issues associated with the term "geoengineering" by highlighting entwined relevance for coupling with agriculture, mining operations, carbon crediting (*EWT3*, *EWT4*, *EWO2*), and supposedly addressing issues most in need of climate-mitigation efforts [129,185]. Concerning agriculture, enhanced weathering materials are envisioned as substitutes for costly fertilizer inputs, their application argued to thereby enhance soil fertility and crop yields – while also building on existing processes and infrastructure (*EWT1*, *EWT2*, *EWT3*, *EWT4*). Sourcing of materials for terrestrial enhanced weathering is notable for attempts to utilize waste materials from mining processes. This positioning seems to dodge questions of potential energy and water use while nestling up to politically popular concepts like the 'circular economy'. In the context of mining, the prospect of reduced GHG emissions and waste has been directly pointed to as a potential source of international competitive advantage (*EWM1*, *EWM2*), while ocean alkalinity enhancement is highlighted as a means to address ocean acidification or provide protection for the Great Barrier Reef (*EWO1*, *EWO4*). The supposed redress of such salient issues or iconic locations acts as a considerable political selling point.

Basic science and co-benefits framings act as ‘social camouflage’, where technologies can be described instrumentally or implicitly as something else to win societal license or avoid debate, and the conditions that might generate opposition are circumvented [186,187].[4] Here, this regards association with the ‘geoengineering’ label. But it is important to note that it is difficult to pinpoint whether use of such camouflage is deliberate or functional. There is a blurry line between avoiding associations with geoengineering and an accurate description of an experiment's intended motivations, e.g. towards co-benefits to encourage uptake by specific industry or resident groups. This is especially true for carbon removal approaches based in natural environments. Still, the record of camouflage when it comes to avoiding controversy is inconclusive – some experiments were connected only belatedly (e.g. *MCB1*, *MCB3*), while others (e.g. enhanced weathering experiments) are still evolving in the public eye. The debate on camouflage will depend on whether the technical and political dimensions of approaches as disparate as marine cloud brightening and enhanced weathering are sufficiently resolved, such that a critical mass of actors comes to (dis)associate them with deliberate, large-scale climate interventions.

4.4. Citizen, indigenous, and entrepreneurial involvement

Experiment planners and stakeholders reflect an increasingly diverse range of actors. Three participatory fault lines are emerging around who is permitted to frame their efforts within the cover of ‘legitimate’ science. Buck [17], in her engaging study of Russ George and the Haida Salmon Restoration Corporation (*OF4*), identifies two of these. The first, represented in the extreme by George, is the demarcation between the science produced by publicly funded scientific institutions (e.g. universities, scientific societies, and national research agencies) and that by individuals and networks without such accreditation. These could be enthusiasts with practical experience rather than formal training; they might possess appropriate qualifications but lack an institutional home. Beyond carbon removal and solar geoengineering experiments, this connects to conversations about the value of ‘citizen science’ in generating new angles of inquiry, increasing basic literacy in complex scientific issues, or unsettling previous results. But such work, if lacking in rigor, or if displaying intent and yielding results contrary to those of established scientific institutions, is readily derided as ‘rogue science’ [17]. Activities of citizen science in solar geoengineering and carbon removal appear limited, mostly to actors in ocean fertilization; in this limited sample, the fears of more established scientists appear borne out. But as the range of experimentation and framings expand, there remain lurking questions on the line between stewardship and gatekeeping.

The second can be seen in indigenous actors: the Haida (*OF4*), the Saami (*SAI3*), and the Pauma Band of Luiseño Indians as well as the Intertribal Agricultural Council (*EWT3*). These peoples and their representatives played different roles – Haida authorities and communities were key planners in the HSRC experiment, while the Saami Council staunchly opposed ScoPEx. But both point to the significance of local jurisdictions in the framing and appraisal of experiments, and highlight that technical work is richly and alternatively depicted (and for the Haida, motivated) by entwined understandings of local culture, economy, and environment. For the Haida, the experiment also leveraged a historic alienation to the Canadian polity – colonialism, and the then-government's questionable commitment to climate mitigation – that may have bled into how established scientific processes were viewed [60]. We should recognize the implications for locally-grounded social groups more broadly. The indigenous tend to be historically marginalized from conventional assessment and policy processes; they bring resonantly local institutions and networks to bear; they confront or combine established science with alternative knowledge systems. These dimensions are increasingly recognized through ‘Indigenous and Local Knowledge’ in global environmental assessments [188]. Scientific networks – especially experiment planners and their governance processes – should be wary of token or instrumental use of local actors, whether to defend or detract from experiments, or solar geoengineering and carbon removal as climate strategies.

A third fault line describes the rise of entrepreneurial actors, aesthetics, and business and funding models in the conduct of research and experimentation. These embody a broad range: individuals and networks in ‘citizen science’ (e.g. Russ George), NGOs and non-profits engaged in research advocacy and funding (e.g. Silver Lining at *MCB2*, Leverhulme Centre for *EWT2*), hybrid initiatives linking scientific and commercial work (e.g. *OF2*, *OF4*, *EWT4*, *EWO2*) and industry actors and corporations (e.g. *EWM1*, *EWM2*). Entrepreneurial actors are more attuned to dimensions of self-advertisement, self-labelling and branding, and camouflage: rejecting geoengineering, stressing business and local development co-benefits, often with an eye towards policy development, and buying time for mitigation.

These arguments leverage and expand the rationales long used by scientific actors to justify further research and experimentation (Section 4.2). Many entrepreneurial actors have sought connections with conventional scientific networks for legitimacy; others have leveraged their projects as attacks upon the supposed gatekeeping efforts of scientific institutions. But most have developed business- and innovation-oriented objectives beyond traditional scientific activity: development and patenting of approaches (*OF2*, *IP1*, *EWO2*), or carbon crediting and accounting approaches in carbon removal projects (numerous examples within ocean fertilization and enhanced weathering), or an orientation towards Silicon Valley networking and philanthropy to generate visibility and funding (e.g. Silver Lining at *MCB2*, Project Vesta at *EWO2*).

Scientists have displayed unease with these modes: marine-science communities largely circumvented arguments favoring commercial ocean fertilization and, more recently, personnel from solar geoengineering experiments (e.g. *SAI2* and *SAI3*) have rejected patenting. At the same time, two factors will continue to drive involvement of entrepreneurial actors: the funding-starved landscape of solar geoengineering work, where the capacity to motivate and organize philanthropical contributions remains significant (e.g. Silver Lining at *MCB2*), and the proliferation of carbon removal approaches framed in terms of purported co-benefits with local development and couplings with industry and innovation, including as a means to much-needed climate neutrality.

4.5. Rules of jurisdiction and jurisprudence

A final dimension regards the formation, interpretation, or selective choice of the rules that apply to experiments. These range from legal stipulations to informal but resonant conventions whose applications depend on the actors engaged in an experiment's planning and governance, as well as where it is held.

Some experiments have been held wholly within a country's territorial boundaries and should thus comply, according to the literature, with domestic law on pollution, environment, and liability [189,190]. The solar geoengineering experiments in Russia (*SAI1*) and Australia's Great Barrier Reef (*MCB3*) were conducted with the approval of national agencies - although due to perceived Russian geopolitical aims, the capacities for domestic law and governmental oversight to provide

[4] The original insight comes from Maines [186,187], whose research was on how the early vibrator's applications were couched within medical terminology and uses to gain acceptance in a more conservative society. The more general insight - camouflage circumvents rather than engages with the conditions that might create controversy - is without prejudice to the technology or issue in question. We might consider that within the climate domain, emissions reductions measures are increasingly filtered through co-benefits to air pollution, local development, and ecosystems services.

transparent governance are regarded differently in the two cases. Enhanced weathering experiments, furthermore, have been entirely located within national boundaries, but their compliance with bodies of domestic law remain unclear, even where benefits of such projects have been framed in terms of the international competitiveness of certain domestic sectors (*EWT1*, *EWM1*; note: interestingly, both with regard to Canada). At the same time, experiments conducted on indigenous lands (*MCB3*; *SAI3*; *IP1*) or planned by or in collaboration with indigenous actors (*OF4*, *EWT3*) highlight the relevance of sub-state jurisdictions - these may not always have a formal legal character, but constrain experiments through local governance procedures and resonant cultural understandings.

Activities occurring beyond or across national boundaries - for now limited to ocean fertilization experiments in international waters - are also subject to international frameworks. The Convention on Biological Diversity (CBD) is a guidance for restricting 'geoengineering' to scientific activity, but it is vague and voluntary [178,191]. The London Convention and Protocol (LC/LP, governing marine pollution) developed an initially non-binding 2008 decision on ocean fertilization into a 2013 amendment for binding regulation of 'marine geoengineering' [192,193], with new approaches being examined by its scientific advisory body [71,194] – but it remains restricted to the marine environment. Atmospheric regimes (e.g. ozone and transboundary air pollution) have relevant mandates for solar geoengineering activity, but remain uninvoked. Engagement is being sought at the UN Environmental Assembly [27,93] and UN General Assembly [195]. Curiously, discussion at the UNFCCC itself has been limited - the Paris Agreement implicates carbon removal [196], but solar geoengineering has never been raised in formal discussion. The objective and enforceability of regulation that each of those venues might provide would differ as well.

The result is a legal patchwork of potentially relevant binding and customary laws, spread across bodies of national legislation and international regimes with overlapping mandates - only a tiny fraction of which has specifically considered geoengineering experiments [190,194]. Some, like evolving decisions at the CBD and LC/LP, have been invoked by experiment opponents, but none have been tested. One danger of this is jurisdictional or forum shopping for the laws, definitions, and politics most favorable to the agendas of experiment planners or opponents [197,198]. The ETC Group repeatedly cites the CBD's 2010 decision as a moratorium, due to its long engagement in that forum. Lohafex (*OF3*) was compelled to adjudicate between the differing definitions on allowable scientific research posed by the CBD and the LC/LP [199]. And the experiments in Russia (*SAI1*) and Australia (*MCB3*) present alternative scenarios for the national oversight of experiments, and even deployment.

5. Conclusion

Planetary-scale 'geoengineering' remains a key motif for the contestation of early-stage experiments. The 'geoengineering' label is increasingly rejected by experiment planners on several grounds: the difference in intent and impact between research and deployment, disparities between solar geoengineering and carbon removal approaches, and co-benefits with industry and local development and ecosystems. For many scientific and commercial actors, 'geoengineering' does not facilitate their goals of integrating plural approaches into assessment, development, and policy at multiple levels. But it can be unclear when camouflage is deliberate or implicit. Certainly, projects that frame themselves as beyond geoengineering, or that emphasize other community co-benefits, garner less social opposition. On the other hand, camouflage also reflects a more granular, fit-to-purpose range of usage descriptions.

For those who remain wary of prioritizing technical criteria and near-term policy and business integration, geoengineering remains a resilient guiding concept for large-scale 'human ecosphere interventions' [3]. Indeed, all small-scale experiments investigate components of what are intended to be regional- or global-scale interventions; some with minimal transparency or wider consultation, and many with unclear incentives couched within the language of 'co-benefits'. Geoengineering is an elastic concept that incorporates new approaches as they emerge, and will continue to be invoked by ENGOs and scientists concerned about techno-optimism, the erosion of natural environments, and the inequities of the carbon economy. Experiment planners may wish the term away, but the concerns that motivate its use may still reappear under a different name – especially given the political allure of 'silver bullet' solutions to climate change.

Incoming actors must grapple with these dimensions. Geoengineering, as a term, does not need to be a pillar of an experiment's or project's framing – but the concerns about local or global inequities that motivate its use must not be dodged. With the rise of stakeholder engagement and consent as benchmarks in experimental conduct, entrepreneurial actors and funding models, and a proliferation of approaches and spaces in which experiments can be planned, new actors and jurisdictions are coming into play. In a plethora of local groups, national boundaries, and forms of international guidance, the key question is: Whose consent is relevant? Jurisdiction shopping, token stakeholder engagement, and issues surrounding philanthropy and commercial orientations present dangers for not only the legitimacy of experiments, but for the distribution of their outcomes.

Can the principles of societal appraisal be of aid to experiment planners in gaining feedback from local stakeholders, and even from entrenched critics? Even if a particular experiment side-steps immediate attention, it may influence how opposition engages with future projects of a similar kind. Experiments would do better to engage up front with the conditions of opposition, beginning with the engagement of local stakeholders as a prerequisite, informed by the input of global scientific and NGO networks. Planners can map and point to local co-benefits and risks – while also anticipating the perverse incentives and uncertainties of large-scale implementation, with dialogue and mitigatory measures built in as early as possible [200].

In closing, we highlight avenues for future research. We have attempted a broad mapping of issues, actors, and tactics for social contestation, across a range of early-stage experiments assessing immature approaches into climate intervention. The wide scope of our study shows that key actors, oppositional and defensive drivers and tactics, proposed frameworks for societal appraisal, as well as issues of unconventional science, indigenous knowledge and sovereignty, entrepreneurial motives, and appropriate jurisdiction are common and comparable across all the technologies, experiment types, and locations assessed. Our mapping brings together insights from past analyses [9,17–20], and lays the groundwork for studies that embrace greater empirical, methodological, and conceptual novelty.

Empirically, the number of experiments in these technological clusters will likely expand – enhanced weathering projects are rapidly increasing, while marine-based initiatives framed as 'eco-restoration' encompass new ocean fertilization projects, ocean-based enhanced weathering, and marine cloud brightening. Future inquiry could encompass pilots and prototypes for direct air capture or bioenergy carbon capture and storage, exploring if the same motivating issues and actors remain resonant. It will be especially important to map the engagements of commercial actors coming to the fore across multiple technologies. Comparative technologies could extend beyond carbon removal and solar geoengineering into areas of prior controversy – such as genetic modification in food or nuclear power. Indeed, we identify one potential overlap between biotechnology and enhanced weathering in open-air mines (*EWM2*), where the former is being employed to develop novel microbes that enhance the efficiency of weathering processes. New emphases on 'co-benefits' between emerging technologies could further highlight such intersections.

Methodologically, in-depth ethnographical work and site visits could be undertaken with experiment planners and/or oppositional actors, to shed new light on the mostly secondary analyses of this paper.

Engagements can also be further undertaken with decision-makers, publics, and other 'users' of the knowledge at the core of the experiments, that is, to inform how experiments should be designed or to better incorporate the concerns of stakeholders.

Conceptually, our mapping provides a foundation for further critical and normative work, evaluating experiments and their motivating issues in relation to justice [27] or the Sustainable Development Goals. Studies can also more strongly probe the shaping and emulative effects that the design of prior experiments – and the conduct of the scientific, commercial, and civic networks engaged therein – holds for future experimental practice or legal guidelines. Such inquiry would supplement our analysis of how key rationales and tactics underpinning the contestation of experiments have spread across time and technology through the operation of common networks and discourses (Sections 4.1–4.4).

Ultimately, our study reminds us that experiments into climate interventions do not occur in a techno-economic vacuum. We appeal to experiment or pilot planners, when confronted with choices over how to engage with societal appraisal or the political implications of research, to consider: Even if they themselves do not see far-reaching and uncertain implications of small-scale research, or global implications in relation to geoengineering, projects wishing to more cynically avoid scrutiny may choose to emulate their tactics and framings. The insular motives of one are a gamble for others, or even all. Rather, planners should seek to create and share best practices that can evolve alongside the relationship between society and emerging science on climate interventions.

Declaration of competing interest

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

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Annex 1. 44 existing or planned early-stage experiments into radical climate interventions from 1990 to present, narrowed to 21 for in-depth study via qualitative comparative analysis

Experiment/main Host	Technology	Year and location	Brief detail; included or excluded as in-depth cases
IronEX I (Moss Landing Marine Laboratories)	Ocean iron fertilization	1993; Eastern equatorial Pacific Ocean	Established proof of iron-seeded phytoplankton blooms. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
IronEX II (Moss Landing Marine Laboratories)	Ocean iron fertilization	1995; Eastern equatorial Pacific Ocean	Confirmed proof of iron-seeded phytoplankton blooms. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
Ocean Farming	Ocean iron fertilization	1998; Gulf of Mexico	Early actor in commercial ocean fertilization, whose founder later started Green Sea Ventures. Excluded – no record of controversy could be analyzed, and documentation of its mode of experiment and governance does not exist. However, elements thereof may be contained in Planktos, *OF1* and Climos, *OF2*.
SOIREE- Southern Ocean Iron Enrichment Experiment (University of Otago)	Ocean iron fertilization	1999; Southern Ocean	Investigated phytoplankton carbon sequestration at expanded scale and process. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
Green Sea Ventures	Ocean iron fertilization	1998; Equatorial Pacific	Early actor in commercial ocean fertilization. Excluded – no record of controversy could be analyzed, and documentation of its mode of experiment and governance does not exist. However, elements thereof may be contained in Planktos, *OF1* and Climos, *OF2*.
CarbonCorp USA	Ocean fertilization patented nutrient supplement	Founded late 1990s; No experiments conducted.	Early actor in commercial ocean fertilization. Ideas inherited by Ocean Carbon Sciences. Excluded – no record of controversy could be analyzed, and documentation of its mode of experiment and governance does not exist. However, elements thereof may be contained in Planktos, *OF1* and Climos, *OF2*.
Ocean Carbon Sciences	Ocean iron fertilization	Founded early 2000s; No experiments conducted.	Early actor in commercial ocean fertilization. Pledged to take part in SERIES; later reneged. Excluded – no record of controversy could be analyzed, and documentation of its mode of experiment and governance does not exist. However, elements thereof may be contained in Planktos, *OF1* and Climos, *OF2*.
EisenEX (Alfred Wegener Institute)	Ocean iron fertilization	2000; Southern Ocean	Investigated phytoplankton carbon sequestration at expanded scale and process. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
	Ocean iron fertilization	2001; Southern Ocean	Investigated phytoplankton carbon sequestration at expanded scale and process.

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Experiment/main Host	Technology	Year and location	Brief detail; included or excluded as in-depth cases
SEEDS I - Subarctic Pacific Iron Experiment for Ecosystem Dynamics Studies (University of Tokyo)			Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
SOFex - Southern Ocean Iron Experiment, North and South (Moss Landing Marine Laboratories)	Ocean iron fertilization	2002; Southern Ocean	Investigated phytoplankton carbon sequestration at expanded scale and process. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
Planktos I	Ocean iron fertilization	2002; Gulf of Alaska	Early actor in commercial ocean fertilization. First of Russ George's 'citizen science' efforts. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Planktos II, *OF1*.
SERIES - Subarctic Ecosystem Response to Iron Enrichment Study (Laval University)	Ocean iron fertilization	2002; Gulf of Alaska	Investigated phytoplankton carbon sequestration at expanded scale and process. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
CYCLOPS - Cycling of Phosphorus in Eastern Mediterranean (University of Leeds)	Ocean fertilization with phosphorus	2002; Eastern Mediterranean	Investigated the use of phosphorus in place of iron. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
EIFEX - European Iron Fertilization Study (Alfred Wegener Institute)	Ocean iron fertilization	2004; Southern Ocean	Investigated phytoplankton carbon sequestration at expanded scale and process. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
SEEDS II - Subarctic Pacific Iron Experiment for Ecosystem Dynamics Studies (University of Tokyo)	Ocean iron fertilization	2004; Subarctic Pacific Ocean	Investigated phytoplankton carbon sequestration at expanded scale and process. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
FeeP (Unclear)	Ocean iron fertilization	2004; Subtropical Northeast Atlantic Ocean	Investigated interaction between phosphorus and iron. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
SAGE - SOLAS Air–Sea Gas Exchange experiment (University of Otago)	Ocean iron fertilization	2004; Southern Ocean	Investigated phytoplankton carbon sequestration at expanded scale and process. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
KEOPS 1 - Kerguelen Ocean and Plateau compared Study (Centre National de la Recherche Scientifique)	Ocean iron fertilization	2005; Southern Indian Ocean	Investigated phytoplankton carbon sequestration at expanded scale and process. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
Planktos II	Ocean iron fertilization	2007; Near Galapagos Islands	Included as *OF1*, Section 3.1 – marked by clear controversy.
Climos	Ocean iron fertilization	No experiments conducted.	Included as *OF2*, Section 3.1 – was mentioned in the same breath as Planktos, despite a lack of experiments conducted.
Lohafex (Alfred Wegener Institute)	Ocean iron fertilization	2009; Southern Ocean	Included as *OF3*, Section 3.1 – marked by clear controversy.
KEOPS 2 - Kerguelen Ocean and Plateau compared Study (Centre National de la Recherche Scientifique)	Ocean iron fertilization	2010; Southern Indian Ocean	Unclear significance as an experiment. Excluded – no record of controversy could be analyzed, and its mode of experiment and governance is summarized in Lohafex, *OF3*.
Haida Salmon Restoration Corporation	Ocean iron fertilization	2012; Northwest Pacific Ocean	Included as *OF4*, Section 3.1 – marked by clear controversy.
Ocean Nourishment Corporation	Ocean fertilization with macronutrients	Unclear if any experiments conducted.	Framing of ocean fertilization as ecosystems restoration with co-benefits for local development and science, and time-buying for mitigation, with lingering elements of commercial ocean fertilization. Excluded due to lack of information, but mentioned in Section 3.1.
Oceanos	Ocean iron fertilization	Unclear if any experiments conducted.	Framing of ocean fertilization as ecosystems restoration with co-benefits for local development and science, and time-buying for mitigation, with lingering elements of commercial ocean fertilization. Excluded due to lack of information, but mentioned in Section 3.1.
E-PEACE - Eastern Pacific Emitted Aerosol Cloud Experiment (University of California San Diego)	Marine cloud brightening	2011; Monterrey, California, USA	Included as *MCB1*, Section 3.2 – raised no significant controversy at the time, but influenced the design and contestation of experiments,
Marine Cloud Brightening Project (University of Washington)	Marine cloud brightening	Delayed since 2018; Monterrey, California, USA	

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Experiment/main Host	Technology	Year and location	Brief detail; included or excluded as in-depth cases
			Included as *MCB2*, Section 3.2 – no experiments conducted, but influences the design and contestation of experiments.
Marine Cloud Brightening for the Great Barrier Reef (Southern Cross University)	Marine cloud brightening	2020; Great Barrier Reef, Australia	Included as *MCB3*, Section 3.2 – no controversy was raised, but influences the design and contestation of experiments.
Yuri Izrael's Field Experiment on Studying Solar Radiation Passing through Aerosol Layers (Roshydromet and Russian Academy of Sciences)	Stratospheric aerosol injection	2008; Saratov, Russia	Included as *SAI1*, Section 3.3 – no controversy was raised, but influences the design and contestation of experiments.
SPICE 'Test bed'- Stratospheric Particle Injection for Climate Engineering (Bristol University)	Stratospheric aerosol injection	2012; Norwich, UK	Included as *SAI2*, Section 3.3 – marked by clear controversy.
SCoPEx - Stratospheric Controlled Perturbation Experiment (Harvard University)	Stratospheric aerosol injection	Suspended 2021; Kiruna, Sweden	Included as *SAI3*, Section 3.3 – marked by clear controversy.
Arctic Ice Project	Hollow glass microspheres	Since 2017 in Alaska and Minnesota, USA; planned for Manitoba, Canada and Svalbard, Norway	Included as *IP1*, Section 3.4 – no controversy was raised, but influences the design and contestation of experiments.
Guelph wollastonite trials (Guelph University)	Enhanced weathering (agricultural)	2015–2018 (and ongoing); southern Ontario, Canada	Included as *EWT1*, Section 3.5 – no controversy has been raised, but influences the design and contestation of experiments, and embody interesting dynamics for future experiments.
Leverhulme Centre for Climate Change Mitigation (LC3M) (University of Sheffield)	Enhanced weathering (agricultural)	Since 2018; Illinois, United States, north Queensland, Australia and Malaysian Borneo	Included as *EWT2*, Section 3.5 – no controversy has been raised, but influences the design and contestation of experiments, and embody interesting dynamics for future experiments.
Working Lands Innovation Center (UC Davis)	Enhanced weathering (agricultural, with biochar and compost)	Since 2019; multiple sites across California and one site in New York	Included as *EWT3*, Section 3.5 – no controversy has been raised, but influences the design and contestation of experiments, and embody interesting dynamics for future experiments.
Project CarbDown	Enhanced weathering (agricultural, with biochar)	Since 2020; across EU (i.e. Greece, Germany, Netherlands)	Included as *EWT4*, Section 3.5 – no controversy has been raised, but influences the design and contestation of experiments, and embody interesting dynamics for future experiments.
One Tree Reef (Carnegie Institution for Science)	Enhanced weathering (ocean)	2014; Great Barrier Reef, Australia	Included as *EWO1*, Section 3.5 – no controversy has been raised, but influences the design and contestation of experiments, and embody interesting dynamics for future experiments.
Project Vesta	Enhanced weathering (coastal, ocean)	Delayed to late 2021; undisclosed coves in the Caribbean	Included as *EWO2*, Section 3.5 – no controversy has been raised, but influences the design and contestation of experiments, and embody interesting dynamics for future experiments.
OceanNETs (GEOMAR Helmholtz Centre for Ocean Research Kiel)	Enhanced weathering (ocean)	Planned to start in 2021; Canary Islands	Included as *EWO3*, Section 3.5 – no controversy has been raised, but influences the design and contestation of experiments, and embody interesting dynamics for future experiments.
GGREW (University of Oxford, Cardiff University, University of Southampton, University of Cambridge)	Enhanced weathering (ocean)	Suspended 2020 (due to COVID); Gulf of Eliat, Israel and Great Barrier Reef, Australia	Included as *EWO4*, Section 3.5 – no controversy has been raised, but influences the design and contestation of experiments, and embody interesting dynamics for future experiments.
FPX Nickel Corporation	Enhanced weathering (open-air mines)	Since 2019; Decar Nickel District and Vancouver, Canada	Included as *EWM1*, Section 3.5 – no controversy has been raised, but influences the design and contestation of experiments, and embody interesting dynamics for future experiments.
CarbonVault™ (De Beers Group)	Enhanced weathering (open-air mines)	Since 2020; Venetia mine in South Africa and Gaucho Kué in Canada	Included as *EWM2*, Section 3.5 – no controversy has been raised, but influences the design and contestation of experiments, and embody interesting dynamics for future experiments.

Source: Authors, with information on ocean fertilization experiments taken from Strong et al. 2009 and Williamson et al., 2012. The table shows: After screening 44 experiments or projects with planned experiments within these technological clusters undertaken or announced from 1990 to 2020/2021, we select 21 as in-depth case studies. Our choice of case studies is guided by two criteria. We focus on (planned) experiments that have been confronted by visible controversy and opposition. However, from the vantage point of 2021, we also look at experiments which raised no significant controversy at the time, but with hindsight have become more controversial, have clearly influenced the design and contestation of experiments, or continue to embody interesting dynamics for future experiments. We chose to be extensive as possible in our coverage of enhanced weathering cases, as it is the newest of the technological clusters.

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