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A survey of interventions to actively conserve the frozen North

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Abstract

The frozen elements of the high North are thawing as the region warms much faster than the global mean. The dangers of sea level rise due to melting glacier ice, increased concentrations of greenhouse gases from thawing permafrost, and alterations in the key high latitude physical systems spurred many authors, and more recently international agencies and supra-state actors, to investigate "emergency measures" that might help conserve the frozen North. However, the efficacy and feasibility of many of these ideas remains highly uncertain, and some might come with significant risks, or could be even outright dangerous to the ecosystems and people of the North. To date, no review has evaluated all suggested schemes. The objectives of this first phase literature survey (which can be found in a separate compendium (https://doi.org/10.5281/zenodo.10602506), are to consider all proposed interventions in a common evaluation space, and identify knowledge gaps in active conservation proposals. We found 61 interventions with a high latitude focus, across atmosphere, land, oceans, ice and industry domains. We grade them on a simple three-point evaluation system across 12 different categories. From this initial review we can identify which ideas scored low marks on most categories and are therefore likely not worthwhile pursuing; some groups of interventions, like traditional land-based mitigation efforts, score relatively highly while ocean-based and sea ice measures, score lower and have higher uncertainties overall. This review will provide the basis for a further in-depth expert assessment that will form phase two of the project over the next few years sponsored by University of the Arctic.

Keywords Arctic · Nature-based approaches · Climate engineering · Geoengineering · Climate action · Cryosphere

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1 Introduction

The Arctic is warming four times faster than the global average rate (Rantanen et al. 2022). The phase change from ice to water leads to drastic alterations in physical properties, including reduced albedo as bright snow yields to dark ground, and similarly, when sea ice transforms to dark ocean. Carbon-rich frozen soils in the permafrost zone have been a sink of carbon, but will by thawing release CO_2 and CH_4 into the atmosphere. In addition to local consequences, the thawing cryosphere will lead to catastrophic and irreversible global impacts, as over half of the 16 "global climatic tipping points" identified by Armstrong McKay et al. (2022) are high latitude processes. Climate damages from sea level rise and carbon release from permafrost thaw will lead to trillions of dollars in damages by 2100 (Yumashev et al. 2019; Brown et al. 2021; Hinkel et al. 2014).

The standard paradigm to guard against these impacts has been, and should continue to be, to limit carbon emissions. Combined with the removal of carbon from the atmosphere this was, and continues to be, a vital aim and the only long-term approach. However, regarding cryospheric tipping points, that ship may have already sailed as global emission mitigation has largely failed to materialize at the levels needed to limit global temperature rise above "safe" targets. Limiting warming to 1.5 °C above preindustrial target is essentially impossible under the emission trajectories explored by the IPCC (2022a, b), and humanity already has a 50% chance to overshoot 2 °C under current emission pledges (Meinshausen et al. 2022). Moreover, even if all greenhouse gas emissions were halted today, the Earth might still experience a certain amount of future warming due to inertia in the system. This poses the risk of crossing several of the potentially cascading Arctic and Northern tipping points (Armstrong McKay et al. 2022).

Many different climate actions and interventions have been suggested to counter or mitigate the effects of climate change in the Arctic and the high North boreal regions, and potentially contribute to positive climate impacts globally. Well-known approaches include afforestation and peatland restoration, but extend to expanding existing industrial-scale carbon capture technologies and prospective but highly controversial solar radiation management schemes. The various methods have been suggested by a very diverse set of groups and individuals across widely diverging media, policy papers and publications. There is very little or no clarity on what contribution and impacts these schemes may actually have – either globally or particularly in the North. However, interest in exploring such actions, interventions, and projects is most definitely growing (See for example the references to Solar Radiation Management in statements by the European Commission (2023) and UNEP (2023), both in light of increasingly dire findings of the effects of warming in the North, and the obvious global impacts of climate-related disasters. Political powers have not embraced such interventions, but are now open with some caution to their study (EU 2023; NASEM 2021; White House Office of Science and Technology Policy 2023). To date, however, there has been no concise study that seeks to provide a common set of metrics to evaluate and compare all suggested climate interventions.

This article presents a summary of suggested interventions, but it is by no means an in-depth evaluation or IPCC-style expert review. The goals of this survey are threefold: (1) create a comprehensive overview, by combing the literature, including published articles in the scientific and popular press, on-line blog posts, and informal suggestions for interventions and projects that have been proposed to mitigate, halt, or reverse the effects of climate change in the northern and Arctic regions, (2) to provide a standardized system of evaluation, and (3) to score all measures according to the evaluation criteria to provide a clearer understanding of the potential of specific techniques or projects. We provide a simple three-level evaluation of each according to a set of 12 criteria, based on what is said in the surveyed literature itself as far as possible. Although this cannot be a conclusive judgement on their feasibility, this literature review and overview study aims to provide a clear image of the most and least promising interventions and suggest an evaluation framework to assess the strengths and weaknesses of each. This review is therefore also meant to encourage debate, be a basis for further in-depth evaluation, and be a useful document for researchers, institutions and policymakers who want to know which measures might be feasible to support and develop further.

We first discuss the methodology used: what the main categories of interventions are and how they were they selected, and what criteria were used to evaluate them. Following this, we give brief descriptions and some key results of the scoring of each measure, before finally ending with some reflections on the merits and limitations of this study and indicating future research potential.

2 Methodology

2.1 Project selection and categorization

The main intent of this project was to provide clarity on which interventions and projects could feasibly help mitigate the effects of climate change in the Arctic over roughly the next 20 years. Any project claiming to have effect has been included in the survey with no pre-judgmental view whether it has merits or not; it is left to the evaluation to clarify risk, effectiveness, etc. This interval was chosen to be reasonably far enough ahead that technological advances could be extrapolated with some confidence, that the interval was commensurate with the time needed to reach international political consensus, and that it was within the lifetime of many readers and political actors. We tried to include as many projects as we could find that were intended to contribute directly to mitigating the effects of climate change. This means that adaptation schemes have been left out as far as possible, as they do not seek to mitigate climate change itself. We also excluded renewable energy production as this is already a well-known area. Some schemes we include might be considered as crossing these boundaries and be viewed as adaptation measures, e.g., artificial glaciers, or as measures that, according to some, do not directly contribute to mitigating climate change, such as Carbon Capture and Storage. In these and other borderline cases we have tried to justify their inclusion in the text.

We conducted our search for suggested measures in the scientific literature through search terms related to geography i.e.: 'Arctic geoengineering' 'polar climate mitigation', and to specific cryospheric elements, i.e. 'permafrost preservation' 'sea ice engineering'. From the found literature, and the literature already familiar to us, we proceeded on 'snowball searches', and followed the references that seemed promising in the articles. Apart from this exploration of the academic literature, we also searched for similar terms on google, and on forums like the geoengineering google group, again trying to follow any threads that appeared to us. There are likely additional schemes suggested in less accessible forums, or in languages unknown to us, or simply published before the internet and not digitized. Our review is based on publications available as of March 2023, and newer publications and material have therefore not been included.

The measures we evaluate can be grouped into seven broad categories based on the system they impact: modification of (1) ice sheets and glaciers, (2) sea ice and icebergs, (3) snowfall, (4) atmospheric processes and aerosols, (5) ocean and marine circulations and biochemistry, (6) land-based processes and ecosystems, and a separate group (7) that can be labeled as “industrial activities”. These are simply functional means through which we provide some order on widely varying proposals. Other divisions are possible, for example, according to function, as some are more traditional mitigation measures, whilst others can be said to fall under the heading of solar radiation management (SRM) or carbon dioxide removal (CDR). However, given that many of these measures fall outside such categorization, and the division in these latter terms is sometimes more a measure of their moral acceptability to society rather than a robust evaluation of their potential, we do not use this classification here.

2.2 Evaluation categories

We defined 12 different categories for evaluation (Table 1). Each category was scored on a three-point scale [low, medium, high, or its equivalent]. We determined these key evaluation-elements through internal discussions and selected those that could together provide a concise picture of the merits and defects of each measure. Many evaluation categories can be found in other reports on climate adaptation, mitigation, or climate intervention measures too, albeit that we selected and applied those to requirements imposed by the specificities of the Arctic (for instance, the importance of indigenous rights, or the difference between the global and Arctic potential of a measure). Because the scope of projects under evaluation is varied and large, for some measures specific categories can seem less relevant, or combinable with others. However, we found that the categories as they are presented here are able to give the most informative overview that includes the main issues to be taken into consideration for specific measures (for example the termination shock risk for Stratospheric Aerosol Injection, even if that is a less relevant issue for many of the other proposals). Because many of the measures are not just meant to be effective in the Arctic, we deem it important to differentiate between the potential effectiveness of ideas in that geographical region and globally. Relatedly, given the importance of tipping points and timely action in the Arctic, we included a sperate category of timeliness, beyond the technological readiness state of techniques to allow for a better understanding of both the state of the technology, and the potential for such measures to be significantly effective, even if the technology were already available.

Some of the categories used in this paper are commonly used in evaluations, such as, technological readiness level. However, given the variety of measures evaluated, some categories proved difficult to concretize, and some contain multiple grading elements. Scalability, for example, in this evaluation refers both to the physical scalability of a measure (how easy is it to expand glacier covering, for example) and to the efficiency of that scalability (how effective is incremental expansion). One category that was subject to particular internal debate is that of cost–benefit. Absolute costing of projects is a poor metric because inaction (not building/developing/researching a proposed intervention) would *not* be cost free. The cost–benefit section considers the perceived benefits of a successful intervention proposal in comparison with the costs of inaction.

While this scoring is necessarily simplistic due to the diverse nature of the categories and proposals, it allows for some statistical analysis, and provides a concise summary of the results. If there is large disagreement in the literature on the grade for some category, or

Table 1 Attribute categories and scoring system for evaluating interventions

Attribute	Description	Grading	Score	Description of scoring
Technological readiness level	Technological Readiness Levels (TRL) as defined by Horizon Europe to measure or indicate the maturity of a given technology	Low	1	Defined as a technology with TRL of between 1–3: TRL 1 – basic principles observed TRL 2 – technology concept formulated TRL 3 – experimental proof of concept
		Medium	2	Defined as a technology with TRL of 4–6: TRL 4 –validated in lab TRL 5 –validated in relevant environment TRL 6 –demonstrated in relevant environment
		High	3	Defined as a technology with TRL of 7–9: TRL 7 – system prototype demonstration in operational environment TRL 8 – system complete and qualified TRL 9 –system proven in operational environment
Scalability	Ability to replicate the same approach, and the efficiency of scalability	Low	1	Physically unable to scale; sub-linear/logarithmic efficiency of scalability
		Medium	2	Physically somewhat able to scale; linear efficiency
		High	3	Physically scalable; exponential efficiencies
Timeliness for near future effects	Significant difference within 20 years	Low	1	Too late to make a significant difference
		Medium	2	May make some difference, although questionable
		High	3	Implemented in time to make a significant difference
Potential to make a difference in Arctic and northern regions given enough time	Would the impacts of this solution benefit the North specifically, and are there specific benefits to deploying this solution in the North vs. elsewhere?	Low	1	No noticeable additional positive impact beyond the global average; technology is unsuited to the Arctic
		Medium	2	Statistically detectable impacts in the Arctic above the global average; no high latitude preferred location
		High	3	Impacts in the Arctic above the global average; technology ideally/preferably located here

Table 1 (continued)

Attribute	Description	Grading	Score	Description of scoring
Potential to make a global difference given enough time	Potential for the technology to make a difference globally, i.e., beyond the North	Low	1	Insignificant at a global scale
		Medium	2	Statistically detectable impacts
		High	3	Major impacts detected
Cost to Benefit Comparison	Cost comparison to other similar technologies in relation to the benefit derived	Low	3	Low cost of investment vs. cost of damages avoided (e.g., a few %) and/or less expensive in comparison to other measures which have similar impact
		Medium	2	Significant costs of investment needed but still much less expensive than cost of damages avoided
		High	1	Comparable to costs of damage
Likelihood of environmental risks	Environmental impacts from deployment	Low	3	Very limited effects which are site-specific to the deployment location only
		Medium	2	More widespread and possibly regional impacts going beyond the immediate deployment location
		High	1	Major, serious risks with a high disaster risk potential; multiple and cascading risks
Effects on Indigenous/local communities	Installation and long-term impacts on livelihood, social and health	Negative	1	Serious detrimental effects
		Neutral	2	No noticeable/negligeable positive or negative effects
		Positive	3	Significant benefits to communities
Ease of reversibility	The ability to reverse back to the original present state prior to deployment	Hard	1	Impossible or very difficult to reverse
		Medium	2	Possible with significant investment
		Easy	3	Easily naturally reversible

Table 1 (continued)

Attribute	Description	Grading	Score	Description of scoring
Likelihood of termination shock	Damage expected if stopped abruptly	Low	3	Low /insignificant termination shock or damage
		Medium	2	Medium / significant termination shock or damage
		High	1	High / very significant termination shock or damage
Suitability within current legal/governance structures	The degree within, and supported by existing governance including laws and policies	Low	1	Illegal/banned or legal regime not fitted at all to deployment
		Medium	2	Fitting within existing structures but some changes to policy would be needed to deploy at scale
		High	3	Currently legal to deploy and/or governance structures in place to facilitate it and/or financial incentives to develop it
Amount of attention within the academic community, public media, and industry	The level of attention from the academic community, public media and industry	Low	1	Fringe attention from individuals and/or abandoned ideas; low media attention; no commercial interest
		Medium	2	Some attention within the scientific community including published research and funding programmes; some media attention; attention of a few companies
		High	3	Many scientific papers and funding to research groups; significant media attention including “hype”; many companies looking at commercialization options

if it simply has not been evaluated, we classed it as "unknown". As many measures covered here are still largely undeveloped and unstudied, or were discussed in passing in obscure non-scientific publications, some categories have been intentionally left unscored. This also happened when we disagreed amongst ourselves over what score to give. However, if we could use what to us seemed like reasonable assumptions, then we preferred to assign a grade rather than populate the list with a great many "unknowns".

Obviously, a proposed intervention may not finally deliver as set out in the literature, which is why we also include a host of other metrics such as environmental and local community risks, degree of attention received, reversibility and termination shocks. While this multi-faceted approach may seem counterintuitive to some, the objective of this survey is neither to find the best approach nor to suggest that any one approach is the way forward. That falls within the realm of policymakers and planners. We here aimed to present a reasonably objective overview of the many and diverse factors that are necessary to make an informed decision.

3 Results

Table 2 provides the mean score of all interventions and also lists the number of unknown scores, and we give a brief explanation of each measure with some key findings from their scoring.

1. Stabilizing glaciers by cloud seeding

   This idea is aimed at increasing glacial mass gain by enhancing precipitation. There is limited research on this, but Wang et al. (2020) described a successful experiment on the Central Asian Muz Tau glacier. Beyond all uncertainties related to cloud seeding, the efficacy of this measure in the Arctic seems limited, and thus would likely be difficult and expensive to apply effectively at scale.
2. Increasing glacier thickness by local artificial snow production

   This idea aims to mitigate the decline of mountain glaciers by localized artificial snow deposition (Oerlemans et al. 2017). Although similar technologies are already widely used in ski resorts, and would probably be unproblematic and low risk, they are likely too costly and difficult to scale enough to be effective beyond specifically valuable mountain glaciers.
3. Glacier Albedo increase

   This measure seeks to mitigate glacial melting by increasing surface reflectivity. This is studied by the non-profit organization Bright Ice Initiative (https://brighticeinitiative.org/), who explore the possibility of increasing glacial albedo by applying a layer of hollow glass microspheres on top of it. Although the organization studies the usage of an already existing product, there are still many uncertainties around the feasibility and potential risks and side effects of its application.
4. Glacier insulation with fabrics

   This technique is already applied on specific glaciers, especially in the European Alps. Apart from worries about effectiveness, environmental impacts, and high costs (Huss et al. 2021), such a measure seems neither feasible nor scalable for any major deployment in the Arctic.
5. Artificial glaciers

Table 2 Interventions evaluated by domain with simple average score and number of unknown attribute scores (fuller descriptions in https://doi.org/https://doi.org/10.5281/zenodo.10602506) in Fig. 1

ID	Domain	Intervention name	Mean score	Unknown scores
1	Ice sheets and glaciers	Stabilizing glaciers by cloud seeding	2.08	0
2	Ice sheets and glaciers	Increasing glacier thickness by local artificial snow production	2.08	0
3	Ice sheets and glaciers	Glacier Albedo increase	1.82	1
4	Ice sheets and glaciers	Glacier insulation with fabrics	2.33	0
5	Ice sheets and glaciers	Artificial glaciers	2.42	0
6	Ice sheets and glaciers	Ice sheet stabilization via seabed curtains	2.20	2
7	Ice sheets and glaciers	Ice sheet stabilization via buttressing	1.25	0
8	Ice sheets and glaciers	Ice sheet stabilization by draining water or bed freezing	1.58	0
9	Ice sheets and glaciers	Pumping of water on ice sheets	1.33	0
10	Ice sheets and glaciers	Increasing humidity around glaciers and ice sheets	1.82	1
11	Icebergs	Iceberg management	1.67	0
12	Icebergs	Modular Iceberg creation by submersibles	1.58	0
13	Sea ice	Sea ice thickening	1.91	1
14	Sea ice	Sea ice Albedo Modification	2.22	3
15	Sea ice	Sea ice breakup in winter	1.45	1
16	Sea ice	Pykrete usage	1.92	0
17	Sea ice	Sea Ice growth management	1.73	1
18	Sea ice	Ice shields and "Volcanoes"	1.45	1
19	Snow	Snowfall enhancement	2.00	0
20	SRM/Atmosphere	Arctic winter high latitude seasonal stratospheric aerosol injection	2.27	1
21	SRM/Atmosphere	Cirrus cloud thinning	2.14	5
22	SRM/Atmosphere	Mixed phase regime cloud thinning over the polar oceans during winter	1.33	9
23	SRM/Atmosphere	Arctic Marine Cloud Brightening	2.36	1
24	SRM/Atmosphere	Space-based solar radiation management	1.89	3

Table 2 (continued)

ID	Domain	Intervention name	Mean score	Unknown scores
25	Oceans & marine	Improved fishing practices and management	2.40	2
26	Oceans & marine	Ocean fertilization	2.00	9
27	Oceans & marine	Seaweed and macro algae cultivation	2.88	4
28	Oceans & marine	Reflective foams and bubbles on oceans	1.67	6
29	Oceans & marine	Enhancing oceanic light availability below the photic layer	1.33	6
30	Oceans & marine	Promoting ocean calcifiers to sequester atmospheric carbon	2.33	0
31	Oceans & marine	Hydrological system modification - Ocean current modification	1.13	4
32	Oceans & marine	Artificial downwelling	1.50	0
33	Oceans & marine	Artificial upwelling	1.55	1
34	Oceans & marine	Re-oxygenating the Baltic	1.78	3
35	Oceans & marine	Ocean Alkalinity enhancement	2.18	1
36	Oceans & marine	River Liming	1.67	9
37	Land based measures	Wildfire management	2.75	0
38	Land based measures	Afforestation, reforestation and forest management	2.75	0
39	Land based measures	Reindeer herding	2.70	2
40	Land based measures	Rewilding	2.27	1
41	Land based measures	Conservation and restoration of peatlands and wetlands in taiga and tundra	2.58	0
42	Land based measures	Agricultural soil management	2.67	1
43	Land based measures	Stabilizing permafrost by covering it	1.36	2
44	Land based measures	Enhancing permafrost refreezing with air pipes	1.40	0
45	Industry	Radiative covering and building technologies/ Passive daytime radiative cooling	1.83	0
46	Industry	Bio-geoengineering (trying to increase crop albedo)	2.25	0
47	Industry	Built-environment albedo enhancement (white roofs etc.)	2.33	8
48	Industry	Arctic Methane capture and usage	1.75	7
49	Industry	Methane flaring (not industrial)	1.80	8

Table 2 (continued)

ID	Domain	Intervention name	Mean score	Unknown scores
50	Industry	Atmospheric Methane destruction: Tropospheric iron salt aerosol injection	2.25	0
51	Industry	Biochar	2.42	0
52	Industry	Bio-energy with carbon storage BECCS	2.36	1
53	Industry	Direct air carbon capture and storage DACCS	2.50	0
54	Industry	CO2 “snow” deposition in Antarctica, cryogenic CO2 capture	1.00	3
55	Industry	Direct ocean capture	2.00	3
56	Industry	Enhanced Weathering (on Land)	2.40	2
57	Industry	Black Carbon Reduction	2.55	1
58	Industry	Carbon capture and storage	2.58	0
59	Industry	Atmospheric Methane removal: Solar Chimney and Photocatalytic semiconductor technology	2.17	6
60	Industry	Atmospheric methane capture by zeolites	2.40	2
61	Industry	Polar chimneys	1.67	3

This idea refers to a sometimes-longstanding tradition amongst high mountain peoples to create structures that function like artificial ice storage sites (Nüsser et al. 2019). Apart from issues with effectiveness and scalability, it appears that such structures are mostly viable in specific mountainous geophysical contexts (Oerlemans et al. 2021) and therefore likely not be effective in the Arctic.

6. Ice sheet stabilization via seabed curtains

   This idea seeks to stabilize ice sheets subject to Marine Ice Sheet Instability by blocking deep, warm water access to their marine terminating glaciers (Keefer et al. 2023). The idea is part of an active research project but has a low TLR. Although significant uncertainties around its potential feasibility remain, it seems to be the most developed proposal to counter ice sheet instability.

7. Ice sheet stabilization via buttressing

   This idea has been abandoned after its proposal as costs and difficulties of building artificial supports for an ice sheet were deemed too great (Wolovick and Moore 2018).

8. Ice sheet stabilization by draining water or bed freezing

   This proposal aims to slow ice sheet collapse by pinning it to its bed (Lockley et al. 2020). The efficacy of such an intervention is disputed, the technological difficulties are challenging enormous, and to date only basic science and engineering calculations have been done.

9. Pumping of water on ice sheets

   This proposal would involve the large-scale pumping of water on ice sheets in the attempt to thicken them (Frieler et al. 2016; Feldmann et al. 2019). The feasibility and effectiveness of this idea is disputed (Moore et al. 2020), and appears to be further problematic because it would require a significant fraction of global energy production to operate.

10. Increasing humidity around glaciers and ice sheets

    This idea would likely seek to increase precipitation, but it is unclear how this would exactly work. It has been suggested in isolation, and has not been developed further (see klinkmansolar.com/knightfog.htm#U2).

11. Iceberg management

    This idea seeks to counter Arctic sea ice dissipation by managing icebergs and holding them in place, but has not been worked out or developed further.

12. Modular iceberg creation by submersibles

    A clip of a submersible that creates artificial icebergs features frequently in popular science videos on possible ways to mitigate climate change in the Arctic. However, it is very unclear how this will function in reality, and the idea seems not to have been developed further after its initial appearance in an international design competition (Griffiths 2019).

13. Sea ice thickening

    This idea involves the artificial thickening of sea ice by pumping water on top of it (Desch et al. 2017). Modeling studies have been conducted and it is currently a part of research projects. There are several uncertainties around the project, but it scores 'medium' on many of our categories, and may have useful local benefits.

14. Sea ice Albedo Modification

    This measure seeks to preserve sea ice by artificially enhancing its albedo. The main project studying this is the non-profit organization Arctic Ice Project, who explore the possibility to spread hollow glass microspheres on top of sea ice (https://www.arcticiceproject.org/theproject/). Several uncertainties about the feasibility and side-effects of potential distribution remain.

15. Sea ice breakup in winter
    The idea to increase outgoing radiation from the Arctic Ocean by removing the sea ice on top of it has been suggested several times in online fora and by Hunt et al. (2020). However, due to its many obvious downsides it is not explored seriously.
16. Pykrete usage
    The idea to use a slow melting mix of ice and sawdust for various purposes has come up in online fora several times, but it has not been specified how this could be considered beneficial.
17. Sea ice growth management
    Although the idea has only been proposed and not fully developed, it has been suggested that sea ice growth could be encouraged by artificially introducing cables or platforms around which ice could grow (see the Google group file stored on https://doi.org/10.5281/zenodo.10602506).
18. Ice shields and "Volcanoes"
    Similar to sea ice thickening, these ideas would seek to create thicker ice by pumping water on top of already existing ice. These ideas, however, have not been developed, and remain difficult to evaluate.
19. Snowfall enhancement
    There are already many operational projects that seek to encourage precipitation by seeding clouds. Most projects aim to increase water availability, but there have been some isolated suggestions to apply this at a larger Arctic scale (see the Google group file stored on https://doi.org/10.5281/zenodo.10602506). It seems, however, unlikely that this could be feasibly scaled and effective at over large and remote areas.
20. Arctic winter high latitude seasonal stratospheric aerosol injection
    Stratospheric aerosol injection refers to the idea of reducing incoming solar radiation by injecting aerosols into the stratosphere. Model studies show that this could effectively help bring down surface temperatures, and that different injection scenarios could help mitigate the decline of essential elements of the cryosphere (Lee et al. 2021). Although this measure is considered a relatively cheap and feasible to develop for the Arctic where existing aircraft can reach the stratosphere, it is highly controversial and comes with significant governance difficulties, moral issues, and risks, and there remain several important uncertainties in its biophysical effects (UNEP 2023, IPCC 2021, chapter 4).
21. Cirrus cloud thinning
    This is an idea to encourage outgoing radiation by thinning cirrus clouds (Storelvmo et al. 2013). Although it is often mentioned in review reports (see for example IPCC 2021 & 2022a), cirrus cloud thinning is not presently funded in research projects. There are, therefore, many unknowns about its potential risks, benefits, as well as efficacy and feasibility.
22. Mixed phase regime cloud thinning over the polar oceans during winter
    This is a relatively new and therefore unexplored idea to thin mixed-phase clouds to increase outgoing radiation (Villanueva et al. 2022). Our scoring reflects the many unknowns and uncertainties around this proposal.
23. Arctic Marine Cloud Brightening
    This is an idea to inject small cloud-creating particles in the air over oceans to brighten low level clouds and reduce incoming solar radiation (Latham et al. 2012). There are active, ongoing experiments, and the idea is studied at several sites around the world and could be developed in a timely manner to make a meaningful difference.

There are, however, questions about its potential cost and ability to scale, as well as about possible climatic and environmental side effects and risk of termination shock.

24. Space-based solar radiation management

    This refers to a plethora of ideas that seek to reflect incoming solar radiation before it enters the atmosphere (Baum et al. 2022). Many of these ideas, however, seem impractical and unfeasible, and will probably take too long to develop to make any timely difference UNEP 2023).

25. Improved fishing practices and management

    This is an idea to mitigate the direct and indirect emissions of the Arctic fishing industry by improving management practices and technological innovations (FAO 2022). Although such projects would likely come with significant environmental and economic benefits for local communities, it is uncertain if such measures could meaningfully contribute to mitigating climate change in the Arctic.

26. Ocean fertilization

    Ocean fertilization refers to the idea of adding nutrients to specific areas of the ocean to increase bio-productivity, thereby sequestering carbon (GESAMP 2019). Several active research projects are looking into different ways to achieve this. All these projects however come which with major uncertainties in almost all our categories.

27. Seaweed and macro algae cultivation

    This idea aims to capture carbon through the cultivation of macroalgae, which can then be used in various products or removed from the carbon cycle (Duarte et al. 2017). This measure could come with human and environmental side-benefits, although it scores many "unknowns" in our evaluation.

28. Reflective foams and bubbles on oceans

    This idea would seek to reflect incoming solar radiation by making ocean surfaces more reflective (Seitz 2011). There are several suggested ways to achieve this, but these are all understudied, and this measure, therefore, has many uncertainties around it.

29. Enhancing oceanic light availability below the photic layer

    This proposal would seek to enhance ocean bio-productivity by providing light to increase the potential depth for phototropic growth. This idea has been suggested only in isolation (see the Google group file stored on https://doi.org/10.5281/zenodo.10602506), and has not been developed further.

30. Promoting ocean calcifiers to sequester atmospheric carbon

    This is an idea to artificially grow shellfish or other calcifiers that would capture carbon in their shells, which could then be easily stored or used (Moore et al. 2023). This could have several beneficial environmental and human side effects, although it is not clear if the claims in the limited literature on this are realistic as they are only written by those arguing for development.

31. Hydrological system modification—Ocean current modification

    This refers to a group of ideas to influence the climate by modifying ocean currents. The proposals that fall under this group are for various reasons all hugely controversial and remain almost completely undeveloped.

32. Artificial downwelling

    This refers to the idea to increase carbon storage by pumping oceanic top-layer water down to increase bio-productivity. This idea, however, has not been widely explored and would likely come with significant side effects and risks, if at all feasible (GESAMP 2019).

33. Artificial upwelling

This idea involves artificially pumping up nutrient rich waters to the surface to increase bio-productivity. This has been studied in models and experiments with mixed results in terms of potential effects and high associated costs (NASEM 2022), as well as environmental risks (Levin et al. 2023).

34. Re-oxygenating the Baltic

This is an idea to increase the bio-productivity of the Baltic Sea which is currently in a severely deoxygenated state (Conley 2012). However, many questions remain about the potential ways and desirability of doing this, and hence its possible environmental and climate effects.

35. Ocean alkalinity enhancement

This proposal would seek to counter the acidification of the oceans and potentially allow them to sequester increased amounts of atmospheric carbon by adding alkalinity (Renforth and Henderson 2017). There are several means to do so, but none of the possible methods have been well studied (GESAMP 2019). Alkalinity enhancement could have significant Arctic and global potential, although its risks and side-effects remain largely unknown.

36. River liming

This is an idea to add alkalinity to river water to allow it to take up more CO_2 (Rønning et al. 2023). It is relatively unexplored and therefore comes with many unknowns in our scoring.

37. Wildfire management

Wildfires are expected to significantly increase in frequency and magnitude (UNEP 2022). Boreal forests will emit increasing amounts of CO_2 (Phillips et al. 2022) and deposit large amounts of albedo-reducing black carbon particles in the Arctic. Although wildfire management would come with many positive side effects, there are still questions remaining regarding the large-scale feasibility and the amount of emissions that could be prevented by better management practices in a warming world.

38. Afforestation, reforestation, and forest management

This is an idea to increase, restore, or better manage forest cover, and plays a major role in all climate scenarios (see IPCC 2022a). Although it has great potential, is relatively cheap, and generally comes with positive social and environmental side effects, the amount of land area required and the sustainability of specific species in a warming world are issues of some concern.

39. Reindeer herding

This refers to the idea of increasing bio-productivity and preserving permafrost by improving reindeer herding practices. This is currently being studied by the CHARTER project (charter-arctic.org/), but has many uncertainties around its potential impact in the Arctic. However, it is likely that it would have many positive side effects due to the crucial role of reindeer in many indigenous Arctic cultures.

40. Rewilding

In the context of the Arctic, this idea focuses on artificially reintroducing wild animals for land management purposes. It is strongly linked to the Pleistocene Park (https://pleistocenepark.ru/) initiative, which aims to discover whether the introduction of large animals could help preserve permafrost. This is one of the only actively studied ideas to preserve permafrost. However, due to practical issues around reproduction rates and costs, it seems very unlikely that this project could scale in time to limit permafrost thaw this century (Macias-Fauria et al. 2020).

41. Conservation and restoration of peatlands and wetlands in taiga and tundra

Peatlands and wetlands play an oversized role in the storage and capture of carbon, and their preservation and restoration has been widely accepted as an essential climate action (UNEP 2021). Generally, such actions come with numerous human and environmental co-benefits, and are relatively straightforward and affordable. Peatlands in the Arctic, however, are still relatively intact, and regional restoration can, therefore, only play a limited climate-positive role.

42. Agricultural soil management

This is an idea to increase the carbon uptake of agricultural soils through various means, depending on local contexts (Lessmann et al. 2022). The technologies for this are already widely available and can be implemented in a timely manner with generally limited risks and high co-benefits (IPCC 2022a). However, for the Arctic this measure would only have limited benefits due to the relatively limited amount of land devoted to agriculture.

43. Stabilizing permafrost by covering it

Similar to covering mountain glaciers, it has been suggested to preserve permafrost by covering it (see the Google group file stored on https://doi.org/10.5281/zenodo.10602506). However, given the many obvious objections to a large-scale project of this kind this idea has not been seriously explored.

44. Enhancing permafrost refreezing with air pipes

This is an idea to use an existing technology to keep permafrost upon which infrastructure is built stable, and expand it on a larger scale (https://klinkmansolar.com/kfrozen.htm). It however seems improbable that such techniques could be used to preserve permafrost in the vast and isolated regions of the North.

45. Radiative covering and building technologies/ Passive daytime radiative cooling

This refers to a set of ideas for the built environment that would enable passive cooling (Yin et al. 2020). Li et al. (2022) suggest that such materials could be used to prevent ice from melting, however, it seems unfeasible that this could be used at scale in the Arctic.

46. Bio-geoengineering (increasing crop albedo)

This is an idea to reflect more incoming solar radiation by planting land with crops that increase its albedo (Ridgwell et al. 2009). Because a large area of the Earth is covered with crops, this could potentially have a significant effect on global temperatures at relatively low cost and risk. However, as there is relatively little Arctic agriculture, this measure is not likely to be very relevant for the region.

47. Built-environment albedo enhancement (white roofs etc.)

This idea involves reflecting more incoming solar radiation by increasing the albedo of the built environment (NASEM 2015). The technology to do so already exists but would mainly have local benefits and would be unsuitable for the relatively sparsely populated Northern regions.

48. Arctic methane capture and usage

Some have suggested it might be possible to capture and use some of the methane or hydrates that escape the thawing permafrost of the Arctic (Salter 2011; Lockley 2012). There has been some public interest, and it has been mentioned by GESAMP (2019). However, these ideas remain largely unexplored and come with many unknowns.

49. Methane flaring (not industrial)

Similar to methane capture, Lockley (2012) and Stolaroff et al. (2012) suggest ways in which to flare off methane or hydrates escaping from permafrost. However, these ideas have not been explored or studied, and seem to be difficult to operationalize or scale.

50. Atmospheric methane destruction: Tropospheric iron salt aerosol injection

    It has been suggested that atmospheric methane might be removed by injecting iron salts, which, according to its advocates, would come with the added benefit of producing reflective clouds and a capacity to increase marine bio-productivity (Oeste et al. 2017). This idea is currently being studied but has received minimal coverage from sources other than those exploring it, and their claims are, therefore, hard to verify.
51. Biochar

    The application of biochar on land to increase carbon storage capacity is the most studied CDR method (Smith et al. 2023). Biochar comes in many different forms that could be applied depending on the context. Various applications could come with significant environmental benefits at relatively low cost and risk. However, application of biochar is not particularly suited for the Arctic and Northern regions for climate purposes.
52. Bio-energy with carbon storage (BECCS)

    BECCS refers to the idea of consuming biomass to generate electricity, and then removing the remains from the carbon cycle, preferably whilst also capturing emitted gasses (Pires 2019). Although the method scores a medium on TRL (Smith et al. 2023), questions remain on the carbon capture potential, scalability, and the effect of a scaled up BECCS process. The Northern region could potentially be a main source of biomass as forestry is already an important industry in the region.
53. Direct air carbon capture and storage (DACCS)

    DACCS refers to the group of technologies that seeks to remove CO_2 directly from the atmosphere and take it out of the carbon cycle (NASEM 2019). Although this technology is a main part of almost all climate mitigation scenarios and has recently gained major interest and financial investments, significant questions remain about its potential to scale up quickly enough to make a timely climate difference (Smith et al. 2023).
54. CO_2 "snow" deposition in Antarctica, cryogenic CO_2 capture

    This concept envisions establishing sites in cold regions worldwide, with a particular focus on Antarctica, where the environment could be further cooled to a temperature at which CO_2 solidifies and precipitates out of the air (Agee et al. 2013). Although there has been some interest in this idea, many questions remain, not least as to how the CO_2 would be feasibly stored once captured.
55. Direct ocean capture

    In this idea, electrochemical means are used to directly capture carbon from ocean water (Jayarathna et al. 2022). This is a relatively understudied method, and still comes with many unknowns. However, NASEM (2022) highlights its limited global potential, and GESAMP (2019) warns of environmental risks.
56. Enhanced weathering (on land)

    Enhanced Weathering involves artificially enhancing natural weathering processes, mainly by grinding up larger rocks to increase their exposed surface area (Schuiling and Krijgsman 2006). There are various research projects looking into this, and IPCC report (2022a) gives it a medium TRL. This measure likely comes with limited risks and some side benefits, although the carbon capture potential would likely be somewhat limited.
57. Black carbon reduction

    As black carbon reduces the high albedo of ice and snow, black carbon mitigation strategies could be important for the Arctic and Northern regions, especially as they would also have major health benefits (IPCC 2022a). Such efforts could moreover be deployed rapidly (Kühn et al. 2020) and are already well known. There are, however, great uncertainties about the magnitude of the climate effects of such mitigation (Kang et al. 2020), especially if they are achieved by simultaneously limiting other emissions that could have a cooling effect (von Salzen et al. 2022).

58. Carbon capture and storage

    This refers to a set of ideas that aims to capture and remove or store carbon emissions from point sources (IPCC 2005). Interest in this technology has been growing steadily over the years and is increasingly being implemented. It is however also clear that not all emitted CO_2 will be captured by this method, and that offset or usage of biofuels (See BECCS) would be needed (IPCC 2022a).

59. Atmospheric methane removal: Solar chimney and photocatalytic semiconductor technology

    This refers to a relatively novel and underexplored idea to suck in large volumes of air from which the atmospheric methane would be removed by photocatalytic reactors (Ming et al. 2017). Although some parts of this technique already exist or are the topic of research projects, many uncertainties still remain. Moreover, given that sunlight plays a key role in the working of the process, it seems unlikely that this measure will work especially well in the Northern regions.

60. Atmospheric methane capture by zeolites

    Several research projects are currently exploring the potential of porous minerals, zeolites, to capture methane and transform it into methanol or CO_2 (Tomkins et al. 2017; Brenneis et al. 2021). Because it is a new application, many open questions remain. However, one of the main benefits of this technology would be its very low cost (Brenneis et al. 2021).

61. Polar chimneys

    This is an idea for structures in the polar regions that would use heat exchange processes to generate electricity and cool sea water (Bonnelle and de Richter 2010), with Ming et al. (2014) claiming it could also increase snowfall. However, these proposals have not been further studied or commented upon.

4 Discussion

After scoring every measure in each category, several patterns emerged (Fig. 1). There are clearly some ideas that score consistently low and are therefore likely not worthwhile pursuing. Examples include hydrological cycle modification, ice sheet stabilization through mechanical buttressing or pumping water on their surface, and CO_2 deposition in Antarctica. Traditional mitigation efforts on land such as afforestation and peatland restoration score particularly high as a group. Several more experimental land-based CDR measures like biochar also score relatively high marks. The good scores of land-based measures contrast rather sharply to ocean-based projects which score lower and have much higher uncertainties overall (Fig. 1). There are not many specific proposals to mitigate the thawing of permafrost, or prevent the melting of sea ice and ice sheets. Moreover, the scalability and potential of most such measures are limited, and are characterized by several major uncertainties in our scoring. Most proposals require considerably more research, this is especially true for impacts on northern communities where many proposed interventions are simply without any research on their local impacts (Fig. 1). Measures aimed at both methane emission mitigation and atmospheric destruction, for example, have many uncertainties

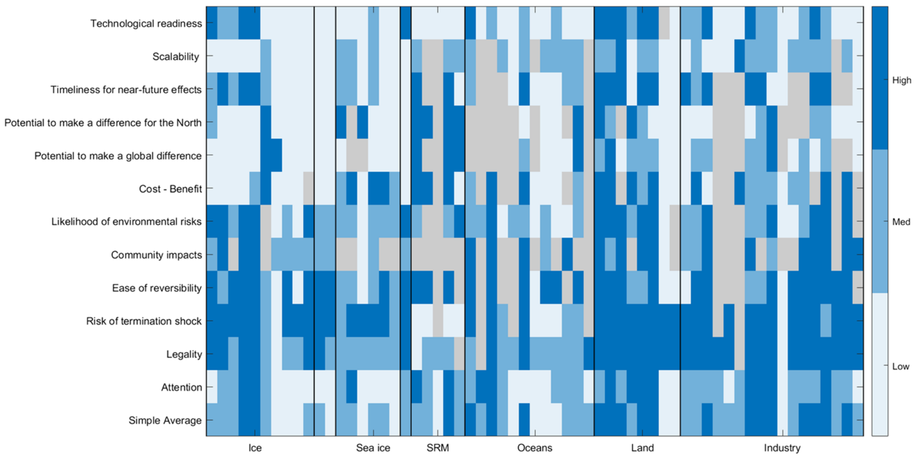

Fig. 1 Interventions and scoring in the 12 attributes and a simple average of the attributes without including unknowns. Grey indicates no score given. Light shades indicate low readiness/high risk/adverse impacts etc. while bluer shades represents higher acceptability. The interventions are grouped by broad domain and listed individually in Table 2. For example, Arctic seasonal SAI (#20 in Table 2), the leftmost column in the block labelled SRM, scores highly for attention, timeliness, effectiveness and scores low for legality and termination shock. Community impact is labelled unknown

which need to be addressed before any real judgement on their feasibility can be given. Some atmospheric solar radiation management schemes score very high marks especially when it comes to their potential for global influence, but could pose significant risks to humans and the environment.

To all these observations, however, it must be added that the grading system purposefully leaves open the relative importance of each category. This is crucial as it allows readers to use this review for different purposes. Measures like glacier covering and artificial glaciers for example score high marks in most categories, but are not scalable to have regionally significant climate effects and are therefore probably not the kind of schemes that could be truly useful in the Arctic and Northern regions. We also leave open the question on how to interpret “unknown” or unscored answers – although we agreed amongst ourselves that measures with too many unknowns should be treated as highly suspicious. It is finally up to the readers to conduct such a weighing of the scoring on their own values and focus, especially when considering highly controversial measures like Stratospheric Aerosol Injection (SAI). Although SAI scores high marks on most categories, it might entail some unacceptable risks, such as termination shock, or even moral or governance issues that are not well reflected in this evaluation.

Although this analysis did provide clear distinctions between promising and likely unfeasible proposals, the authors are well aware that this literature review is likely to have missed or misrepresented certain ideas due to practical limitations in terms of time, expertise, and resources. We tried to avoid scoring errors as much as possible by having each evaluation checked by other members of our group, however, we encourage others to interpret these findings as they wish and to improve upon them. We will start a second phase of this project in which experts will be asked to evaluate the projects – especially those that we deemed most promising in this first phase. Upon completion of this second phase in 2024, we expect a more comprehensive evaluation of projects that may be worthwhile pursuing. Furthermore, the project will be maintained on-line as new ideas are proposed, and others fall by the wayside.

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Declarations

Disclaimer The views and interpretations in this publication are those of the author(s). They are not attributed to the University of the Arctic, of the Arctic Centre/University of Lapland or GRID-Arendal and do not imply the expression of any opinion concerning the legal status of any country, territory, city or area of authority, or concerning the delimitation of frontiers or boundaries, or the endorsement of any product.

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