Collaborative Earth
Carbon dioxide removal prepurchase application
Summer 2024

General Application

(The General Application applies to everyone; all applicants should complete this)

Public section

The content in this section (answers to questions 1(a) - (d)) will be made public on the [Frontier GitHub repository](#) after the conclusion of the 2024 summer purchase cycle. Include as much detail as possible but omit sensitive and proprietary information.

Company or organization name

Collaborative Earth

Company or organization location (we welcome applicants from anywhere in the world)

USA, India

Name(s) of primary point(s) of contact for this application

Anthony Acciavatti, James Smoot

Brief company or organization description <20 words

Ganges Lab is a multidisciplinary team charting pathways to sustainability and health in the world's most densely populated river basin.

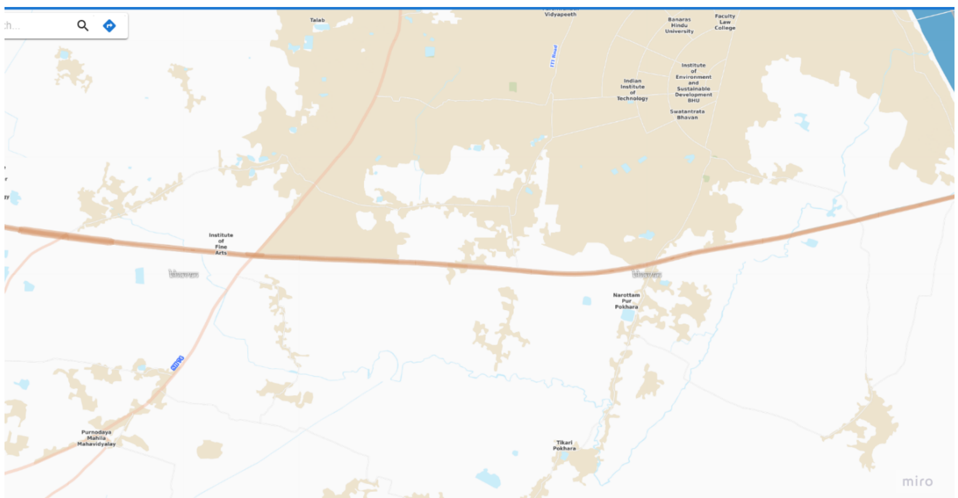
1. Public summary of proposed project[1] to Frontier

a. **Description of the CDR approach:** Describe how the proposed technology removes CO_2 from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar approach. If your project addresses any of the priority innovation areas identified in the RFP, tell us how. Please include figures and system schematics and be specific, but concise. 1000-1500 words

[1] We use "project" throughout this template, but the term is not intended to denote a single facility. The "project" being proposed to Frontier could include multiple facilities/locations or potentially all the CDR activities of your company.

Our carbon removal approach is to integrate olivine sand into civic infrastructure that mitigates pollution runoff into rivers such as the Ganga/Ganges. Civic infrastructure projects must address many socioeconomic and environmental factors and thus design elements that meet several of these demands simultaneously are highly advantageous. Two such design elements, bioswales and terraced constructed wetland garden beds can be engineered to include ERW. Bioswales are a "low impact development" stormwater control feature that reduce pollutant runoff and may include sand and other filtration media (Soberg et al., 2017; Ekka et al., 2021).

We are expanding municipal deployment of ERW to the Global South by locating the project in Varanasi, India. Our deployment of olivine sand as a filtration matrix in bioswales and terraces is designed to mitigate sanitary wastewater that enters a naala near Banaras Hindu University in a periurban section of Varanasi, Uttar Pradesh, India. The naala is a 14 km channel that drains both rural agricultural lands and dense urban areas prior to joining with Ganga in Varanasi. The Ganga continues about an additional 1150 km prior to flowing into the Bay of Bengal in the Indian Ocean.



A key feature of this use case is that olivine sand may be replenished as part of well-established and standardized bioswale maintenance procedures, thus providing for future deployment of olivine sand and more carbon sequestration. Similarly, olivine sand may be added to terraced constructed wetland garden beds engineered to facilitate percolation while removing carbon dioxide, which may provide for community green spaces or peri-urban cultivation of food (olivine sand would be isolated from edible plants in this use case) while redirecting nutrients that cause eutrophication (nitrogen and phosphorus) away from waterways and potentially back toward human nutrition. Furthermore, our approach has the **capacity** to result in a distributed and continuous removal of hundreds of millions to gigatons of carbon dioxide. However, the breadth of the approach needs to be expanded beyond deployment in drainage channels and integrated into low impact development best management practices for roadway stormwater management to reach such scales. For instance, lining 10% of roadways with olivine sand infused bioswales could sequester over 150 million tonnes of carbon dioxide in India (6.33 million km * 237.5 kgCO_2/m * 50% net efficiency * 2 sides of a road * 10% of roads * 1000 m/km / 1000 kg/tonne = 150.6 million t CO_2). Extrapolated globally, this approach represents a sequestration potential of more than 1 Gt of carbon dioxide along 52.5 million km of roads in addition to 425 million t carbon dioxide removal with bioswales along agricultural canals and ditches. This approach has the potential for >0.5 Gt CO_2 annual removal once integrated into standard maintenance practices. Of note, these estimates are based on the bed volumes described for the current project, and thus overall amounts of captured carbon dioxide may be increased with larger bed feature shapes.

Specifically, our process of removing carbon dioxide from the atmosphere is ERW of alkaline silicate sand used to treat pollutants in the naalas; thus olivine sand will be added to bioswales and terraced constructed wetland beds as part of our civic infrastructure interventions. The use of olivine sand in these applications is **100% additional** as quartz sand is usually the filtration medium used in these approaches, and it is completely optional to substitute an alkaline rock sand for quartz sand. Moreover, including ERW in our design plans **does not increase the physical footprint of the project** because we are simply exchanging one filtration medium for another. Olivine sand milled to 150 microns has a bulk density of 1.9 g/ml, and it is anticipated that complete weathering of the olivine sand and subsequent uptake of carbon dioxide will be between 3 and 30 years based on prior olivine weathering assessments (Hangx and Spiers, 2009). The rate of weathering and carbon dioxide removal will depend largely on the pH of the water that percolates through the sand. Flow, pH, and BOD loads will be monitored during all phases of the monsoonal cycle to estimate annual rates of carbon dioxide removal. While residence times are sufficiently long in the open ocean for dissolved inorganic carbon (DIC) to be considered **a durable form of carbon dioxide storage (10,000 to 100,000 years)**, DIC fate and its potential leakage prior to reaching the open ocean require tracking. DIC, Total Alkalinity, calcium, magnesium, salinity, and water temperature will be measured so that site and basin specific carbon dioxide removal results may be coupled with prior investigations of carbon flux along the Ganges Basin and dynamic river network models as well as ultimately Bay of Bengal ROMS-PISCES models to perform DIC tracking and to predict probabilistically the portion of atmospheric carbon dioxide removed by our ERW approach that is stably stored in the ocean (Joshi et al., 2020; Zhang et al., 2024; Upadhyay et al., 2024).

ERW costs depend on CDR efficiency and sand transport requirements (Zhang et al., 2023). India has active quarries for dunite olivine (CDR efficiency of 0.9 t CO_2 per ton of rock), and olivine dolerite dykes are associated with gold mines in India (Roy and Raju, 1980; Anon., 2015). Current estimated **cost of olivine-based CCS is about \$65/t CO_2 in India**; and although dolerite-based ERW may be more costly due to its inherent lower amounts of calcium and magnesium per ton of sand (CDR efficiency of 0.3 based on composition reported by Roy and Raju (1980) and R_{CO2} estimate from Renforth (2012)), its overall availability may make it a preferred source of alkalinity for locations near the mines (Zhang et al., 2023). Moreover, industrial byproducts such as steel slag and waste concrete have the potential to be feedstocks (Moras et al., 2024; McDermott et al., 2024). As the approach scales, feedstock source characterization will be included in MRV protocols to verify site-specific CDR efficiency and the degree of net negativity.

In summary, our approach is an ERW deployment in open sanitary sewer channel waters rich in biogenic carbon dioxide in India. The project is 100% additional and is likely to benefit river health and mitigate acidification. Moreover, it may represent a cradle-to-cradle opportunity through co-product sales of end-of-life residuals as concrete supplements or agricultural amendments. We are fully committed to publishing our findings in support of identifying and understanding optimal weathering environments, particularly under non-agricultural, aqueous conditions in hot and humid climates such as the water that flows through naalas of the Ganges Basin. Of note, we are keen to elucidate in situ microbial biofilm performance at facilitating weathering and DIC formation and how that translates to improved olivine-to-carbon dioxide sequestration efficiencies.

b. **Project objectives:** What are you trying to build? Discuss location(s) and scale. What is the current cost breakdown, and what needs to happen for your CDR solution to approach

Frontier's cost and scale criteria?[2] What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. 1000-1500 words

We are building waterway environments that exemplify multi-use green infrastructure: Redesigned naalas will not only improve water quality and reduce CO_2 emissions, they will also offer much-needed green public spaces for recreation and leisure. Vitally, green infrastructure is a broad-spectrum intervention to reduce wastewater contamination and remove carbon using olivine sand. Moreover, in settings where electricity service tends to be unreliable, green infrastructure offers advantages of reliability in comparison with energy-intensive forms of water purification like sewage treatment plants (STPs). In this project, two distinct forms of in-situ green infrastructure will be used to deliver the benefits of removing carbon as well as improving water, sanitation and hygiene (WASH): bioswales, vertical constructed wetlands.

Our new infrastructure project will be along a naala that enters the Ganga River channel near Banaras Hindu University in a peri-urban section of Varanasi, Uttar Pradesh, India. The naala is a 14 km channel that drains both rural agricultural lands and dense urban areas prior to joining with the Ganga in Varanasi. It is archetypical of naalas throughout the region, sharing many of the same characteristics in terms of its patchwork of dense urban settlement, agrarian and pastoral lands, as well as new highways crisscrossing it. Specifically, the project is focused on three distinct sections totaling 3 km of the naala north of National Highway 19 (NH-19) to its confluence with Ganga. Phase 1 is the most densely populated section and limited space is available for bioswales in the larger catchment, although swales will be included along sections of paths designed to connect the naala as an urban greenspace with its surrounding community. Otherwise, in situ constructed wetland structures will be built through Phase 1 of the naala and terraces will be added to the region closest to Ganga. Phase 2 is a peri-urban region and bioswales as well as in situ constructed wetlands will be built along the length of the naala including in low lying areas that are inundated throughout most of the year. Phase 3 is a more agricultural section of the naala that is impacted by NH-19 which cuts it off from the upper reaches of the naala except during the monsoon. As with Phase 2, in situ constructed wetlands will be constructed along the channel and in low lying inundated areas of Phase 3. Moreover, catchment bioswales will be positioned along roads and the park's network of paths in Phase 3.

[2] We're looking for approaches that can reach climate-relevant scale (about 0.5 Gt CDR/year at $100/ton). We will consider approaches that don't quite meet this bar if they perform well against our other criteria, can enable the removal of hundreds of millions of tons, are otherwise compelling enough to be part of the global portfolio of climate solutions.

In total, 18 100-m demonstration bioswales will be constructed; and if we adopt our highest-likelihood projection of 23.75 t CO_2 sequestered per bioswale, we forecast that a total of 427.5 t CO_2 is anticipated to be removed from the atmosphere. Briefly, our pilot design is as follows: left and right bank pairs of 100 m length bioswales will be constructed in triplicate; and given the diversity of conditions along the length of Naala 24, there will be three different sites. Pilot bioswales will include 10 cm deep x 100 cm wide sand beds per unit such that each meter of swale has 190 kg sand, which reasonable estimates suggest will sequester 237.5 kg CO_2 (Hangx and Spiers, 2009). In addition to bioswales a total of 12 terraced beds will be constructed. These beds are also expected to sequester 427.5 t CO_2 from the atmosphere because each bed will have about 28.5 t of sand (10 cm deep x 1000 cm x 1500 cm of sand per bed) and is estimated to sequester 35.6 t CO_2. Our pilot design is as follows: six terrace beds will be constructed on both the left and right banks immediately upstream of the naala's confluence with Ganga.

Major cost drivers for the project are olivine sand production, MRV and modeling, and energy associated with transportation of the olivine sand. We estimate a \$345/t CO_2 cost for olivine at an olivine-to-CDR rate of 0.52. We believe that this cost may be substantially reduced to \$43/t CO_2 after mining and milling operations scale to meet market demand and as uncertainty bounds are lowered, which will improve and better constrain olivine-to-CDR efficiencies. Our MRV and modeling efforts (\$540/t CO_2) will provide an in-depth analysis of olivine weathering including nickel toxicity assessments, rock dissolution and DIC production, clay formation, and stable isotope analyses. However, as more projects come on line we anticipate that streamlining of sampling and testing regimes, dedicated sensor and modeling systems, and economies of scale with respect to both empirical analysis as well as digital verification schemes will greatly reduce these costs to about \$24/t CO_2. Finally, our energy cost for transporting olivine sand for this project is \$50/t CO_2. Assuming improved market and operational efficiencies as well as adjusting for conventional sand energy costs we anticipate future energy cost of \$15/tCO_2.

MRV, including the potential for ecotoxicity from nickel, will be based on Vink et al., 2022 and Vink and Knops, 2023. Briefly, grain size distribution and elemental composition will be measured in triplicate per batch of olivine sand prior to deployment. At each site, profiles of pore water pH, dissolved inorganic carbon, and metal concentrations as well as olivine weathering will be measured. In addition, surface and ground water flow will be assessed to determine alkalinity and metal transport to Naala 24 and Ganga during pre-monsoon, monsoon, and post-monsoon seasons. Together, these data will be used to model carbon removal. LCA analysis will determine the carbon intensity of 150-µm olivine sand production and transportation in India compared to base-case carbon intensity of local river sand. Any emissions greater than the base case scenario will be subtracted from the carbon sequestered by olivine sand, so a true mass balance of sequestration may be determined. Moreover, weathering results will provide a refined time horizon for carbon sequestration. Furthermore our modeling efforts will include modeling carbon flux along the Ganges Basin with dynamic river network models and Bay of Bengal ROMS-PISCES models to perform DIC tracking and to predict probabilistically the portion of atmospheric carbon dioxide removed by our approach.

c. **Risks:** What are the biggest risks and how will you mitigate those? Include technical, project execution, measurement, reporting and verification (MRV), ecosystem, financial, and any other risks. 500-1000 words

In-situ systems like the one we are proposing require routine maintenance to ensure maximum benefits. Maintenance requires an institutional architecture that provides training to maintenance crews and that incorporates routine maintenance—particularly before and after the monsoon rains, when over one meter of rainfall occurs in three months (typically between June and September). Building on contacts we have established, alongside working with existing government institutions and private companies, we have incorporated maintenance in our budgeting and lifecycle of the project. The maintenance training program will be conducted in partnership with three local stakeholder institutions with deep roots in the community, namely: Ganga Mitra, a grassroots community-led organization in Varanasi dedicated to conducting on-the-ground outreach and engagement with communities along the Ganges River; Sankat Mochan, founded in 1982 in Varanasi, a non-governmental and non-political organization drawing leaders and youth together to raise awareness about and reduce pollution in the Ganges; and the Department of Geography at the University of Allahabad, which specializes on the intersection between human geography and the social sciences. All three institutions are along the main channel of the Ganges and have wide and overlapping networks to draw from within the region.

Along with the maintenance systems, we will also need to ensure that the ecosystems in place are working at maximum capacity. In order to do this, the structures must be well maintained to accommodate the monsoonal deluge to prohibit channels from forming in the vertical constructed wetlands so that wastewater is treated and the olivine sand reduces carbon.

Mineral weathering, secondary mineral formation, and leakage by outgassing are the largest sources of technical risk and the major reasons why we currently discount gross CDR by 50% when estimating the overall net CDR of this TRL-6 project. To better understand these risks and the degree to which they are relevant to future TRL-9 deployments, we are sampling and testing for both rock weathering and alkalinity. Furthermore, XRD and stable isotopes will be used to monitor secondary mineral formation and cation exchange capacity to determine scope of clay influence on CDR. Finally, leakage by outgassing will be assessed with Total Alkalinity and DIC testing as well as stable isotope tracing. Moreover, the fate of DIC during transport to the Indian Ocean via Ganga and the Bay of Bengal will be modeled both with dynamic river network models and ROMS-PISCES models for the Bay of Bengal.

The greatest ecological risks are associated with mining, and environmental impacts specific to olivine mining may include bioaccumulation of nickel and chromium in lower trophic levels (primary producers and filter feeders) but not a higher level carnivore due to dust produced during mining activities (Søndergaard and Asmund, 2011). The release of these metals is dependent on weathering and their secondary precipitation. Our MRV includes sampling for nickel accumulation in plants, algae, and periphyton as well as primary consumers such as mussels and aquatic insects. These findings will be compared to predictions based on particle size, metal dissolution rates, and biotic ligand models (BLM) to determine the system-specific robustness of the models and the likelihood of chronic nickel exposure over the life of the project.

d. **Proposed offer to Frontier:** Please list proposed CDR volume, delivery timeline and price below. If you are selected for a Frontier prepurchase, this table will form the basis of contract discussions.

Proposed CDR over the project lifetime (tons) *(should be net volume after taking into account the uncertainty discount proposed in 5c)*	356 t CO_2
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	June 2025-June 2028
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	$935/ton CO_2
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	$1403/ton CO_2

[3] This does not need to exactly match the cost calculated for “This Project” in the TEA spreadsheet (e.g., it’s expected to include a margin and reflect reductions from co-product revenue if applicable).