CLIMATE OVERSHOOT COMMISSION

2. Assessing Adaptation, CDR, and SRM Options

Climate overshoot is increasingly likely, and greenhouse gas (GHG) emissions reductions alone—while it should remain the primary means to combat climate change—will probably be incapable of avoiding dangerous climate impacts. This document is intended to provide more detailed information regarding three additional approaches: adaptation, carbon dioxide removal (CDR), and sunlight reflection options (or solar radiation modification, SRM), building on briefs 3, 4, and 5 developed for the first meeting of the Commission. Following the recommendation of the Science Advisors, the starting points for this document are the comprehensive assessments of these options recently carried out by the Intergovernmental Panel on Climate Change (IPCC) as part of its recent Sixth Assessment Report (AR6). In what follows, options associated with adaptation, CDR, and SRM approaches are described in the context of their IPCC AR6 assessments. These overviews are followed by a discussion and early development of the concept of deployability as applied to adaptation, CDR, and SRM options.

Adaptation Options

Adaptation to climate change allows society to adjust and build resilience to escalating impacts, and to help nature do the same. Yet while adaptation to warming is essential, adaptation needs and capacity vary widely and there are hard limits to how much adaptation can achieve. Most adaptation involves local actions targeting local benefits. Because many adaptation actions are costly or politically difficult, adaptation is often inadequate. Adaptation shortfalls are universal, but are especially consequential for developing countries, which are facing the most severe climate impacts.

The "feasibility assessment framework," in which feasibility is defined as "the degree to which climate goals and response options are considered possible and/or desirable," represents the state of the art in assessing adaptation options (Singh et al. 2020). This framework assesses different adaptation options across six dimensions of feasibility: economic, technological, institutional, sociocultural, geophysical, and environmental.

Table 1 (below) summarizes the current IPCC feasibility assessments of 23 key options for adapting to the risks and impacts of climate change. These options overlap with one another to varying degrees, and they also overlap with some CDR options as indicated under "synergies with mitigation." ("Mitigation" is defined by the IPCC as emissions reductions plus CDR.)

From the perspective of working to address climate overshoot in an integrated manner, the most important attributes of adaptation options arguably are high potential feasibility and high synergies with mitigation.

The following presents brief descriptions of each of these options, organized on the basis of the system transitions to which they relate (based on Singh et al. 2020):

Land and ocean ecosystems

- **Coastal defence and hardening**—Conservation, restoration, and management of coastal ecosystems and associated ecological and social systems. Examples include building seawalls, storm surge gates, groynes, breakwaters, and artificial reefs; land raising; restoring and managing salt marshes; mangrove replanting; etc.

- **Integrated coastal zone management**—A strategic, holistic, and adaptive approach to coastal management which aims at sustainable, cooperative outcomes. One example is shoreline management plans, which seek to mitigate risks from flooding and coastal erosion. Another example is risk-based zoning and siting for marine aquaculture, which aims to ensure equitable use, support production, minimize conflicts with other uses, and maintain environmental integrity in the context of growing climate risks.

- **Forest-based adaptation**—Includes conservation, restoration, and improved land management such as reducing deforestation rates, forest reforestation and management, institutional mechanisms such as REDD+ (reducing emissions from deforestation and forest degradation), and ecosystem-based adaptation. The sustainable management of forests reduces vulnerability to climate change by, for example, regulating water flow and water resources and controlling soil degradation.

- **Sustainable aquaculture and fisheries**—Can maintain or improve livelihoods of those that depend on aquatic systems (freshwater and sea) for income. Diversification of aquaculture (by shifting toward new genetic strains or different cultured species) and fisheries (by shifting toward alternative species) can reduce vulnerability to climate change.

- **Agroforestry**—Broadly refers to integrating trees, shrubs, and reforestation initiatives with crop and livestock systems to improve land use efficiency, prevent soil erosion, facilitate water infiltration, and improve yields and water use. Agroforestry can enhance food security, help sustain livelihoods and reduce poverty, and make agriculture more sustainable.

- **Biodiversity management and ecosystem connectivity**—Includes strategies to restore, protect, and manage biodiversity such as through wetland management, ecosystem restoration, protected areas, facilitating species movement, etc. Ecosystem-based approaches help ensure protection against floods and other climate-related hazards, prevent soil and coastal erosion, and regulate microclimates. Ecological corridors bolster ecosystem adaptation processes and preserve ecosystem services. Adaptive management of ecosystems through an iterative process can maintain a wide range of ecosystem services that help stabilize local climates.

- **Water use efficiency and water resource management**—Improving irrigation efficiency includes a range of strategies to reduce leakages (e.g., lining of water channels), reducing water consumption (e.g., through drip or sprinkler irrigation), and augmenting water supply (e.g., through watershed development activities). Water retention measures can help reduce impacts from droughts. More robust water management is required to manage competing demands among agriculture, energy, conservation, and human settlements.

- **Improved cropland management ("conservation agriculture")**—Broadly understood as a suite of soil management approaches that reduce the disruption of soil structure and biotic processes by minimizing tillage. Examples include no-till farm practices, residue retention, and crop rotation. Minimizing soil disturbance, crop diversification, and permanent soil cover work to protect soil from erosion and degradation, improve soil quality, and optimize crop yields.

- **Efficient livestock systems**—Improving efficiency in livestock systems includes strategies to overcome inefficiencies in the conversion of agricultural primary production (i.e., crops) in the feed-animal products pathway; using different breeds and their wild relatives to develop a genetic pool resilient to climatic shocks and longer-term temperature shifts, improving feed management, shifting to drought-tolerant fodder, and disease prevention and control.

Urban and infrastructure systems

- **Green infrastructure and ecosystem services**—Encompasses the hybrid infrastructure of green spaces and built systems, e.g., forests, wetlands, parks, green roofs that incrementally contribute to urban resilience and human benefits through ecosystem services. Green infrastructure can reduce the urban heat island effect through improved ventilation, shading, and enhanced evapotranspiration. Examples include investing in and implementing street trees, parks, green roofs and facades, and water features in urban areas.

- **Sustainable land use and urban planning**—Actions influencing the spatial distribution of economic, social, and environmental activities through land use planning, zoning, building controls, and urban planning. Integrated land use planning can protect against flooding, drought, water scarcity, and heat stress. Urban planning and design can be climate-proofed through sustainable building codes and standards for new construction and retrofits.

- **Sustainable urban water management**—Refers to a suite of infrastructural, behavioural, and policy practices that support human and ecological systems in and around cities. Includes wastewater recycling, storm water management, flood mitigation, and protecting and maintaining urban water bodies. Water-sensitive urban design integrates stormwater, groundwater, and wastewater management to minimize the hydrological impacts of urban development on the environment.

Energy systems

- **Improve water use efficiency**—Includes securing vulnerable industry infrastructure (e.g., against climate-induced extreme events) and ensuring necessary water availability for industrial operations. Options include energy and water efficiency measures (e.g., in locations experiencing increased temperatures and decreased water availability need water for cooling). Power plants can reduce water consumption by switching from once-through cooling systems to recirculating tower cooling or dry cooling.

- **Resilient power systems**—Includes securing vulnerable power infrastructure (e.g., against climate-induced extreme events) and ensuring the necessary generation capacity. E.g., controllable and "islandable" microgrids; using residential batteries to increase resiliency, especially after extreme weather events; and hybrid renewables-based power systems. Transmission and distribution systems can be protected by upgrading overhead power lines or underground cabling.

- **Energy reliability**—Ensuring the availability of adequate, ideally low-carbon baseload power as intermittent renewables make up a larger share of the energy mix.

Cross-sectoral

- **Health and health systems adaptation**—Synthesized option to capture interventions such as improving basic health services, such as providing access to safe water and improved sanitation; access to essential health services, such as vaccination; and increasing disaster preparedness and response focusing on health impacts. Heat health action plans can improve public health responses to heatwaves and extreme temperatures.

- **Livelihood diversification**—Strategies adopted by smallholders in rural settings to diversify employment to reduce vulnerability and improve living standards. Strategies include switching from farm to nonfarm sectors, switching from self-employment to wage employment, and moving off farms.

- **Planned relocation and resettlement**—Organized, government-led movement of populations to less vulnerable, more secure areas on a permanent basis in response to anticipated or experienced disasters and/or climate impacts. Spatial planning can incorporate provisions for managed retreat.

- **Human migration**—Migration of individuals, households, communities from areas facing climatic risks. Includes temporary, seasonal, and permanent migration.

- **Disaster risk management**—Includes prevention, protection, preparedness, response, recovery, and review. Includes designing, implementing, and evaluating a range of strategies, policies, and measures including contingency planning and emergency management, for responding to climate risks up to and including systemic risks.

- **Climate services, including early warning systems**—Modelling, monitoring, and forecasting capabilities support a suite of information production, delivery, and uptake systems to improve adaptation decision-making. Examples are short-term services such as weather advisories and daily forecasts, longer-term information such as seasonal forecasts and multi-decadal projections, and early warning systems. Early warning systems for tropical cyclones, floods, storms, heatwaves, wildfires, droughts, etc. can help avoid or reduce damages from climate-related hazards.

- **Social safety nets**—Includes social protection programs such as cash and in-kind transfers to protect poor and/or vulnerable households from the impact of economic shocks, natural disasters, and climatic risks as well as informal ways of insuring against risk (e.g., pooling resources, relying on kinship networks).

- **Risk spreading and sharing**—Includes formal, market-based insurance and reinsurance mechanisms (e.g., weather insurance). Risk transfer protects policyholders against adverse events like droughts or floods by providing ex-post pay-outs. Index-based parametric insurance, for example, can help farmers hedge against poor harvests caused by increased weather variability and extreme events.

Table 1: Feasibility Assessment of Adaptation Options

					Dimensions of potential feasibility					
System transitions	**Representative key risks**	**Climate responses and adaptation options**	**Potential feasibility**	**Synergies with mitigation**	**Economic**	**Technological**	**Institutional**	**Social**	**Environmental**	**Geophysical**
Land and ocean ecosystems	Coastal socio-ecological systems	Coastal defence and hardening	Medium (high confidence)	Not assessed	Medium	Medium	Medium	Medium	Low	Medium
		Integrated coastal zone management	Medium (high confidence)	Low (low confidence)	Medium	Low	Low	Medium	High	Medium
	Terrestrial and ocean ecosystem services	Forest-based adaptation	High (high confidence)	High (high confidence)	Medium	High	Medium	High	Medium	High
		Sustainable aquaculture and fisheries	Medium (medium confidence)	Medium (medium confidence)	Medium	Low	Low	Medium	High	Medium
		Agroforestry	Medium (medium confidence)	High (high confidence)	Medium	High	Medium	Medium	High	Medium
		Biodiversity management and ecosystem connectivity	Medium (medium confidence)	High (high confidence)	Medium	High	Medium	High	Medium	High
	Water security	Water use efficiency and water resource management	Medium (medium confidence)	Medium (medium confidence)	Medium	Medium	Medium	Medium	Medium	Medium
	Food security	Improved cropland management	Medium (medium confidence)	High (high confidence)	High	Medium	Medium	Medium	High	Medium

					Dimensions of potential feasibility					
System transitions	**Representative key risks**	**Climate responses and adaptation options**	**Potential feasibility**	**Synergies with mitigation**	**Economic**	**Technological**	**Institutional**	**Social**	**Environmental**	**Geophysical**
		Efficient livestock systems	Low (medium confidence)	Medium (medium confidence)	Medium	Low	Low	Medium	High	Medium
Urban and infrastructure systems	Critical infrastructure, networks, and services	Green infrastructure and ecosystem services	Medium (high confidence)	High (medium confidence)	High	High	Low	High	High	Medium
		Sustainable land use and urban planning	Medium (medium confidence)	High (low confidence)	Medium	Medium	Medium	Medium	High	High
		Sustainable urban water management	Medium (medium confidence)	Low (low confidence)	Medium	High	Low	Medium	High	High
Energy systems	Water security	Improve water use efficiency	High (medium confidence)	Low (low confidence)	High	High	Medium	/	High	High
	Critical infrastructure, networks, and services	Resilient power systems	High (high confidence)	High (medium confidence)	High	High	Medium	High	Medium	Not applicable
		Energy reliability	High (high confidence)	High (high confidence)	Medium	High	Medium	High	High	Not applicable
Cross-sectoral	Human health	Health and health systems adaptation	Medium (medium confidence)	High (medium confidence)	Medium	Medium	Low	Medium	High	/
	Living standards and equity	Livelihood diversification	Medium (medium confidence)	High (medium confidence)	Medium	Medium	Low	Medium	Medium	Low
	Peace and human mobility	Planned relocation and resettlement	Low (low confidence)	Low (low confidence)	Low	Low	Low	Low	Low	Low

					Dimensions of potential feasibility					
System transitions	**Representative key risks**	**Climate responses and adaptation options**	**Potential feasibility**	**Synergies with mitigation**	**Economic**	**Technological**	**Institutional**	**Social**	**Environmental**	**Geophysical**
		Human migration	Medium (medium confidence)	Low (low confidence)	Medium	Medium	Medium	Medium	Low	Medium
	Other cross-cutting risks	Disaster risk management	Medium (high confidence)	High (medium confidence)	Medium	Medium	Low	Medium	Medium	High
		Climate services, including Early Warning Systems	Medium (high confidence)	/	Medium	Medium	Medium	Medium	High	Medium
		Social safety nets	Medium (medium confidence)	Low (low confidence)	Medium	Medium	Medium	Medium	High	High
		Risk spreading and sharing	Medium (medium confidence)	Low (low confidence)	Medium	High	Medium	Medium	Medium	Medium

Note: The symbol “/” refers to insufficient evidence. Source: IPCC AR6 WGII SPM Figure SPM.4(a).

CDR Options

Carbon dioxide removal (CDR), also known as carbon removal or negative emissions technologies, refers to a set of technologies and practices that remove carbon dioxide (CO_2)—the most important greenhouse gas—from the atmosphere and store it on a permanent and reliable basis to reduce global warming. CDR could be used to remove excess atmospheric CO_2 and thus reduce global warming, at a faster rate than would naturally occur.

Removing emissions would enable 1) recovering from overshoot by removing an amount of atmospheric CO_2 sufficient to return global average temperatures back to the exceeded warming goal, and 2) reaching net-zero emissions, that is, the point at which CO_2 emissions are balanced by CO_2 removals. Given likely global emissions trajectories, the IPCC has concluded that large-scale CO_2 removal from the atmosphere will be "unavoidable" if the world is to meet net-zero CO_2 and other key internationally agreed climate goals.

But like emissions cuts, carbon removal is slow to act, and the types of CDR with the largest potential are more expensive than emissions cuts. CDR will also take time to develop and scale. Current net-zero commitments and low-emission scenarios rely on extreme scale-up of CDR technologies that appear promising but whose success and acceptable impact and cost are not yet assured.

Key metrics for assessing CDR options include technology readiness levels (TRLs), cost (USD per tonne of CO_2 removed per year), removal potential (gigatonnes CO_2 removed per year), and timescale of CO_2 storage.

From the perspective of working to address climate overshoot in an integrated manner, the most important attributes of CDR options arguably are large carbon removal potential, permanence of storage, and overlap with adaptation options.

CDR can be roughly divided into biological and industrial options. Biological options rely on the uptake of CO_2 by plants and soils to remove carbon from the atmosphere and store it in natural carbon sinks. Biological options include:

- **Afforestation/Reforestation** (tree planting)—Forestry projects have been used as offsets in both voluntary and mandatory carbon markets for decades. The vulnerability of forests to wildfires, diseases, subsequent deforestation, and other threats raises questions about the permanence of CO_2 stored in trees. May compete for land with agriculture and conservation. Monoculture plantations could threaten biodiversity.

- **Soil Carbon Sequestration in croplands and grasslands**—Consists of a suite of agricultural practices that stimulate CO_2 uptake in soils, typically enhancing productivity. Practices include no-till farming, planting cover crops, and crop rotation. Net removal per hectare is small and difficult to monitor.

- **Peatland and coastal wetland restoration**—Peatlands are a significant carbon sink, and restoring them—for example, through rewetting—can increase the amount of CO_2 they store. Similarly, restoring coastal wetlands such as mangroves can enhance carbon storage in vegetation and soil. Opportunities may be limited.

- **Agroforestry**—Broadly refers to integrating trees, shrubs, and reforestation initiatives with crop and livestock systems to improve land use efficiency, prevent soil erosion, facilitate water infiltration, improve yields and water use, and store CO_2. Agroforestry can enhance biodiversity and improve system resilience.

- **Improved forest management**—Measures to increase carbon stocks in managed forests include longer rotations, reduced harvests, planting more resilient species, etc. Improved forest management can enhance biodiversity and increase productivity.

- **Biochar**—Biochar is a charcoal-like substance composed of stable CO_2 produced when biomass is heated under low-oxygen conditions. It can be produced using multiple feedstocks and spread over agricultural land to improve crop yields and enhance resilience to drought. Inappropriate production methods could cause pollution and promote unsustainable biomass harvest.

- **Preservation of "blue carbon" in coastal wetlands**—Reducing conversion of carbon stocks in mangroves, marshes, and seagrass ecosystems to avoid emissions from degradation or loss. Loss of blue carbon cannot be easily reversed. Efforts to preserve blue carbon may boost coastal protection and increase biodiversity but may also cause ecological disruptions. Carbon removal potential is small.

- **Ocean fertilization**—Adding nutrients like iron to the ocean to promote phytoplankton growth and associated carbon uptake via photosynthesis; when phytoplankton die, some settle in the deep ocean where carbon is stored on a long-term basis. Ocean fertilization may increase productivity including for fisheries. Research indicates that ocean fertilization would negatively affect marine ecosystems, including by altering oceanic food webs.

By contrast, industrial CDR options rely on technology to remove carbon from the atmosphere. Industrial options include:

- **Direct air carbon capture and storage (DACCS)**—DACCS would entail capturing CO_2 directly from the ambient air through chemical means and permanently storing it. The relatively low concentration of CO_2 in the atmosphere makes the DACCS capture process energy-intensive and thus comparatively expensive. To ensure that the CO_2 directly captured and stored is net-negative, DACCS would need to be powered by low-carbon energy sources.

- **Bioenergy with carbon capture and storage (BECCS)**—BECCS would involve combusting biomass to generate electricity, capturing the CO_2 released as a by-product, and permanently storing the CO_2 (generally underground). Because biomass absorbs atmospheric CO_2, capturing and storing the CO_2 produced by combustion would result in net carbon removal. The prospect of large-scale BECCS deployment and related land use change has raised serious concerns about food and water security, the security of land tenure (particularly in developing countries), and biodiversity loss.[1]

- **Enhanced weathering**—Natural chemical rock weathering could be accelerated by grinding rocks like olivine and basalt and spreading the powder over croplands or forests in tropical and subtropical areas, drawing down atmospheric CO_2. The mining, grinding, and distribution infrastructure required to implement enhanced weathering would be vast, costly, and energy-intensive.

[1] While we have opted to categorize BECCS as an industrial CDR option based on its large-scale industrial infrastructure, note that the IPCC categorizes BECCS as a biological option due to its reliance on large quantities of biomass feedstocks. Ultimately BECCS may be most accurately characterized as a hybrid biological/industrial option.

- **Ocean alkalinity enhancement**—This option involves adding alkaline substances like lime to surface waters to enhance absorption of atmospheric CO2 by the ocean and, importantly, reduce ocean acidification. Technical carbon removal potential is very large, but mining, processing, transport, and deployment operations would be vast, costly, and energy-intensive.

Table 2 summarizes CDR options as assessed by the IPCC. In comparative terms, overall, biological CDR options are more developed and overlap with adaptation options but have smaller carbon removal potentials and less reliable storage, whereas industrial CDR options are less developed and do not overlap with adaptation options but have larger carbon removal potentials and permanent storage.

Box 1: Nature-Based Solutions (NBS)

Nature-based solutions (NBS) is a relatively new concept focused on how nature protection and restoration can generate societal benefits including sustainable development, climate protection, and biodiversity conservation. From a climate perspective, NBS pertain primarily to adaptation and CDR: nature-based activities can boost resilience to climate change and/or remove CO2 from the atmosphere. Much of the promise associated with NBS relates to their potential for synergies, that is, the possibility that nature-based interventions might enhance adaptation at the same time as they draw down atmospheric CO2.

In terms of the framework used in this document, NBS occupy the space where nature-based adaptation and nature-based (biological) CDR intersect. Figure 1 illustrates this relationship.

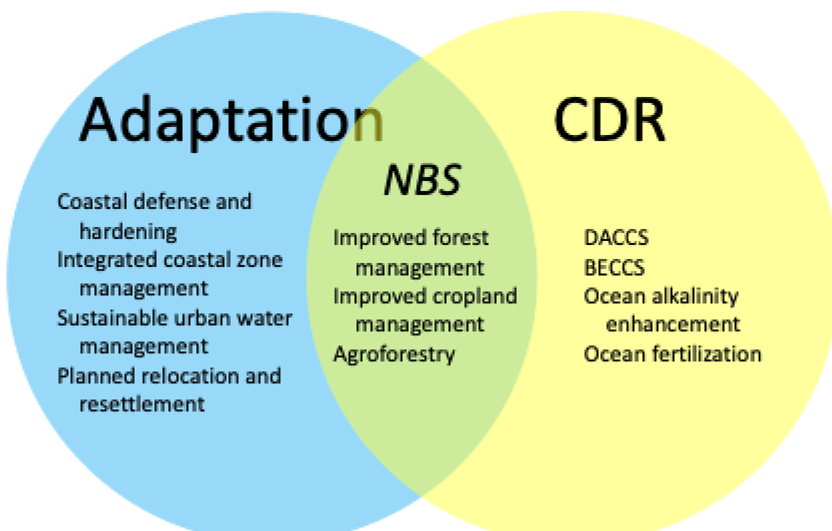

Figure 1: Relationship Among Adaptation, CDR, and Nature-Based Solutions

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Table 2: Summary of CDR Options

Method	CDR option	Status (TRL)	Cost (USD tCO_2^{-1})	Mitigation potential ($GtCO_2$ yr^{-1})	Timescale of C storage	Risk and impacts	Co-benefits	Trade-offs and spill over effects	Role in mitigation pathways
Biological	Afforestation/ Reforestation	(8-9)	0-240	0.5-10	Decades to centuries.	Reversal of carbon removal through wildfire, disease, pests may occur. Reduced catchment water yield and lower groundwater level if species and biome are inappropriate.	Enhanced employment and local livelihoods, improved biodiversity, improved renewable wood products provision, soil carbon and nutrient cycling. Possibly less pressure on primary forest.	Inappropriate deployment at large scale can lead to competition for land with biodiversity conservation and food production.	Substantial contribution in IAMs and also in bottom-up sectoral studies.
	Soil Carbon Sequestration in croplands and grasslands	(8-9)	45-100	0.6-9.3	Decades to centuries.	Risk of increased nitrous oxide emissions due to higher levels of organic nitrogen in the soil; risk of reversal of carbon sequestration.	Improved soil quality, resilience, and agricultural productivity.	Attempts to increase carbon sequestration potential at the expense of production. Net addition per hectare is very small; hard to monitor.	In development – not yet in global mitigation pathways simulated by IAMs in bottom-up studies: with medium contribution.
	Peatland and coastal wetland restoration	(8-9)	Insufficient data	0.5-2.1	Decades to centuries.	Reversal of carbon removal in drought or future disturbance. Risk of increased CH_4 emissions.	Enhanced employment and local livelihoods, increased productivity of fisheries, improved biodiversity, soil carbon, and nutrient cycling.	Competition for land for food production on some peatlands used for food production.	Not in IAMs but some bottom-up studies with medium contribution.

Method	CDR option	Status (TRL)	Cost (USD tCO_2^{-1})	Mitigation potential ($GtCO_2$ yr^{-1})	Timescale of C storage	Risk and impacts	Co-benefits	Trade-offs and spill over effects	Role in mitigation pathways
	Agroforestry	(8-9)	Insufficient data	0.3-9.4	Decades to centuries.	Risk that some land area lost from food production; requires very high skills.	Enhanced employment and local livelihoods, variety of products, improved soil quality, more resilient systems.	Some trade off with agricultural crop production, but enhanced biodiversity, and resilience of system.	No data from IAMs, but in bottom-up sectoral studies with medium contribution.
	Improved Forest management	(8-9)	Insufficient data	0.1-2.1	Decades to centuries.	If improved management is understood as merely intensification involving increased fertilizer use and introduced species, then it could reduce biodiversity and increase eutrophication.	In case of sustainable forest management, it leads to enhanced employment and local livelihoods, enhanced biodiversity, improved productivity.	If it involves increased fertilizer use and introduced species it could reduce biodiversity and increase eutrophication and upstream GHG emissions.	No data from IAMs, but in bottom-up sectoral studies with medium contribution.
	Biochar	(6-7)	10-345	0.3-6.6	Decades to centuries.	Particulate and GHG emissions from production; biodiversity and carbon stock loss from unsustainable biomass harvest.	Increased crop yields and reduced non-CO_2 emissions from soil; and resilience to drought.	Environmental impacts associated with particulate matter; competition for biomass resources.	In development – not yet in global mitigation pathways simulated by IAMs.

Method	CDR option	Status (TRL)	Cost (USD tCO_2^{-1})	Mitigation potential ($GtCO_2\ yr^{-1}$)	Timescale of C storage	Risk and impacts	Co-benefits	Trade-offs and spill over effects	Role in mitigation pathways
	"Blue carbon" in coastal wetlands	(2-3)	Insufficient data	<1	Decades to centuries.	If degraded or lost, coastal blue carbon ecosystems are expected to release most of their carbon back to the atmosphere; potential for sediment contaminants, toxicity, bioaccumulation and biomagnification in organisms; issues related to altering degradability of coastal plants; use of subtidal areas for tidal wetland carbon removal; effect of shoreline modifications on sediment redeposition and natural marsh accretion; abusive use of coastal blue carbon as means to reclaim land for purposes that degrade capacity for carbon removal.	Provide many non-climatic benefits and can contribute to ecosystem-based adaptation, coastal protection, increased biodiversity, reduced upper ocean acidification; could potentially benefit human nutrition or produce fertilizer for terrestrial agriculture, anti-methanogenic feed additive, or as an industrial or materials feedstock.		Not incorporated in IAMs, but in some bottom-up studies: small contribution.

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Method	CDR option	Status (TRL)	Cost (USD tCO_2^{-1})	Mitigation potential ($GtCO_2\ yr^{-1}$)	Timescale of C storage	Risk and impacts	Co-benefits	Trade-offs and spill over effects	Role in mitigation pathways
	Ocean fertilization	(1-2)	50-500	(1-3)	Centuries to millennia.	Nutrient redistribution, restructuring of the ecosystem, enhanced oxygen consumption and acidification in deeper waters, potential for decadal-to-millennial-scale return to the atmosphere of nearly all the extra carbon removed, risks of unintended side effects.	Increased productivity and fisheries, reduced upper ocean acidification.	Subsurface ocean acidification, deoxygenation; altered meridional supply of macro-nutrients as they are utilized in the iron-fertilized region and become unavailable for transport to, and utilization in, other regions, fundamental alteration of food webs, biodiversity.	No data.
Industrial	DACCS	6	100-300 (84–386)	(5-40)	Potentially permanent.	Increased energy and water use.	Water produced (solid sorbent DAC designs only).	Potentially increased emissions from water supply and energy generation.	In a few IAMs; DACCS complements other CDR options.
	BECCS	(5-6)	15-400	0.5-11	Potentially permanent.	Inappropriate deployment at very large-scale leads to additional land and water use to grow biomass feedstock. Biodiversity and carbon stock loss if from unsustainable biomass harvest.	Reduction of air pollutants; fuel security, optimal use of residues, additional income, health benefits and if implemented well can enhance biodiversity.	Competition for land with biodiversity conservation and food production.	Substantial contribution in IAMs and bottom -up sectoral studies. Note-mitigation through avoided GHG emissions resulting from the bioenergy use is of the same magnitude as the mitigation from CDR.
	Enhanced weathering	(3-4)	50-200 (24-578)	2-4 (<1-95)	10 to 100 thousand years.	Mining impacts; air quality impacts of rock dust when spreading on soil.	Enhanced plant growth, reduced erosion, enhanced soil carbon, reduced pH, soil water retention.	Potentially increased emissions from water supply and energy generation.	In a few IAMs; EW complements other CDR options.

Method	CDR option	Status (TRL)	Cost (USD tCO_2^{-1})	Mitigation potential ($GtCO_2$ yr^{-1})	Timescale of C storage	Risk and impacts	Co-benefits	Trade-offs and spill over effects	Role in mitigation pathways
	Ocean alkalinity enhancement	(1-2)	40–260	1-100	10 to 100 thousand years.	Increased seawater pH and saturation states and may impact marine biota. Possible release of nutritive or toxic elements or compounds. Mining impacts.	Limiting ocean acidification.	Potentially increased emissions of CO_2 and dust from mining, transport and deployment operations.	No data.

Source: IPCC AR6 WGIII Table TS.7. Note: Ranges based on IPCC estimates assessed from literature (full literature ranges in parentheses).

SRM Options

Sunlight reflection methods (SRM), also known as solar radiation management, solar radiation modification, or solar geoengineering, are a group of proposed technologies that would reflect a small fraction of incoming sunlight back to space using aerosol particles suspended in the air to partially offset climate change.

SRM appears capable of reducing global temperatures and other impacts much faster than emissions reductions or CDR. Unlike adaptation, SRM's effects would generally be global, not local (although there might be exceptions to this). But SRM would present several novel challenges. Its restoration of prior climate conditions would be imperfect. It would have environmental impacts, which presently appear modest or correctible but need more study. And it poses serious new governance challenges for managing overshoot, including the need to maintain and control interventions over multiple decades while emissions cuts and adaptation scale up—sudden and sustained termination would result in rapid warming.

The possible combination of global-scale effects delivered at low cost makes SRM a high-leverage set of technologies. The fast-acting nature of this high-leverage approach makes SRM particularly well-suited to "shave the peak" off the sort of dangerous multidecadal warming likely to result from climate overshoot.

From the perspective of working to address climate overshoot in an integrated manner, the most important attributes of SRM options arguably are efficacy and risk manageability.

The following presents brief descriptions of each of these options.

- **Stratospheric aerosol injection (SAI)** —This option would involve dispersing aerosols in the upper atmosphere (stratosphere). SAI is inspired by the known effects of large volcanic eruptions, sulphates from which cause global temperatures to measurably decline in the year or two that follow. SAI would slow global warming and moderate temperature, precipitation, and weather extremes, but also alter precipitation patterns. Possible side effects include delayed recovery of the ozone layer, altered atmospheric dynamics, and slightly whiter skies (although perhaps barely perceptible). SAI could be implemented by a fleet of aircraft at an estimated annual cost of tens of billions of dollars.

- **Marine cloud brightening (MCB)** —This option would involve spraying seawater from ships into low-lying clouds, causing them to whiten and increasing their reflectivity. More reflective clouds would cool underlying air and waters in the same way that ship tracks reduce temperatures in their wake. MCB might be capable of cooling small patches of ocean surface; areas off the western coasts of North and South America and Africa offer particularly suitable conditions. Such application would, however, result in patchy effects at regional and global levels, which could exacerbate some climate impacts. Scalability is uncertain.

- **Ocean albedo change (OAC)** —Would involve increasing the surface reflectivity of the ocean by creating microbubbles, dispersing foam, or through other means.

- **Ground-based albedo modification (GBAM)** —Would enhance the reflectivity of terrestrial surfaces by, for example, whitening roofs, using cover crops, bioengineering crops to increase reflectivity, or covering deserts or melting portions of glaciers with more reflective materials. GBAM could be applied locally or regionally.

- **Cirrus cloud thinning (CCT)** —Would involve seeding high-altitude clouds above the poles to facilitate heat flow out of the atmosphere. Unlike SRM, which would block incoming sunlight, CCT would act primarily by increasing the amount of heat transferred from the Earth's surface back to space.

Table 3 summarizes SRM options as assessed by the IPCC.

Deployability

For all options—adaptation, CDR, and SRM—an additional attribute of significant importance is *deployability*, or the extent to which a given option can be applied in practice in the near- to medium-term at acceptable cost with acceptable risk and with sufficient levels of public support. Deployability shares much in common with the concept of feasibility developed to assess adaptation options, and overlaps some with TRLs assessed for CDR options. Each element of deployability—appropriate timeframe and cost, risk, and public acceptability—is unavoidably subjective and political. Different judgments regarding deployability depend heavily on assumptions, scenarios, and criteria.

These considerations notwithstanding, the Commission has requested guidance on timelines for deployment for different options. To provide this, the Science Advisors are exploring the possibility of adapting an integrated assessment model (IAM) to project the evolution of individual adaptation, CDR, and SRM technologies (and potentially technology combinations) based on different levels of R&D spending and assumed rates of learning. These uncertainties or risks would drive the relative competitiveness of the technologies and impact the timing and extent of their possible deployment. When completed, this effort may facilitate prioritizing options within each type of approach.

References

IPCC, 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate* Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://www.ipcc.ch/report/ar6/wg2/.

IPCC, 2022. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://www.ipcc.ch/report/ar6/wg3/.

Singh, C., Ford, J., Ley, D. *et al.* , 2020. Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. *Climatic Change* 162, 255–277. https://doi.org/10.1007/s10584-020-02762-x.

Table 3: Summary of SRM Options

SRM option	SAI	MCB	OAC	GBAM	CCT
Description	Injection of reflective aerosol particles directly into the stratosphere or a gas which then converts to aerosols that reflect sunlight	Spraying sea salt or other particles in marine clouds, making then more reflective	Increase surface albedo of the ocean (e.g., by creating microbubbles or placing reflective foam on the surface)	Whitening roofs, changes in land use management (e.g., no-till farming, bioengineering to make crop leaves more reflective), desert albedo enhancement, covering glaciers with reflective sheeting	Seeding to promote nucleation of cirrus clouds, reducing optical thickness and cloud lifetime to allow more outgoing longwave radiation to escape to space
Potential climate impacts *other than reduced warming*	Change precipitation and runoff pattern; reduced temperature and precipitation extremes; precipitation reduction in some monsoon regions; decrease in direct and increase in diffuse sunlight at surface; changes to stratospheric dynamics and chemistry; potential delay in ozone hole recovery; changes in surface ozone and UV radiation	Change in land- sea contrast in temperature and precipitation, regional precipitation, and runoff changes	Change in land-sea contrast in temperature and precipitation, regional, precipitation and runoff changes.	Changes in regional precipitation pattern, regional extremes, and regional circulation	Changes in temperature and precipitation pattern, altered regional water cycle, increase in sunlight reaching the surface
Potential impacts on human and natural systems	Changes in crop yields, changes in land and ocean ecosystem productivity, acid rain (if using sulphate), reduced risk of heat stress to corals	Changes in regional ocean productivity, changes in crop yields, reduced heat stress for corals, changes in ecosystem productivity on land, sea salt deposition over land	Unresearched	Altered photosynthesis, carbon uptake and side effects on biodiversity	Altered photosynthesis and carbon uptake

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SRM option	SAI	MCB	OAC	GBAM	CCT
Termination effects	Sudden and sustained termination would result in rapid warming, and abrupt changes to water cycle. Magnitude of termination depends on the degree of warming offset.	Sudden and sustained termination would result in rapid warming, and abrupt changes to water cycle. Magnitude of termination depends on the degree of warming offset.	Sudden and sustained termination would result in rapid warming. Magnitude of termination depends on the degree of warming offset.	GBAM can be maintained for several years without major termination effects because of its regional scale of application. Magnitude of termination depends on the degree of warming offset.	Sudden and sustained termination would result in rapid warming. Magnitude of termination depends on the degree of warming offset.

Source: IPCC AR6 WGII Ch. 16 Table Cross-Working Group Box SRM.1.