# Frozen Arctic

## Horizon scan of interventions to slow down, halt, and reverse the effects of climate change in the Arctic and northern regions

A UArctic Rapid Response Assessment

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# Key findings

- In this initial assessment, certain traditional land-based mitigation activities (such as afforestation and peatland restoration), as well as some more experimental carbon dioxide removal measures (for example, biochar), scored relatively high as potential interventions to address climate change.

- Some proposed solutions, such as hydrological cycle modification and carbon dioxide deposition in Antarctica, scored low against most criteria rendering them unsuitable for further consideration at this time.

- Generally, ocean-based measures tended to receive lower scores compared to land-based ones and exhibited higher degrees of uncertainty.

- There have only been a few suggestions on how to mitigate the melt or preserve the current extent of sea ice and ice sheets, and most of these measures come with significant uncertainties or limitations.

- Some atmospheric solar radiation management measures score very high in this assessment, particularly in terms of their potential global impact, although they also come with significant risks.

- The scores of the industry measures varied widely. Those related to methane especially showed many uncertainties.

- Significantly more research is required for most measures, particularly regarding their potential impacts on local communities.

- This preliminary, high-level analysis raises many questions that will be examined in a more comprehensive evaluation during Phase II of the Frozen Arctic project.

# Introduction

The polar regions and the northern boreal zone contain elements critical to the global climate system, including the Greenland and Antarctic ice sheets, Arctic sea ice, and Arctic permafrost (McKay *et al.* 2022; see box). Although the goal of the Paris Agreement on climate change is to limit mean global temperature rise to between 1.5°C and below 2°C, the world is currently on track for an increase of approximately 2-3°C. Already the Arctic is warming at a rate four times faster than the global average (Rantanen *et al.* 2022). At this level of warming, it is highly likely that many of these vital components will be irrevocably lost.

Rapid climate change, driven mainly by human activities, is leading to significant environmental changes both in the polar regions and around the world. Global sea levels are rising as the Greenland and West Antarctic ice sheets decay. The catastrophic and irreversible loss of permafrost at somewhat higher temperature thresholds has the very real potential to release vast amounts of carbon that could dwarf all national emission reductions pledges. The boreal forest, a globally important carbon store, is advancing northwards into tundra landscapes. Replacing tundra vegetation with low-lying shrubs, bushes, and trees lowers the surface albedo (reflectivity) and does not lead to increased carbon sequestration (Zona *et al.* 2022).

The loss of carbon, especially in the form of greenhouse gas emissions from permafrost thaw, coupled with reduced albedo, creates a positive feedback loop for global warming. By 2100, financial damages stemming from sea level rise and permafrost carbon feedback are projected to reach trillions of dollars (Yumashev *et al.* 2019; Brown *et al.* 2021). Additionally, further positive feedback is anticipated from the continued loss of Arctic sea ice. As sea ice melts, less sunlight is reflected back into the atmosphere and more solar energy is absorbed by the ocean. The risk of globally significant changes in high latitude ocean circulation patterns, such as the Labrador/subpolar gyre and overturning regions of the Atlantic Meridional Overturning Circulation, is closely associated with increasing meltwater from the Greenland ice sheet.

It is now acknowledged that global ambitions to reduce greenhouse gas emissions to reach the 1.5 °C target are highly unlikely and that there is only a 50 percent chance of limiting the increase to 2°C (Meinshausen *et al.* 2022). In addition to reducing emissions, there is a critical need for an unbiased examination of potential solutions to slow down, halt, and reverse the effects of climate change in the Arctic and northern regions and prevent tipping points from occurring.

Numerous interventions to address climate change have been proposed in policy papers, by interest groups, and within the scientific literature. Nevertheless, to our

### Box 1: Over 50% of climate tipping points with global repercussions are located in the Arctic

McKay *et al.* 2022 identify 16 major Global Climate Tipping Points. Nine of these are in the Arctic and northern regions (in order of the estimated global warming needed to pass their tipping point):

- Collapse of the Greenland ice sheet
- Abrupt thaw of northern permafrost
- Loss of Barents Sea ice
- Collapse of Labrador Sea current
- Collapse of northern permafrost
- Southern dieback of boreal forests
- Northern expansion of boreal forests
- Collapse of North Atlantic deep-water formation
- Collapse of the Arctic winter sea ice

Global consequences of these tipping points include:

- Amplified global warming
- Rapidly increasing sea level
- Changes in weather patterns and weather extremes
- Changes in ocean currents
- Ocean acidification, de-oxygenation
- Impact on ecosystems (fisheries, wildlife, plants)
- Impact on food production
- Impact on freshwater supply

knowledge, an overview that enables comparison of potential options for implementation in the northern and Arctic regions – the region where the majority of the tipping points are expected to occur – does not exist (Figure 1).

This short report presents the findings of Phase I of the Frozen Arctic Conservation project, a collaborative undertaking between the Secretariat of the University of the Arctic, GRID-Arendal, and the Arctic Centre/University of Lapland.

The goals of Phase I were:

1. To capture and effectively map out the range of possible interventions that exist or have been proposed to reverse, stabilize, or delay climate change impacts in the northern and Arctic regions for the benefit of the world;
2. To create a standardized evaluation matrix against which possible interventions could be scored;
3. To evaluate possible interventions according to an evaluation matrix in order to gain a preliminary understanding of the strengths and weaknesses of each.

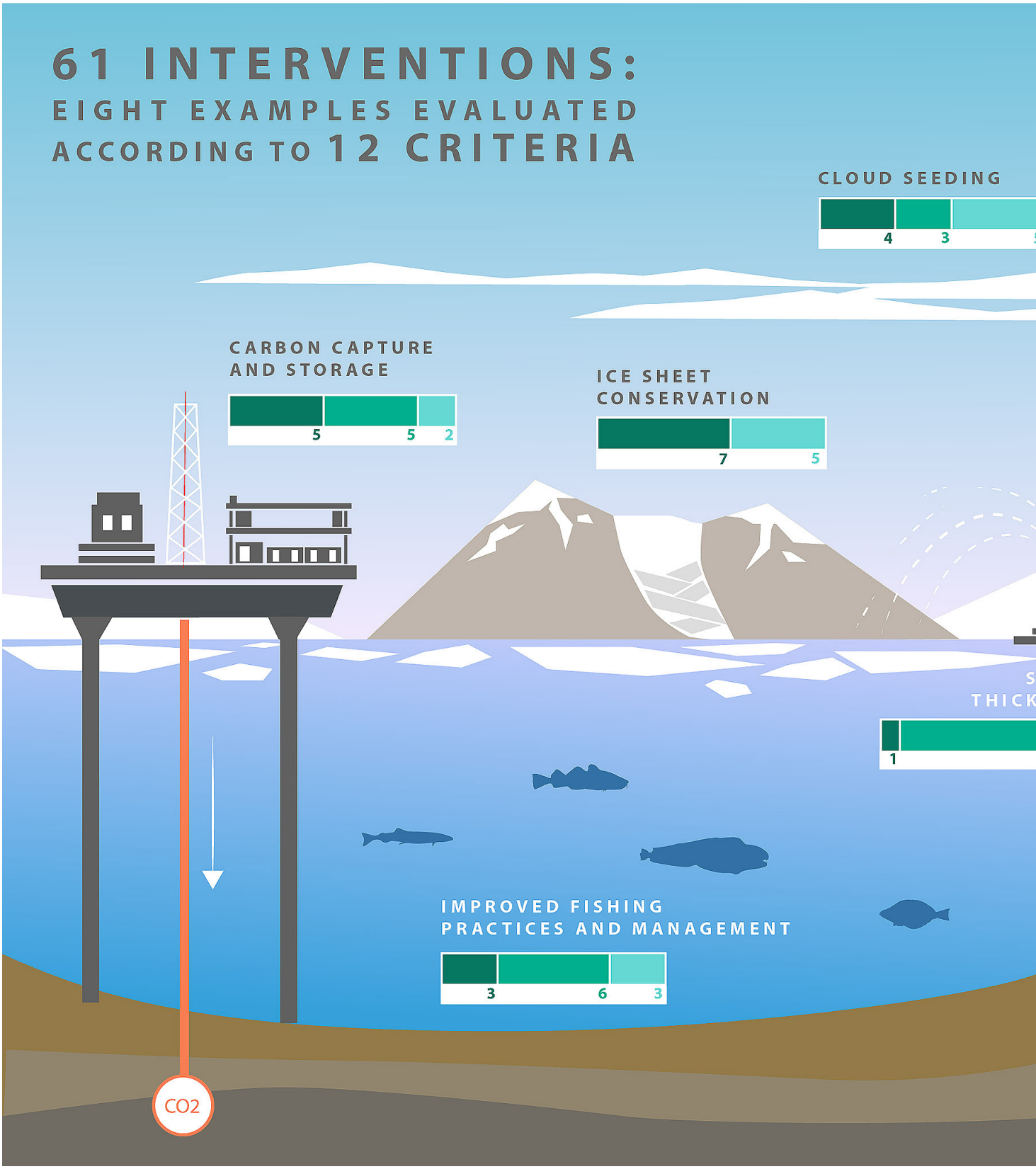
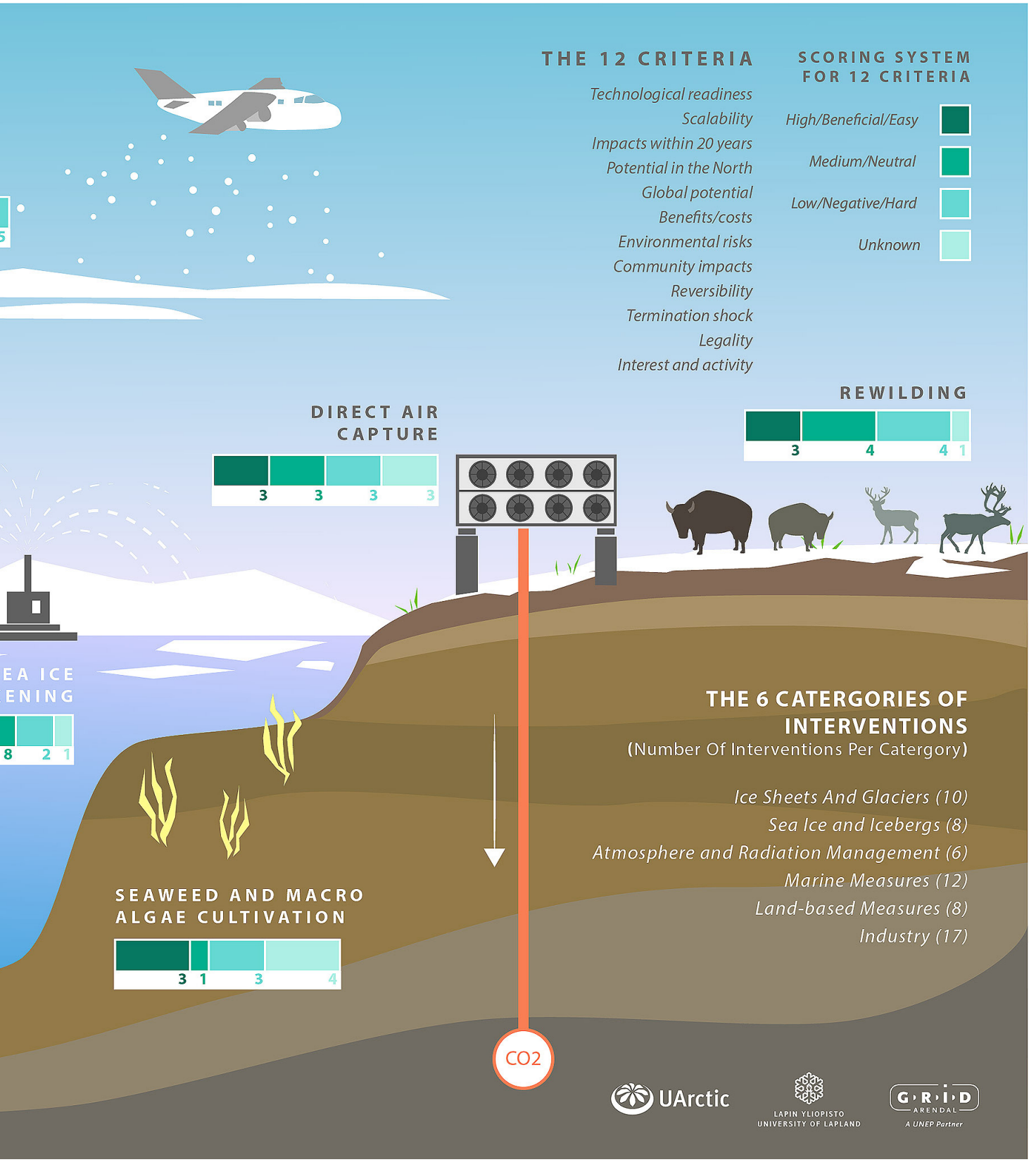



***Figure 1:*** *Comparison of selected interventions according to the 12 criteria.*


THE 12 CRITERIA
Technological readiness
Scalability
Impacts within 20 years
Potential in the North
Global potential
Benefits/costs
Environmental risks
Community impacts
Reversibility
Termination shock
Legality
Interest and activity
SCORING SYSTEM FOR 12 CRITERIA
High/Beneficial/Easy
Medium/Neutral
Low/Negative/Hard
Unknown
REWILDING
3 4 4 1
DIRECT AIR CAPTURE
3 3 3 3
EA ICE
ENING
8 2 1
SEAWEED AND MACRO ALGAE CULTIVATION
3 1 3 4
THE 6 CATERGORIES OF INTERVENTIONS
(Number Of Interventions Per Catergory)
Ice Sheets And Glaciers (10)
Sea Ice and Icebergs (8)
Atmosphere and Radiation Management (6)
Marine Measures (12)
Land-based Measures (8)
Industry (17)
CO2
UArctic
LAPIN YLIOPISTO
UNIVERSITY OF LAPLAND
GRID ARENDAL
A UNEP Partner

# Limitations of this report

This report constitutes a “rapid assessment”. The project team confined itself to a desktop review of available literature (including academic, grey, opinion forums, etc.) within a span of 3 months (January to March 2023). Extensive interviews with experts or stakeholders were not conducted. The documentation of interventions and subsequent evaluations were undertaken with the information available which, for many solutions, was found to be incomplete. Our cut-off date for papers and other information was March 2023; any information available after this date has not been included. Each solution was scored by a member of the author team and then reviewed by the other team members. We, therefore, emphasize that an extensive peer review should be undertaken in phase II of this assessment.

# Method

## Identification of possible interventions

Our intention was to identify and document the full range of interventions that have been proposed to reverse, stabilize, or delay climate change impacts in the northern and Arctic regions. This includes back-of-the-envelope calculations and "fringe" ideas through to seriously studied and researched ideas. For this reason, we have included ideas for which there is very little documentation.

The literature review took place between January to March 2023 and included online searches of academic literature, grey literature, as well as opinion forums (e.g., active Google groups). During the conceptual stage and prior to commencing the literature review, the project team developed the following initial solution list based on their own knowledge and grouped them into three broad categories (see Table 1).

As the literature review progressed, more proposed interventions presented themselves. Ultimately, the solutions were assigned to six categories: ice sheets and glaciers, sea ice and icebergs, atmosphere and radiation, oceans and marine, land-based measures, and industry.

***Table 1:*** *The initial list of interventions identified in the concept stage (prior to literature review).*

| Ecosystem management | Geo-engineering | Industry approaches |
|---|---|---|
| • Re-wilding<br>• Blue forest stimulation<br>• Fishing practices (trophic level)<br>• Potential increases in oceanic and coastal blue carbon with, for example, naturally retreating sea and coastal ice, seaweed farming<br>• Boreal forest management<br>• Peatlands and wetlands management in tundra and taiga<br>• Northern wildfire management<br>• Permafrost landscapes/tundra surface albedo stabilization and increases, e.g., whiter plants<br>• Herding and land management change | • Ice sheet stabilization via seabed curtains<br>• Pumping of water or snow making on the ice sheets<br>• Sea ice and glacier albedo increase<br>• Sea ice thickening to extend the ice season<br>• Sea ice breakup in winter by icebreakers to cool the ocean<br>• Modifying ocean density structure, e.g., pumping deep waters<br>• Glacier insulation and ice storage<br>• Increased snow season duration, e.g., albedo enhancement with particles<br>• Cirrus cloud thinning in the Arctic winter<br>• High latitude seasonal stratospheric aerosol injection<br>• Arctic marine cloud brightening | • Direct air capture potential in cool polar conditions<br>• Urban albedo enhancement, e.g., white roofs.<br>• Energy production in Arctic communities<br>• Energy sources for Arctic shipping & fishing fleets (hydrogen/ammonium)<br>• Arctic and northern process industries – raw materials and processing |

# Development of evaluation criteria and scoring process

A set of criteria was developed to establish a structured and comparable approach for documenting and evaluating potential interventions. Following internal discussions, the team defined a set of 12 criteria that were deemed to be important benchmarks for evaluating solutions (see Table 2). To provide a basis for understanding the performance of each intervention, the team also devised a simple 3-point scoring system (i.e., low, medium, high; negative, neutral, beneficial), along with qualifying statements.

Each intervention was researched, documented, and evaluated by a team member. Individuals were assigned interventions according to their background and prior knowledge related to each proposed intervention. A concise narrative evaluation of each intervention was included according to the 12 criteria. This was accompanied by a brief introductory description of the proposed solution and the challenge it claims to address.

To facilitate future statistical analysis, a numerical score was also assigned to each criteria. For parameters where “high” is the desirable quality, a score of 3 was given; “medium” was scored 2; and “low” was scored 1. Conversely, when “low” is the preferred quality, it was assigned a score of 3; 2 for “medium”, and 1 for “low”. If there was no available information, “unknown” was used.

The narrative descriptions and assigned scores were reviewed by at least one other person in the team. The evaluation results are presented in Table 3.

***Table 2:*** *Criteria and scoring system for evaluating interventions.*

| Criteria | Description | Scoring levels | Score | Scoring statement |
|---|---|---|---|---|
| Technological Readiness Level | Technological Readiness Levels (TRL) as defined by Horizon Europe to measure or indicate the maturity of a given technology (hereafter referred to as solutions) | Low | 1 | Defined as a technology with TRL of between 1-3:<br>TRL 1 – basic principles observed<br>TRL 2 – technology concept formulated<br>TRL 3 – experimental proof of concept |
| | | Medium | 2 | Defined as a technology with TRL of between 4-6:<br>TRL 4 – technology validated in lab<br>TRL 5 – technology validated in relevant environment (industrially-relevant environment in the case of key enabling technologies)<br>TRL 6 – technology demonstrated in relevant environment (industrially-relevant environment in the case of key enabling technologies) |
| | | High | 3 | Defined as a technology with TRL of between 7-9:<br>TRL 7 – system prototype demonstration in operational environment<br>TRL 8 – system complete and qualified<br>TRL 9 – actual system proven in operational environment (competitive manufacturing, in the case of key enabling technologies, or in space) |
| Scalability | Ability to replicate the same approach in terms of the space available, 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 | High ability to scale physically; exponential efficiencies |
| Timeliness for near-future effects. | Ability to get the solution in place in time to make a significant difference within the coming 20 years | Low | 1 | Implemented too late to make a significant difference |
| | | Medium | 2 | Implemented in time to 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 effects of this solution benefit the Arctic/northern regions specifically, and are there specific benefits to deploying this solution in the Arctic/northern regions vs elsewhere? | Low | 1 | No noticeable extra positive effect beyond the global average; technology is unsuited to the Arctic |
| | | Medium | 2 | Statistically detectable impacts in the Arctic above the global average; no difference to deploying the solution here or elsewhere |
| | | High | 3 | Very detectable impacts in the Arctic above the global average; technology ideally/preferably located here |

***Table 2:*** *Criteria and scoring system for evaluating interventions (continued).*

| Criteria | Description | Scoring levels | Score | Scoring statement |
|---|---|---|---|---|
| Potential to make a global difference given enough time | Potential for the technology to make a difference globally, i.e., beyond the Arctic/ northern regions | Low | 1 | Insignificant to be detected 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 inexpensive in comparison to other measures which have similar impact |
| | | Medium | 2 | Significant costs of investment needed but these still much cheaper than cost of damages avoided (e.g., 30%) |
| | | High | 1 | Comparable to damage |
| Likelihood of environmental risks | The likelihood of side effects on the environment as a result of the deployment of a solution | Low | 3 | Very limited effects which are site-specific to the solution deployment location only |
| | | Medium | 2 | More widespread and possibly regional impacts going beyond the immediate solution deployment location |
| | | High | 1 | Major, serious risks with a high disaster risk potential; multiple and cascading risks |
| Effects on Indigenous/local communities | The actual effect of installing solutions and long-term impact of solutions on communities, from a livelihood, social and health-related perspective. | Negative | 1 | Serious detrimental effects |
| | | Neutral | 2 | Unnoticeable/negligeable positive or negative effects |
| | | Beneficial | 3 | Significant benefits to communities |
| Ease of reversibility | The ability to reverse back to the original present state prior to solution deployment (once a solution is stopped). | Low (hard) | 1 | Impossible or very difficult to reverse |
| | | Medium | 2 | Possible with significant investment |
| | | High (easy) | 3 | Easily reversible naturally |
| Likelihood of termination shock | The level of damage that could be expected if the solution were to be stopped abruptly | Low | 3 | Low/insignificant termination shock or damage |
| | | Medium | 2 | Medium/relatively significant termination shock or damage |
| | | High | 1 | High/very significant termination shock or damage |

***Table 2:*** *Criteria and scoring system for evaluating interventions (continued).*

| Criteria | Description | Scoring levels | Score | Scoring statement |
|---|---|---|---|---|
| Suitability within current legal/ governance structures | The extent to which solutions are adapted to, can fit within, and are supported by existing governance including laws and policies | Low | 1 | Illegal/banned or legal regime not suited to deployment |
| | | Medium | 2 | To a certain degree 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 that solutions are receiving from the academic community, public media, and industry | Low | 1 | Very 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 from a few companies |
| | | High | 3 | Lots of scientific papers with large amounts of funding and ongoing research groups; significant media attention including "hype"; many companies looking at commercialization options |

# Results

Table 3 provides a summary of the results of the analysis undertaken by the project team. In total, 61 possible interventions were identified, documented, and evaluated according to the criteria. The full compendium is available at DOI: 10.5281/zenodo.8408608.

***Table 3:*** *Evaluation of interventions according to 12 criteria.*

| ID | Category | Title | Technological readiness | Scalability | Timeliness for near-future effects | Potential to make a difference in Northern + Arctic | Potential to make a global difference |
|---|---|---|---|---|---|---|---|
| 1 | Ice sheets and glaciers | Stabilizing glaciers by cloud seeding | High | Low | Medium | Medium | Low |
| 2 | Ice sheets and glaciers | Increasing glacier thickness by local artificial snow production | Medium | Low | High | Low | Low |
| 3 | Ice sheets and glaciers | Glacier albedo increase | Medium | Low | Medium | Low | Low |
| 4 | Ice sheets and glaciers | Glacier insulation with fabrics | High | Low | High | Low | Low |
| 5 | Ice sheets and glaciers | Artificial glaciers | High | Low | High | Low | Low |
| 6 | Ice sheets and glaciers | Ice sheet stabilization via seabed curtains | Low | Medium | Medium | Unknown/ High | High |
| 7 | Ice sheets and glaciers | Ice sheet stabilization via buttressing | Low | Low | Low | Low | High |
| 8 | Ice sheets and glaciers | Ice sheet stabilization by draining water or bed freezing | Low | Low | Low | Low | Low |
| 9 | Ice sheets and glaciers | Pumping of water on ice sheets | Low | Low | Low | Low | Low |
| 10 | Ice sheets and glaciers | Increasing humidity around glaciers and ice sheets | Low | Low | Low | Low | Low |

| Cost – Benefit | Likelihood of environmental risks | Effects on local/ indigenous communities | Ease of reversibility | Risk of termination shock | Suitability within current legal/ governance structures | Amount of attention in scientific journals, and public media, and currently ongoing research programs |
|---|---|---|---|---|---|---|
| High | Low | Neutral | Easy | Low | High | Low |
| High | Low | Beneficial | Medium | Low | High | Medium |
| High | Medium | Unknown | Easy | Low | Medium | Medium |
| High | Low | Beneficial | Easy | Low | High | High |
| Medium | Low | Positive | Easy | Low | High | High |
| Low | Unknown | Unknown | Medium | Medium | Medium | Medium |
| High | High | Neutral | Hard | High | Low | Low |
| High | Medium | Neutral | Easy | Low | Medium | Low |
| High | High | Neutral | Hard | Low | Medium | Low |
| Unknown | Low | Neutral | Easy | Low | High | Low |

***Table 3:*** *Evaluation of interventions according to 12 criteria (continued).*

| ID | Category | Title | Technological readiness | Scalability | Timeliness for near-future effects | Potential to make a difference in Northern + Arctic | Potential to make a global difference |
|---|---|---|---|---|---|---|---|
| 11 | Sea ice and icebergs | Iceberg management | Low | Low | Low | Low | Low |
| 12 | Sea ice and icebergs | Modular iceberg creation by submersibles | Low | Low | Low | Low | Low |
| 13 | Sea ice and icebergs | Sea ice thickening | Low | Medium | Medium | High | Low |
| 14 | Sea ice and icebergs | Sea ice albedo Modification | Low | Medium | Medium | Unknown | Unknown |
| 15 | Sea ice and icebergs | Sea ice breakup in winter | Low | Low | Low | High | Unknown |
| 16 | Sea ice and icebergs | Pykrete usage | Medium | Medium | Medium | Low | Low |
| 17 | Sea ice and icebergs | Sea ice growth management | Low | Low | Low | Low | Low |
| 18 | Sea ice and icebergs | Ice shields and “volcanoes” | Low | Low | Low | Low | Low |
| 19 | Atmosphere and radiation management | Snowfall enhancement | High | Low | Low | Low | Low |
| 20 | Atmosphere and radiation management | Arctic winter high latitude seasonal stratospheric aerosol injection | Low | Medium | High | High | High |
| 21 | Atmosphere and radiation management | Cirrus cloud thinning | Low | Unknown | Unknown | High | Unknown |
| 22 | Atmosphere and radiation management | Mixed phase regime cloud thinning over the polar oceans during winter | Low | Unknown | Unknown | Unknown | Unknown |
| 23 | Atmosphere and radiation management | Arctic marine cloud brightening | Low | Medium | High | High | High |

| Cost – Benefit | Likelihood of environmental risks | Effects on local/ indigenous communities | Ease of reversibility | Risk of termination shock | Suitability within current legal/ governance structures | Amount of attention in scientific journals, and public media, and currently ongoing research programs |
|---|---|---|---|---|---|---|
| High | Medium | Neutral | Easy | Low | High | Low |
| High | Medium | Neutral | Easy | Low | Medium | Low |
| Medium | Medium | Unknown | Medium | Medium | Medium | Medium |
| Low | Medium | Unknown | Medium | Low | Medium | High |
| High | High | Negative | Hard | Low | Medium | Low |
| Low | Medium | Neutral | Medium | Low | Medium | Low |
| Low | Medium | Unknown | Easy | Low | Medium | Low |
| Medium | Medium | Unknown | Medium | Medium | Medium | Low |
| High | Low | Neutral | Easy | Low | High | Medium |
| Low | Medium | Unknown | Easy | High | Low | High |
| Low | Unknown | Unknown | Easy | High | Medium | Medium |
| Unknown | Unknown | Unknown | Unknown | Unknown | Medium | Low |
| Low | Medium | Unknown | Easy | High | Medium | High |

***Table 3:*** *Evaluation of interventions according to 12 criteria (continued).*

| ID | Category | Title | Technological readiness | Scalability | Timeliness for near-future effects | Potential to make a difference in Northern + Arctic | Potential to make a global difference |
|---|---|---|---|---|---|---|---|
| 24 | Atmosphere and radiation management | Space-based solar radiation management | Low | Medium | Low | High | High |
| 25 | Marine measures | Improved fishing practices and management | High | Medium | Medium | Low | Low |
| 26 | Marine measures | Ocean fertilization | Low | Unknown | Unknown | Unknown | Unknown |
| 27 | Marine measures | Seaweed and macro-algae cultivation | Medium | Unknown | Unknown | Unknown | Unknown |
| 28 | Marine measures | Reflective foams and bubbles on oceans | Low | Medium | Unknown | Unknown | Unknown |
| 29 | Marine measures | Enhancing oceanic light availability below the photic layer | Low | Low | Low | Unknown | Unknown |
| 30 | Marine measures | Promoting ocean calcifiers to sequester atmospheric carbon | Medium | Medium | High | Low | Medium |
| 31 | Marine measures | Hydrological system modification – ocean current modification | Low | Unknown | Low | Unknown | Unknown |
| 32 | Marine measures | Artificial downwelling | Low | Medium | Low | Low | Low |
| 33 | Marine measures | Artificial upwelling | Medium | Medium | Low | Low | Low |
| 34 | Marine measures | Re-oxygenating the Baltic | Low | Medium | Medium | Unknown | Low |
| 35 | Marine measures | Ocean alkalinity enhancement | Low | Medium | Medium | High | High |
| 36 | Marine measures | River liming | Low | Unknown | Unknown | Unknown | Unknown |

| Cost – Benefit | Likelihood of environmental risks | Effects on local/ indigenous communities | Ease of reversibility | Risk of termination shock | Suitability within current legal/ governance structures | Amount of attention in scientific journals, and public media, and currently ongoing research programs |
|---|---|---|---|---|---|---|
| High | Low | Unknown | Unknown | High | Unknown | Medium |
| Medium | Medium | Beneficial | Easy | Low | Medium | Medium |
| Unknown | Medium | Unknown | Unknown | Unknown | Unknown | High |
| Low | Low | Beneficial | Easy | Low | High | High |
| Unknown | High | Unknown | Unknown | Medium | Medium | Medium |
| Unknown | Medium | Unknown | Unknown | Unknown | Medium | Low |
| Low | Medium | Beneficial | Easy | Low | High | Low |
| High | High | Unknown | Low | High | Medium | Low |
| High | Medium | Neutral | Easy | High | Medium | Low |
| High | High | Unknown | Easy | High | Medium | Medium |
| Unknown | High | Beneficial | Unknown | Medium | Medium | Medium |
| Medium | Medium | Unknown | Easy | Medium | Medium | Medium |
| Unknown | Unknown | Unknown | Unknown | Unknown | High | Low |

***Table 3:*** *Evaluation of interventions according to 12 criteria (continued).*

| ID | Category | Title | Technological readiness | Scalability | Timeliness for near-future effects | Potential to make a difference in Northern + Arctic | Potential to make a global difference |
|---|---|---|---|---|---|---|---|
| 37 | Land-based measures | Wildfire management | High | Medium | High | High | Medium |
| 38 | Land-based measures | Afforestation, reforestation, and forest management | High | Medium | High | Medium | High |
| 39 | Land-based measures | Reindeer herding | High | High | High | Unknown | Low |
| 40 | Land-based measures | Rewilding | Medium | Low | Low | High | Medium |
| 41 | Land- based measures | Conservation and restoration of peatlands and wetlands in taiga and tundra | High | Medium | High | Medium | Medium |
| 42 | Land-based measures | Agricultural soil management | High | Medium | High | Low | Medium |
| 43 | Land based measures | Stabilizing permafrost by covering it | Unknown | Low | Low | Low | Low |
| 44 | Land-based measures | Enhancing permafrost refreezing with air pipes | Low | Low | Low | Low | Low |
| 45 | Industry | Radiative covering and building technologies/ passive daytime radiative cooling | Medium | Low | High | Low | Low |
| 46 | Industry | Bio-geoengineering (to increase crop albedo) | Medium | Medium | Medium | Low | Medium |
| 47 | Industry | Built-environment albedo enhancement (white roofs, etc.) | High | Low | High | Low | Medium |
| 48 | Industry | Arctic methane capture and usage | Low | Low | Unknown | Unknown | Unknown |

| Cost – Benefit | Likelihood of environmental risks | Effects on local/ indigenous communities | Ease of reversibility | Risk of termination shock | Suitability within current legal/ governance structures | Amount of attention in scientific journals, and public media, and currently ongoing research programs |
|---|---|---|---|---|---|---|
| Low | Low | Beneficial | High | Low | High | Medium |
| Low | Low | Neutral | Easy | Low | High | High |
| Unknown | Low | Beneficial | Easy | Low | High | Medium |
| Low | Medium | Unknown | Medium | Low | High | High |
| Medium | Low | Beneficial | Medium | Low | High | High |
| Low | Low | Beneficial | Easy | Low | High | High |
| High | High | Negative | Hard | Low | High | Low |
| High | Unknown | Unknown | Hard | Low | High | Low |
| High | Medium | Neutral | Hard | Low | High | Medium |
| Low | Medium | Neutral | Easy | Low | High | Medium |
| High | Low | Beneficial | Easy | Low | High | Medium |
| Unknown | Unknown | Unknown | Unknown | Unknown | High | Medium |

***Table 3:*** *Evaluation of interventions according to 12 criteria (continued).*

| ID | Category | Title | Technological readiness | Scalability | Timeliness for near-future effects | Potential to make a difference in Northern + Arctic | Potential to make a global difference |
|---|---|---|---|---|---|---|---|
| 49 | Industry | Methane flaring (not industrial) | Low | Low | Unknown | Unknown | Unknown |
| 50 | Industry | Atmospheric methane destruction: tropospheric iron salt aerosol injection | Low | High | Unknown | Unknown | Unknown |
| 51 | Industry | Biochar | High | Medium | High | Low | Medium |
| 52 | Industry | Bio-energy with carbon storage (BECCS) | Medium | Medium | High | Medium | Medium |
| 53 | Industry | Direct air carbon capture and storage (DACCS) | Medium | Medium | Low | High | High |
| 54 | Industry | $CO_2$ "snow" deposition in Antarctica, cryogenic $CO_2$ capture | Low | Low | Low | Unknown | Unknown |
| 55 | Industry | Direct ocean capture | Low | Medium | Unknown | Unknown | Low |
| 56 | Industry | Enhanced weathering (on land) | Medium | Medium | Unknown | Unknown | Medium |
| 57 | Industry | Black carbon reduction | High | Medium | High | Medium | Low |
| 58 | Industry | Carbon capture and storage | Medium | Medium | High | Medium | Medium |
| 59 | Industry | Atmospheric methane removal: solar chimney and photocatalytic semiconductor technology | Low | Unknown | Unknown | Low | Unknown |
| 60 | Industry | Atmospheric methane capture by zeolites | Low | Medium | Unknown | Low | Unknown |
| 61 | Industry | Polar chimneys | Low | Low | Low | Low | Low |

| Cost – Benefit | Likelihood of environmental risks | Effects on local/ indigenous communities | Ease of reversibility | Risk of termination shock | Suitability within current legal/ governance structures | Amount of attention in scientific journals, and public media, and currently ongoing research programs |
|---|---|---|---|---|---|---|
| Unknown | Unknown | Unknown | Unknown | Low | High | Low |
| Low | Unknown | Unknown | Unknown | Unknown | Unknown | Medium |
| Medium | Medium | Beneficial | Medium | Low | High | High |
| Medium | Medium | Unknown | Medium | Low | High | High |
| Medium | Low | Neutral | Easy | Low | High | High |
| High | High | Unknown | Hard | High | Low | Low |
| Medium | High | Unknown | Easy | Low | High | Medium |
| Medium | Medium | Beneficial | Easy | Low | High | Medium |
| Unknown | Low | Beneficial | Easy | Low | High | Medium |
| Low | Low | Beneficial | Medium | Easy | High | High |
| Unknown | Unknown | Unknown | Easy | Low | High | Medium |
| Low | Low | Beneficial | Easy | Low | High | Medium |
| Unknown | Unknown | Beneficial | Unknown | Low | High | Low |

# References

*A full reference list for each intervention can by found in the compendium. DOI: 10.5281/zenodo.8408608.*


Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S. *et al.* 2022. Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*. 377, eabn7950. DOI:10.1126/science.abn7950

Brown S, Jenkins K, Goodwin P. et al (2021) Global costs of protecting against sea-level rise at 1.5 to 4.0 °C. *Climatic Change.* 167, 4. https://doi.org/10.1007/s10584-021-03130-z

Rantanen, M., Karpechko, A.Y., Lipponen, A. *et al.* 2022. The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment.* 3, 168. https://doi.org/10.1038/s43247-022-00498-3

Meinshausen, M., Lewis, J., McGlade, C. *et al.* 2022. Realization of Paris Agreement pledges may limit warming just below 2 C. Nature, 604(7905), 304-309.

Yumashev, D., Hope, C., Schaefer, K. *et al.* 2019. Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements. *Nature Communications.* 10. 10.1038/s41467-019-09863-x

Zona, D., Lafleur, P.M., Hufkens, K. *et al.* 2022. Earlier snowmelt may lead to late season declines in plant productivity and carbon sequestration in Arctic tundra ecosystems. *Scientific Reports.* 12, 3986. https://doi.org/10.1038/s41598-022-07561-1

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