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Geochemical Negative Emissions Technologies: Part II. Roadmap

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Geochemical negative emissions technologies (NETs) comprise a set of approaches to climate change mitigation that make use of alkaline minerals to remove and/or permanently store carbon dioxide (CO_2) as solid carbonate minerals or dissolved ocean bicarbonate ions. This roadmap accompanies the comprehensive review of geochemical NETs by the same authors and offers guidance for the development and deployment of geochemical NETs at gigaton per year (Gt yr.$^{-1}$) scale. We lay out needs and high-priority initiatives across six key elements required for the responsible and effective deployment of geochemical NETs: (i) technical readiness, (ii) social license, (iii) demand, (iv) supply chains, (v) human capital, and (vi) infrastructure. We put forward proposals for: specific initiatives to be undertaken; their approximate costs and timelines; and the roles that various actors could play in undertaking them. Our intent is to progress toward a working consensus among researchers, practitioners, and key players about initiatives that merit resourcing and action, primarily focusing on the near-term.

KEYWORDS

carbon dioxide removal, enhanced weathering, CO_2 mineralization, ocean alkalinity enhancement, geochemical CDR, CDR roadmap, negative emissions technologies, negative emissions roadmap

Introduction

The recent IPCC AR6 report reflects a broad consensus that, even under optimistic decarbonization scenarios, a non-trivial amount of negative emissions will be necessary within a generation to minimize catastrophic warming, irreversible damage to ecosystems, and reduced quality of life (Shukla et al., 2022). Geochemical NETs are a set of technologies that use alkaline minerals for removing and/or permanently storing atmospheric CO_2 (Campbell et al., 2022). Research suggests that geochemical NETs offer potential scalability within time periods relevant to climate targets, an ability to simultaneously capture and store CO_2 (Campbell et al., 2022) and an ability to permanently store CO_2 away from the active carbon cycle (Carton et al., 2021). However, the possible externalities and impacts of geochemical NETs have not been fully explored, nor rigorously tested in the field. A rapid large-scale deployment of geochemical NETs as they stand today could therefore be accompanied by unacceptable environmental or social burdens. Moreover, geochemical NET projects will take time to site and scale. In our view, this suggests there is no time to waste: we must fast-track the research, development, and stakeholder engagement required for potential deployment of geochemical NETs at scale.

In our review of the current body of knowledge on geochemical NETs, various gaps were identified between the present state of research and activity, and what is required for a fully functioning, effective, safe and responsible deployment at the scale of megatons (Mt), and eventually gigatons (Gt), annual removal of atmospheric CO_2 (Campbell et al., 2022). Here, we provide suggestions for closing those gaps in the form of a roadmap for the responsible and expeditious development and deployment of geochemical NETs. We begin with a needs assessment, outline opportunities at the research and innovation frontier, and then present recommendations covering initiatives, approximate resource needs, and roles for different actors, including researchers, governments, startups, industry, investors, philanthropists and non-profits.

Needs assessment

A safe, high-functioning, Gt $yr.^{-1}$ scale ecosystem for geochemical NETs would require at least six supporting elements: technical readiness, social license, demand, supply chains, human capital, and infrastructure. The gaps between what is needed across these elements and what exists today are profound.

Technical readiness

Geochemical NETs harness chemical reactions between alkaline minerals and CO_2 to form stable carbonate compounds or dissolved ocean bicarbonate anions. Approaches include CO_2 mineralization (Power et al., 2013; Sanna et al., 2014), enhanced weathering (Renforth et al., 2015; Montserrat et al., 2017; Rigopoulos et al., 2018), electrochemical seawater splitting (de Lannoy et al., 2018; Eisaman et al., 2018), ocean liming (Renforth and Henderson, 2017; Caserini et al., 2021), and hybrid direct air capture (DAC) systems utilizing solid minerals (McQueen et al., 2020).

Further research and development (R&D), including additional studies across all geochemical NETs in different environments, are critical to achieving requisite technology readiness levels (TRLs) for deployment. Current TRLs for *in situ* mineralization approaches range from 2 to 6 (*i.e.*, from "technology concept formulated" to "technology demonstrated in relevant environment" on a scale of 1–9) (Kearns, 2021). Other techniques, such as enhanced weathering in soils and ocean alkalinity enhancement, rank even lower (e.g., TRL 1; "basic principles observed"). Substantial work is required in the laboratory, in small-scale field studies, and finally larger scale demonstration studies in industrial settings, before geochemical NETs achieve TRL 8 or TRL 9, required for deployment.

There are significant gaps in particular in our understanding of the underlying kinetics of geochemical NETs, the effects of secondary minerals and their re-dissolution, and their impacts on ecosystems, the environment, and public health, as well as pore clogging and cracking for *in situ* methods (Kelemen et al., 2019; Fuhr et al., 2022). Work is required to demonstrate that geochemical NETs can be effective, reliable, and safe, to a high degree of confidence, and to lay the foundation for robust methods for measurement, monitoring, and verification (MMV) that can support result-based investment decisions, such as carbon credit procurement.

Social license

The active removal of Gt of CO_2 from the atmosphere, equivalent in scale in terms of infrastructure and resource use to major global industries, will require non-tacit acceptance from wide publics, stakeholders, and policymakers. Today, public awareness of geochemical NETs is generally low. The public's views on these approaches are at a formative stage and are beginning to be investigated by researchers (Cox et al., 2020; Spence et al., 2021).

This provides a challenge for the geochemical NETs research community in how it develops its research agenda with growing exposure of the field. An opaque research effort led primarily by commercial actors, effectively isolated from stakeholders and wider publics, may struggle to secure broad-based, durable support from the public and policymakers. In contrast, co-development through principles of responsible research and innovation (Owen et al., 2012) may provide the means by which the eventual costs, benefits, and other trade-offs of scaled-up approaches are accurately defined, broadly understood, and equitably shared.

Awareness among policy makers is also generally low and compared to other NET approaches geochemical NETs have the lowest ratio of policy coverage to potential impact, highlighting a further gap (Sandalow et al., 2021). Most relevant existing policy frameworks (e.g., 45Q, California Low Carbon Fuel Standard, EU Emissions Trading System

[Federal Register, 2021; EU Emissions Trading System (EU ETS), 2015; Low Carbon Fuel Standard)] include criteria that leave out geochemical NETs unintentionally. Furthermore, international agreements disallow the release of alkaline minerals into the ocean beyond contained research experiments (Verlaan, 2013), constraining the deployment of ocean-based geochemical NETs. New frameworks for projects involving multiple jurisdictions and/or the oceans are of particular priority. Overall, for geochemical NETs, gaps in demand, infrastructure and other areas will not be met without policy intervention on local, national and international levels, which in turn will be reliant on our ability to address gaps in social license.

Demand

Today, demand for geochemical NETs is generated primarily through voluntary carbon markets and corporate commitments (Battersby et al., 2022). Demand for durable forms of carbon removal has been increasing, with the most significant recent commitment being the $925 million advance market commitment by Frontier (2022). Geochemical NETs offer permanent CO_2 storage and may be competitive applicants for such funding (Joppa et al., 2021). However, the potential volume of these voluntary funding flows is unknown, and they may be unsuitable funding mechanisms for some of the work that needs to be done. For example, voluntary payments to commercial companies for carbon credits or carbon removal delivery may well be insufficient to support geochemical NETs at a Gt or even Mt-scale, and an inappropriate or ineffective tool for funding research, development, and stakeholder engagement in a manner that is open, inclusive, robust, and aligned with the principles for responsible research and innovation.

Given this, philanthropic and public sources of funding and demand must be increased dramatically, if geochemical NETs are to be researched in a robust manner and then deployed at meaningful scale. Specifically, government procurement of carbon removal from geochemical NETs and/or the inclusion of geochemical NETs into compliance-based regimes more significant than those that exist today will be necessary (Rickels et al., 2021). Geochemical NETs have considerable potential scalability, coupled with tangible durability of the resulting minerals (Lackner, 2003), and as such, we anticipate that significant demand for durable carbon removal outcomes generally would translate into significant demand for geochemical NETs specifically, particularly as other NETs that are more established but perhaps limited in their potential scale, such as BECCS, saturate.

Beyond demand for the carbon removal outcomes generated by geochemical NETs, there may be opportunities to expand demand for the physical products and byproducts of geochemical NETs, which will improve their economics as carbon removal solutions. For instance, calcium carbonate is a product itself (chalk, talc), but more importantly, it is also an additive in numerous materials: paper, plastic, paint, adhesives, sealants, and coatings, among many others. Current demand for $CaCO_3$ is ~125 Mt $yr.^{-1}$ (~$45 billion) and has been growing >5% a year driven largely by packaging, shipping and hygiene applications (Grand View Research, 2022). In particular, new high-volume products such as carbon-negative $CaCO_3$-based cements could bring demand to Gt $yr.^{-1}$ (Hargis et al., 2021).

$MgCO_3$ is used in flooring, fire-retardant materials, rubber, and in food and cosmetics. It has lower demand than $CaCO_3$, at ~2 Mt $yr.^{-1}$ ($300 million). Exciting growth opportunities include Mg-rich alloys for automotive and aerospace applications (Magnesium Carbonate Market) and Sorel cement ("magnesium cement"), which holds certain advantages over Portland cement for specific applications and can be prepared from relatively impure materials (Jurišová et al., 2015).

Finally, demand for silica (SiO_2), another product of mineral carbonation, is immense (~500 Mt. $yr.^{-1}$, ~$6 billion) and growing rapidly (>8% annually)—fueled largely by the semiconductor and glass industries. Silica may also find increased applicability at relevant scales in concrete, where its use as a substitute cementitious material could potentially enhance concrete strength while reducing emissions from cement manufacture (Gadikota et al., 2015). Altogether, there are many potential market opportunities for the products of geochemical NETs.

It is likely that reaching Gt $yr.^{-1}$ scale by 2030 will require mechanisms beyond creation of markets for value-added products. Nonetheless, these sources of demand warrant development.

Supply chain

Supply of alkaline mineral feedstock is not expected to be limiting, as such minerals comprise the bulk of the Earth's crust. However, at Gt $yr.^{-1}$ scale, the availability of low-cost, low-carbon electricity for grinding may be a major limitation for some approaches (Strefler et al., 2018; Eufrasio et al., 2022). Land based *in situ* mineralization methods may require significant amounts of water, up to 25–30 tons of H_2O per ton CO_2 (Gunnarsson et al., 2018). All *in situ* methods will require access to enough concentrated CO_2, which may become a bottleneck if DAC or bioenergy with carbon capture and storage (BECCS) do not scale alongside CO_2 mineralization efforts. For surface geochemical NETs (*ex situ* and surficial), the need for enhancements—e.g., acid, heat, grinding, catalysts, microbes, *etc.*—is the focus of ongoing research (Campbell et al., 2022), and whether these enhancements are inhibited by, or met with, new bottlenecks at greater deployment scales is a key uncertainty.

A complicating factor is that alkaline minerals are not uniformly distributed across the Earth's surface. However, they

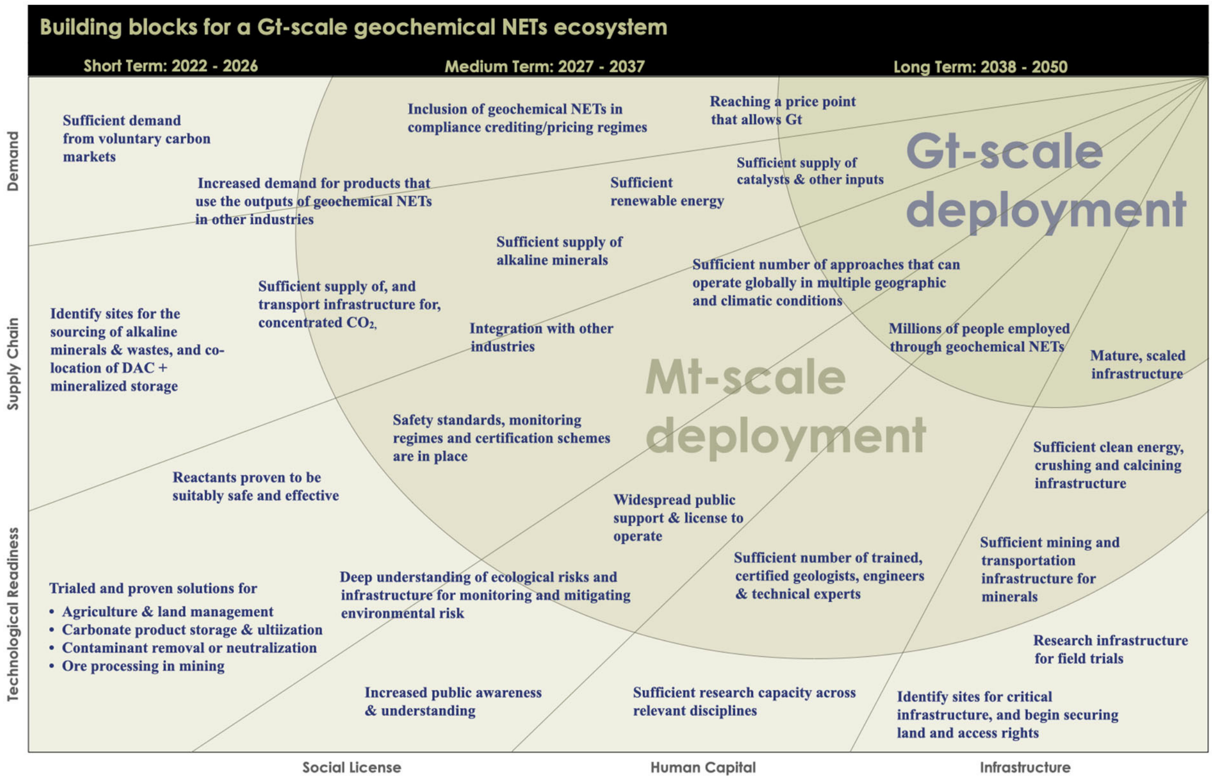

FIGURE 1
Building blocks for the construction of a safe, functioning Gt-scale geochemical NETs ecosystem, across six supporting elements, according to whether they represent roadblocks for near-, medium- or long-term deployment.

are widely available, with several noteworthy hotspots of surface accumulation. *In situ* mineralization could store >1 Gt CO_2 yr.$^{-1}$ in peridotite massifs of Oman alone (Kelemen and Matter, 2008). At regional levels, megatons of alkaline wastes are available (Riley et al., 2020), which could also potentially be used by geochemical NETs. Use of waste products such as mine tailings and industrial slag for carbonation serves the added purpose of potentially reducing the toxicity of such wastes, through fixation of heavy metal ions and stabilization of pH (Gomes et al., 2016). For large-scale projects, a balance must be struck between minimizing excavation and transport with the efficiency and throughput of industrial-scale processing, the latter of which will likely require centralized infrastructure.

Human capital

While the current number of researchers, engineers, skilled technicians and other experts dedicated to geochemical NETs is certainly not sufficient for wide-scale deployment, these approaches employ similar skill sets to the mining, cement manufacture and concrete production, agricultural liming, fossil fuel and other industries, creating opportunities for the transfer of human capital into the deployment of geochemical NETs. It is of paramount importance that programs focused on talent transitions to "green" jobs involve transfer into NET industries. University modules focused on training students in the science, engineering processes and impacts behind geochemical NETs should be created to increase available talent. Such programs would also benefit current and future generations of students who will likely be increasingly required to work in the climate mitigation sector, since geochemical NETs provide opportunities for a wide range of interests, skill sets and geographies.

Infrastructure

Mining, transport, and clean energy infrastructure is not expected to be sufficient in the near-term for Mt yr.$^{-1}$ scale, and deployment at Gt yr.$^{-1}$ scale would require massive investment and buildout, especially in non-fossil energy. For some geochemical NETs, particularly applications in *ex situ*, *in situ*, and surficial carbon mineralization, pre-concentration of CO_2 from air will be required, suggesting that energy requirements might become tangled with those of DAC. For *in situ* methods in particular, transport of CO_2 may become a challenge both logistically and in terms of public support, especially where pipelines are involved (Teng et al., 2021). Furthermore, existing mining, crushing, and calcination infrastructure cannot cope with the needs of geochemical NETs at scale and therefore will need to be substantially expanded (Caserini et al., 2021). Depending on the geochemical NETs employed, increased transport, storage, burial or utilization of the reaction products would be required.

Gap assessment

The most significant specific gaps across the six supporting elements above are depicted in Figure 1 according to whether they represent roadblocks for near-, medium- or long-term deployment. This figure assumes that the next 4 years constitute a continued research phase, Mt $yr.^{-1}$ deployment will be reached between 5 and 10 years from now, and Gt $yr.^{-1}$ deployment before 2050.

In the near term, addressing many of the gaps for reaching a Mt $yr.^{-1}$ deployment should be achievable, as they are primarily focused on the research required to vet geochemical NETs and establish their effectiveness. As such, they require limited amounts of funding, people, land, and social license, relative to the amounts required for subsequent stages of deployment.

However, if the timescale for this vetting stretches too far, we risk two things: First, geochemical NETs may be deployed anyway due to high demand for permanent removals, but without full knowledge of how to manage impacts. This could create problems in terms of human and environmental wellbeing and could also jeopardize any future deployment of geochemical NETs, similar to the observed controversy surrounding ocean iron fertilization (Fuentes-George, 2017). Second, we risk deployment too far in the future to achieve the primary goal of geochemical NETs, which is to reduce the atmospheric CO_2 concentration in time to avoid climate catastrophes and tipping points (Boers and Rypdal, 2021; Fewster et al., 2022; Shukla et al., 2022).

The gaps between the Mt and Gt $yr.^{-1}$ scenarios are far more considerable. The energy and transport infrastructure required is a substantial increase from that which exists today (Renforth, 2012; Lefebvre et al., 2019), and mining activity would be expected to increase significantly (Goll et al., 2021). Both government procurement and inclusion in compliance carbon markets would be required to support demand, though unique problems will emerge in bringing down price, and a greater number of efficiencies come under consideration. The approximate cost estimates and minimum timescales required to close gaps are explored further in the section Action plan and shown graphically in Figure 2.

An agenda for advancing Geochemical NETs

We propose an agenda for research and innovation that includes essential priorities and other opportunities that merit exploration and investment. Many of these opportunities lie at the intersections among different research disciplines, or among NETs, or large-scale industries, such as concrete or steel production. Our priorities build on those put forth by the non-profit organization Ocean Visions (Ocean Visions, 2021) and the Innovation for Cool Earth Forum (Sandalow et al., 2021), among others.

First-order priorities for research and development

Research advances essential for the safe, timely, and effective demonstration and deployment of geochemical NETs include:

- Integration of the principles of responsible research and innovation (Owen et al., 2012) into research agendas, including the co-development of programs with wider stakeholders and publics.
- Confirming net carbon fluxes in surface systems, accounting, e.g., for groundwater effects (Sandalow et al., 2021).
- Identification of the ecological effects of enhanced weathering and surficial mineralization techniques, and downstream effects on natural assets, economic activity, and public health. Further work is also needed to address the impacts of enhanced weathering on, for example, the eutrophication of aquatic systems, biodiversity, biosphere–atmosphere feedbacks, and air, water and soil pollution (Strefler et al., 2018).
- Development of a range of techniques, technologies, and protocols for the modeling, monitoring, measurement, and verification aspects of geochemical NETs. Development of standardized methodologies for the sampling and analysis of solid alkaline materials to determine the mineralized CO_2 and facilitate regulatory oversight and carbon crediting for geochemical NETs. These will enable authorities to ensure proper carbon accounting.
- Resolution of legal challenges pertaining to ocean dispersion to enable rapid scale-up of ocean-based geochemical NETs once the ecological impacts have been determined and can be properly managed.

Priority initiatives to address gaps

Minimum estimated time to bridge each gap between 2022 and a Mt or Gt scale ecosystem (years)

0 2 4 6 8 10 12 14

		Cost*	Academia	Startups	Government	Industry	Investors	Nonprofits	Philanthropy
Technical Readiness	Identify locations for industrial clusters for Mt/Gt-scale geochemical NETs, and initiate stakeholder engagement.	Low	Striped	Striped	Solid	Solid	Open	Striped	Striped
Technical Readiness	Lab-based research on novel feedstocks.	Low	Solid	Open	Striped	Striped	Open	Open	Striped
Technical Readiness	Lab-based research on contaminant removal or hazardous material removal & handling.	Low	Solid	Open	Striped	Striped	Open	Open	Striped
Technical Readiness	Field trials, to assess kinetics, net carbon fluxes, impacts, and MMV systems under different conditions.	Med	Solid	Solid	Striped	Striped	Open	Solid	Striped
Technical Readiness	Field research and modelling on net carbon fluxes in surface systems (accounting for e.g., groundwater impacts).	Med	Solid	Solid	Striped	Striped	Open	Open	Striped
Technical Readiness	Research on reaction rates of alkaline materials in ambient conditions.	Med	Solid	Open	Striped	Striped	Open	Open	Striped
Technical Readiness	Lab-based research and field trials on controls for negative-feedback passivation and clogging, and positive-feedback cracking and channeling mechanisms.	Med	Solid	Solid	Striped	Striped	Open	Solid	Striped
Technical Readiness	R&D of soil amendments for commercial use in agriculture & land management.	Med	Solid	Solid	Striped	Striped	Open	Open	Striped
Technical Readiness	R&D of screening & engineering platforms for organisms & biomolecules with geochemical activity.	Med	Solid	Solid	Striped	Striped	Open	Open	Striped
Technical Readiness	R&D of new design possibilities for integration of biotechnology into geochemical NETs, and associated techno-economic analyses.	Med	Solid	Solid	Striped	Striped	Open	Open	Striped
Technical Readiness	R&D of new carbonate materials for commercial use in construction, paving, and other industries.	Med	Solid	Solid	Striped	Striped	Open	Open	Striped
Technical Readiness	R&D of other storage, utilization or valorization solutions for carbonates.	Med	Solid	Solid	Striped	Striped	Open	Open	Striped
Technical Readiness	R&D of novel solutions for ore processing in mining.	Med	Solid	Solid	Striped	Striped	Open	Open	Striped
Technical Readiness	R&D of sensors for use in MMV, for all geochemical NETs.	Med	Solid	Solid	Striped	Striped	Open	Solid	Striped
Technical Readiness	Assessment of existing satellite data applicable to MMV for geochemical NETs.	Low	Solid	Open	Striped	Solid	Open	Solid	Striped
Technical Readiness	Develop MMV tools that can be used in the field, by commercial labs, & in routine monitoring of mining wastes and industrial wastes.	Med	Solid	Solid	Striped	Solid	Open	Solid	Striped
Technical Readiness	Research into the health impacts resulting from real-world deployment of geochemical NETs.	Low	Solid	Open	Striped	Open	Open	Solid	Solid
Technical Readiness	Lifecycle analyses across all specific geochemical NETs.	Low	Solid	Open	Solid	Open	Open	Striped	Striped
Technical Readiness	Geological surveys to assess potential sites for relevant properties, mineralization potential, and ecological concerns.	Med	Striped	Striped	Solid	Solid	Open	Striped	Solid
Technical Readiness	Industry-government-university collaborations on R&D and tech transfer for mining and industrial wastes.	Low	Solid	Open	Solid	Solid	Open	Striped	Solid
Technical Readiness	Large-scale demo projects, for system integration, energy efficiency, and cost reduction.	Hi	Striped	Solid	Solid	Solid	Solid	Open	Striped
Demand	Multi-stakeholder protocol design for voluntary carbon markets: for a range of geochemical NETs.	Low	Solid	Solid	Open	Striped	Open	Solid	Solid
Demand	Lobbying for inclusion/carve-outs within existing carbon pricing and subsidy regimes.	Low	Open	Striped	Solid	Striped	Open	Solid	Solid
Demand	Lobbying for carbon emissions taxes/regulations/standards for specific strategic sectors, e.g., agriculture, coal, construction, mining, iron, steel.	Low	Open	Open	Solid	Striped	Open	Solid	Solid
Demand	Expanding demand for the physical products & byproducts of geochemical NETs, including $CaCO_3$, $MgCO_3$, Mg-rich alloys and silica.	Med	Open	Solid	Striped	Solid	Open	Open	Open
Demand	Investment commitments by corporates in strategic sectors such as mining and cement production as part of their transition to carbon free or carbon negative production.	Hi	Open	Open	Striped	Solid	Solid	Striped	Open
Demand	Direct procurement by governments of either geochemical NETs or CDR outcomes.	Hi	Open	Striped	Solid	Striped	Open	Solid	Striped
Demand	Expanded carbon pricing and subsidy regimes sufficient to support Gt scale.	Hi	Open	Striped	Open	Solid	Striped	Open	Open

Mt-scale Gt-scale

*Estimated Costs 'Hi' >$100M by 2030, 'Med' = $10-100M by 2030, 'Low' <$10M, total

**For actors, block color: solid box = leadership is essential, striped box = significant opportunity to contribute, and open box = some opportunity to contribute

FIGURE 2 (Continued)

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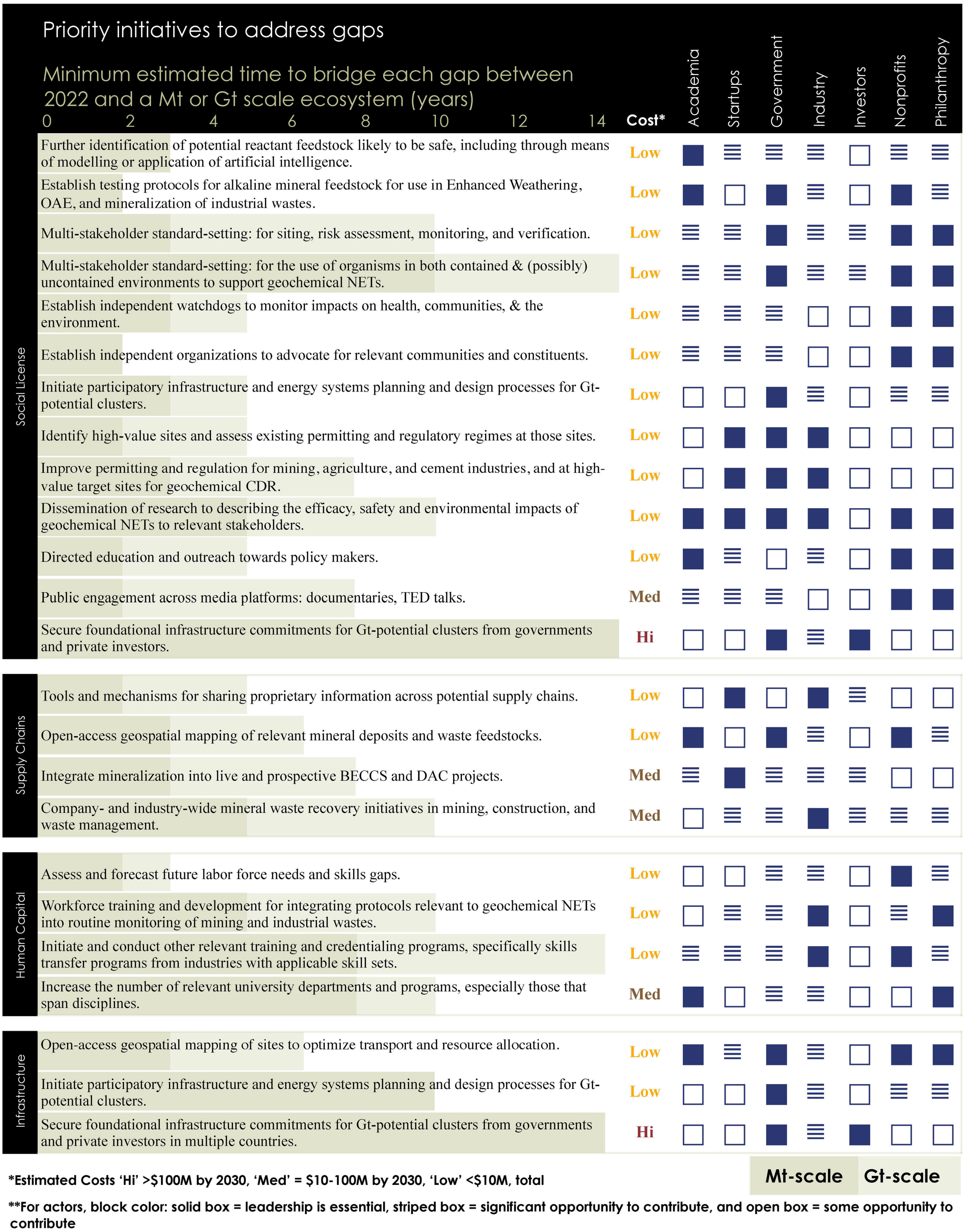

FIGURE 2
Proposed priority initiatives and relevant actors, based on assessment of our work presented in Campbell et al. (2022), along with previous reports and roadmapping efforts (National Academies of Sciences, Engineering, and Medicine, 2019; Sandalow et al., 2021; Ocean Visions, 2021). Solid blue squares indicate a role in which leadership is essential, striped squares indicate a role in which there is significant opportunity to contribute, and open squares indicate a role in which there is some opportunity to contribute. The provided cost estimates represent best guesses based on available information, where "Hi" >$100 M by 2030, "Med" = $10–100 M by 2030, and "Low" <$10 M by 2030. The rough time estimates for reaching Mt CO_2 yr.$^{-1}$ and Gt CO_2 yr.$^{-1}$ scales are provided to help illustrate the overall scope of work.

Other research and development opportunities that merit exploration and investment

Other initiatives that merit exploration and investment because they could yield important and valuable new gains include:

- Research infrastructure to enable the cross-disciplinary study across physics, geology, chemistry, biology, ecology, engineering, social sciences, law and governance necessary to bridge gaps and address problems in tangible and actionable ways.
- Selection and optimization of mineral deposits/feedstocks to maximize the labile Mg^{2+} and Ca^{2+} content and enhance reaction rates, while reducing the release of toxic metals and limiting environmental impacts. This work may benefit from computer modeling and artificial intelligence, to identify potential candidate feedstocks and materials.
- Advancement of methods for studying and manipulating soil and root microbiomes to promote weathering in soils of various biomes, including agricultural fields.
- Advancement of understanding of the mechanisms of chemical catalysts of dissolution of alkaline minerals, identification of optimal catalysts, and assessment of their utility, including development of platform technologies for their study and engineering.
- Advancement of understanding of the biological mechanisms influencing mineral weathering and CO_2 mineralization and their utility, through development of new platform technologies for their study and engineering (e.g., methods for high-throughput study of relevant mechanisms and biomolecules in microbes and microbial communities).
- Design and techno-economic assessment of methods leveraging chemical and biological enhancement.
- Improvement in understanding potential co-benefits of enhanced weathering in soils, including whether release of key limiting nutrients (e.g., P or K) from basalt weathering has the potential to boost biomass production, resulting in additional CO_2 removal (Goll et al., 2021).
- Further lab and field testing of the complex interactions and feedbacks between permeability, reaction rate, reactive surface area, fluid flow dynamics, and in particular, the effects of pore clogging and cracking, during circulation of CO_2-rich fluids through subsurface mafic and ultramafic rocks (Kelemen et al., 2020).
- Creating databases and maps of sub-surface mafic and ultramafic rock resources, as well as alkaline material deposits at Earth's surface, to help identify, with the aid of multi-criteria decision analysis or other decision-making tools, prime sites for negative emissions *via* mineralization (Raza et al., 2022).
- Greater exploration of the potential synergies between mineralization technologies and DAC and BECCS, and in particular, the benefits of producing and using gasses with a range of CO_2 purities, with their potential to lower costs compared to systems requiring pure CO_2 (Wilcox et al., 2017; Kelemen et al., 2020). Co-location of *in situ* CO_2 mineralization activities with geothermal energy production.
- Further development of solid mineral DAC systems, which utilize abundant, low-cost natural and artificial alkaline minerals (e.g., lime, magnesia, or other alkaline materials), to remove CO_2 from the air. In particular, there is potential for new materials, other than lime, which can capture ambient CO_2 at comparable rates, but which have lower kiln temperatures for regeneration (*i.e.*, more facile carbonate decomposition) thus decreasing energy consumption and enabling integration with renewable energy (e.g., enabling a move away from natural gas-based kilns toward renewable-energy powered kilns) (Nikulshina et al., 2008; Campbell, 2019; Kelemen et al., 2020; McQueen et al., 2020).
- Innovation in developing new products or disposal techniques for the carbonates produced, as well as in commercial and societal side-products, such as fertilizers, soil remediation, coastal protection, or hydrogen production (Beerling et al., 2018; Hargis et al., 2021).
- Creation of Focused Research Organizations (FROs), which exist outside traditional research infrastructure to streamline and fast track research, in order to tackle some of the outstanding challenges listed in this and the previous section (Marblestone et al., 2022).

Opportunities for innovation in partnership with existing industries

Other opportunities for innovation in partnership with many of the world's largest existing industries include:

- Deployment of enhanced weathering in soils in combination within agriculture, forestry, and soil management, including in combination with biochar.
- Integration of CO_2 mineralization into cement/concrete and construction industries as a storage option for distributed DAC.
- Integration of CO_2 mineralization into ore mining and processing. Mining activities that deliver carbon removal and produce metals and minerals for other uses, such as the extraction of rare earth metals, could enhance economics and sustainability. Carbonation could provide the mining

industry with valuable carbon offset opportunities, while simultaneously reducing safety risks from mine tailings (Harrison et al., 2013).

- Integration of CO_2 mineralization into other existing large-scale industries, such as iron and steel production, could provide feedstocks, reaction sites, or storage solutions for carbon mineralization in a manner that is relatively economical and highly scalable.
- Innovations in the decarbonization of processes like calcination, e.g., development of non-fossil fuel-powered kilns, which could simultaneously advance decarbonization in cement production (Fennell et al., 2021) and the prospects for ocean liming, or hybrid metal oxide looping approaches (Kelemen et al., 2020; McQueen et al., 2020).
- Many large commercial companies, in construction, mining, and other sectors, produce waste streams that could be used as CO_2 mineralization reactants. Demonstration trials with these wastes may be relatively economical and low-hanging fruit for deployment-led innovation, with the potential for upscaling.

Action plan

Requisite scales of carbon removal through geochemical NETs will never be reached without engagement across multiple domains. Coordination and collaboration across sectors and domains are required to advance the field on relevant timescales, similar to the accelerated development of multiple COVID-19 vaccines (Bok et al., 2021). Ensuring efficient information exchange between groups in a way that leads to relevant and timely action may require creativity in terms of strengthened interactive discussions and sharing of informational resources and datasets, as well as accelerated technology transfer from laboratories to the public or private sector.

Near-term, many required actions focus on the research and development needed to assess risks, improve efficiencies, and establish robust MMV systems that enable public acceptance and market systems for carbon removal outcomes. All actions undertaken will need to consider environmental justice and equity concerns, as public acceptance will only build as successful projects including geochemical NETs are seen to benefit communities, through means such as increased employment, revenue-sharing schemes, environmental restoration, or combinations of these.

While action is required across all sectors, local, national and international governments deserve special mention, as it is their role to provide leadership in addressing climate change. They are uniquely able to establish laws and regulations, assemble and distribute certain types of data, and incentivize behavior and markets through policy decisions. They can act as major leaders in the marketplace through procurement decisions and setting of geochemical NET targets. They can also ensure that data and information are collected and shared openly. Furthermore, governments can develop integrated regional strategies for industrial and economic development based on assessments of local assets, such as mineral deposits, clean energy sources, deployment locations, R&D capabilities, and transportation infrastructure. They can identify locations for Gt $yr.^{-1}$ clusters and lead early planning and stakeholder engagement. Additionally, governments can make foundational investments in infrastructure, energy systems, feedstock sourcing, and/or storage sites to catalyze those clusters. They can lead R&D funding on integral and structurally important technologies across domains, e.g., calcination for cement manufacturing and for various geochemical NET pathways, construction materials, energy systems, and mining practices. Governments should also lead on setting and harmonizing standards and permitting regimes, defining acceptable ecosystem impacts, and providing targeted subsidies and carbon pricing.

Figure 2 lists detailed recommendations for actions by all actors in addressing gaps across the six elements in the section Needs assessment, as well as levels of requisite engagement by each actor, highlighting specific initiatives for which specific actors have opportunities to lead or to contribute. These recommendations are presented along with rough cost estimates in order to signal the level of effort required to undertake these recommendations and the degree to which certain actors can spark activity through funding mechanisms [e.g., the recent Ocean Alkalinity Enhancement Engineering Award funded through philanthropy (Additional Ventures, 2022)].

Also depicted in Figure 2 are rough estimates for the minimum time necessary for each recommended action to help bridge gaps between now and Mt $yr.^{-1}$ and Gt $yr.^{-1}$ deployment scenarios, which are included as a means of reckoning with the overall scope of work required. For example, we generally expect that lab research and field trials might require ~2–5 years, but larger scale demos might require at least ~5–8 years, and any significant deployment cannot take place before then. And while we may be only partially confident we have cost and time estimates for each initiative correct, we are confident that these are initiatives that must begin happening now if we are to achieve Mt $yr.^{-1}$ deployment of geochemical NETs by 2030, with a path toward Gt $yr.^{-1}$ deployment during the following two decades.

Discussion

With increasing consensus on the need for NETs to limit warming to 1.5°C (Shukla et al., 2022), the question is no longer whether negative emissions are necessary to stay within carbon budgets, but how we develop and implement them. Geochemical NETs are a potential opportunity to not only remove atmospheric CO_2, but to address wider environmental and sustainability issues, such as ocean acidification. This roadmap highlights gaps in current technical readiness, social license, demand, supply chains, human capital, infrastructure for geochemical NETs, and that required for Gt yr.$^{-1}$ deployment, and provides our initial ideas for how to address these gaps.

Decarbonizing industry while developing NETs is a daunting challenge. Geochemical NETs could potentially reduce the need for land- or energy-intensive carbon removal approaches, as well as enhance synergetic approaches, such as coupling with biochar or DAC (Buss et al., 2021). Further, wide-scale deployment of geochemical NETs could help enable some of the world's largest industries, including agriculture, concrete, mining, shipping, and steel, to reduce their emissions, toward net zero and perhaps even achieve net negative, in line with global climate targets. Application of geochemical NETs should not be considered a parallel track to reach these climate targets separate from decarbonization efforts; rather, the two should complement and reinforce one another and reciprocally unlock possibilities.

Geochemical NETs are generally characterized by low technology/system readiness, and there are significant gaps in our understanding of their kinetics and impacts. In our view, this only highlights the imperative to accelerate and expand research and development efforts in this field.

For geochemical NETs, large quantities of material will need to be safely extracted, transported, and transformed, and large quantities of low-emissions energy will be needed. Generating economies of scale, scope, and learning may require the development of regional clusters, in which mineral resources, modeling and monitoring tools, energy and transportation infrastructure, processing facilities, deployment sites, and labor pools can be strategically developed and maximally utilized and provide a basis for continuous learning and improvement. This suggests a need for geospatial assessments to map available mineral and infrastructure resources and ecological considerations and facilitate intelligent long-term regional planning and cluster development.

So how do we suggest prioritizing next steps? Near term, R&D is the priority. It should be accelerated across all aspects of geochemical NETs, including through multiple pilot projects and research experiments to evaluate the efficacy of carbon drawdown and the ecological impacts across geographies, climates and feedstocks. Activities advancing MMV of all geochemical NETs will be critical to getting them off the ground. Dedicated activities to address the lack of public understanding should begin now. The synergism with existing mining and mineral processing and distribution activities, critical for large scale-up of geochemical NETs, should be exploited as a way to make use of existing feedstocks and infrastructure. Finally, we encourage leaders in government, philanthropy, finance, and in relevant industries—such as agriculture, lime and cement/concrete, mining, shipping, and iron/steel—to assess what they can uniquely add to advance geochemical NETs, given the assets, capabilities, and opportunities of each specific region or organization.

Ultimately, society must be confident that it can deploy geochemical NETs safely, and that these technologies are competitive with other possible climate remediation efforts in terms of efficacy, cost, and other less tangible impacts and benefits, such as biodiversity, impacts on land and ocean ecosystems, social equity, economic activity, and political acceptability. And while there is a growing community of research and practice, dominated by North America and Europe, a considerably more global set of actors and efforts are needed to advance the field. We propose a concerted effort to engage and cultivate this global community, using this roadmap and others that follow it, to coordinate and strategically grow the field of geochemical NETs in a way that is safe, scalable, effective, and timely.

Author's note

This novel roadmap work is a collaboration between academics and NGO The Climate Map, which brings a fresh perspective to an academic-heavy field.

Data availability statement

This perspective article is based on a comprehensive review on Geochemical NETs, available here: Campbell et al. (2022).

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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