Tropicarbon, Inc.

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

Tropicarbon, Inc.

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

Colombia

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

Ludwig Ritter
Wilson Escobar
Camilo Montes

Brief company or organization description <20 words

We remove carbon at scale with enhanced rock weathering in Colombia, while enabling farmers to achieve larger yields.

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

Introduction

Tropicarbon utilizes Enhanced Rock Weathering (ERW) as a scientifically robust method to permanently remove CO2 from the atmosphere while benefiting regional farmers. Our goal is to scale ERW in the Latin American tropics, aiming to permanently remove CO2 at megaton-scale by 2030, while reaching and growing sustainable cost levels. We will achieve this goal by focusing on furthering scientific understanding of weathering in tropical environments, scaling novel feedstock blends that increase CDR capacity, and advancing MRV technologies for remote locations.

Description of the CDR approach and its advantages in the tropics

Enhanced Rock Weathering

Enhanced Rock Weathering (ERW) consists of applying finely ground mafic rocks, such as basalt and peridotite, to agricultural soils. Mafic rocks are rich in unstable silicates with high crystallization temperatures, essential for an efficient weathering process. When these unstable minerals come into contact with atmospheric CO2 dissolved in soil water, they undergo a series of chemical reactions, which are accelerated by the increased surface area of ground rock powder. Initially, CO2 reacts with water to form carbonic acid. This carbonic acid then reacts with the minerals (e.g., magnesium silicate) to release cations (like Mg^{2+}) and form bicarbonate ions (source). The bicarbonate ions are soluble and can be transported by leachate waters through soil columns into groundwater systems, eventually reaching the oceans, where they can be stored for thousands of years as stable dissolved forms of inorganic carbon (source). Additionally, under certain conditions, they can precipitate as carbonate minerals, further sequestering CO2 for even longer periods, up to millions of years (source).

Optimal conditions for accelerated weathering in Colombia

Due to higher temperatures and the abundant water availability, various studies demonstrate accelerated weathering in the tropics (source). Colombia, located in the Latin American tropics, offers ideal conditions for ERW with its high precipitation rates, acidic top soils, warm tropical temperatures, and high humidity levels. Early data from our experiments indicate that weathering rates in tropical Colombia can be more efficient (approximately 0.3 ton CO2 per ton of feedstock)

[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.

than in projects located in the global north (source), with values of 0.2 tCO_2 per ton feedstock with similar application rates (see section 5 for more detail).

Geological and Agricultural Context in Colombia

Colombia's rich geological diversity provides an abundance of mafic rocks, particularly basalt and peridotite. These rocks are widely available and easily accessible in western and northwestern Colombia (source; source; source; source). Many of these mafic sequences are located near major agro-industrial production centers in the Caribbean plains and the inter-Andean valleys, connected by developed truck roads or maritime routes. This distributed network of local rock suppliers will be crucial in achieving CO_2 removal at costs below \$100/tCO_2, as proximity to these suppliers minimizes transportation costs and emissions.

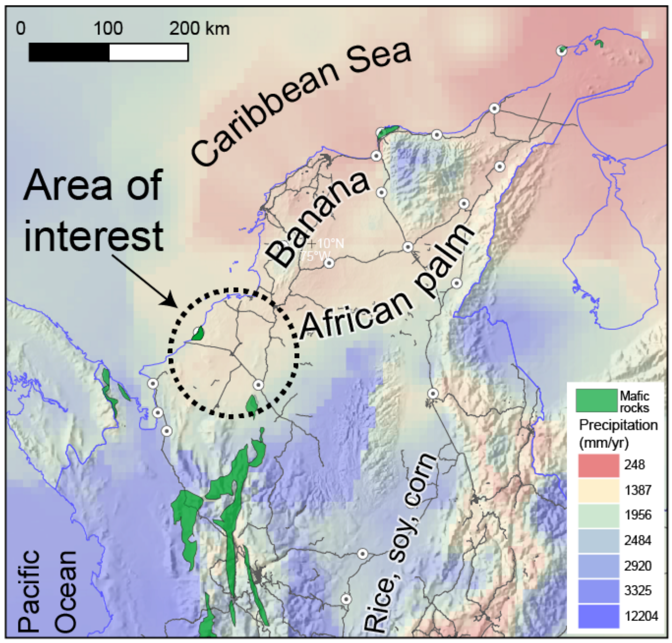

Figure 1: Map showing northern Colombia's multiple advantages for ERW. Color shades show precipitation in mm/yr (source), green polygons represent mafic rock outcrops (source), gray lines represent main roads. First, a humid tropical climate with precipitation in excess of 1400 mm per year, and easily 3000 mm per year in a bimodal pattern (April and October), and ambient temperatures above 28°C year round. Second, flat-lying lowlands with extensive agriculture (banana and African palm, but many others as well). Third, abundant mafic rocks nearby, less than 100 km away connected through a primary road network.

Proximity to Agricultural Lands

Colombia's agricultural industry is rich with banana, sugar cane, rice, African oil palm, and soy crops, which amounts to as much as 5 million hectares (source). In the same region where these crops are abundant, large piles of mafic and ultramafic rocks, discarded from industrial quarrying activities, nickel mines, and other ore deposits, are readily available (source). The availability of these agricultural lands, in close proximity to the discarded rocks as by-products of mines, make

Colombia an ideal place to perform long-term field projects in the tropics (see Fig. 1).

Colombia's advantages over other tropical regions

Colombia's unique combination of wet, tropical croplands near naturally outcropping mafic rocks, in combination with large areas of acidic soils, converge to put Colombia at the forefront of CDR in the tropics. Other countries may have similar climatic conditions, but for instance, Brazil's mafic rock belt is far removed (~2000 km) from the tropical agricultural lands of the north (source), while Indonesia relies on African Palm plantations that have expanded at the expense of primary forest (source).

Pioneering ERW in Colombia: Scaling and Scientific Advancements

Tropicarbon is pioneering ERW in Colombia and is one of the first companies globally to scale ERW projects in tropical environments. Our goal is to achieve megaton-scale CDR. To reach these targets, we plan to expand our projects beyond northwestern Colombia to other Latin American countries with similar climatic, agricultural and geologic conditions in the future.

Scaling to this magnitude requires not only space, feedstock supply, and infrastructure but also advancements in the scientific understanding of weathering in tropical environments and the rapid development of MRV methodologies. Tropicarbon aims to address these knowledge gaps by experimenting with the application of novel feedstock blends to enhance CDR capacity, increasing transparency around reaction kinetics in tropical settings, and advancing MRV technologies focused on high-frequency aqueous phase monitoring.

Our goal is to enrich the ERW community with data-driven knowledge and reliable, cost-effective MRV solutions, facilitating progress towards our common objective of gigaton-scale CDR removal.

Novel Feedstock Blend

Over the last year, we conducted several lab and field-scale experiments that tested weathering potentials of diverse feedstock blends in various soil environments. Experiments focused on blending basalt and peridotite feedstock blends, as these rocks are most abundant in Colombia's geological landscape (source; source). To find the ideal proportional blend, we leveraged initial weathering data of our pilot projects and evaluated geochemical characteristics of our feedstock blend. We landed on a feedstock blend of 70% basalt and 30% peridotite, which demonstrates an optimized CO_2 capture capacity based on its chemical characteristics (see here) compared to commonly used pure basalt feedstocks.

Accelerated Weathering Rates

The reactivity of mafic rocks in the tropics, particularly basalt and peridotite, is significantly higher than other silicates. Our preliminary field experiments show that a blend of 70% basalt and 30% peridotite reacts slightly faster than basalt alone (from 0.3 to 0.4 mmol HCO_3^- in two months), and more than two times faster if chicken manure (constraining strong acid dissolution) is applied with the blended rock powder (up to ~0.8 mmol $HCO3^-$ in two months). Additionally, similar experiments in the global north report similar uptake rates, but with slower accumulated alkalinities (source, see section 5), signaling a validation of accelerated weathering kinetics in the Colombian tropics.

MRV: High-Frequency Monitoring of Bicarbonate Alkalinity

Our goal is to close existing knowledge gaps around ERW in Colombia. To achieve this, Tropicarbon is committed to advancing MRV technologies, which will be made available to the broad ERW community. We have chosen to focus on monitoring bicarbonate alkalinity complemented with solid phase changes (using XRD and XRF techniques) because this MRV pathway lacks extensive field-scale deployment and experimental data. This project will be the largest of its kind to deploy field-scale, high-frequency monitoring (weekly during the rainy seasons) of the aqueous phase in the tropics. Monitoring of solid phase changes will take place every three months.

Leveraging a proprietary lysimeter design, our methodology involves digital titration to measure alkalinity in soil leachate, converting these measurements to CO_2 equivalents. Additionally, we use solid restite samplers to assess mineralogical and mass changes in amendment rocks. This dual redundant approach ensures comprehensive and independent quantification of carbon removal through both soluble products and solid mineral changes. Current field-scale monitoring shows that our methodology is adequate and can quantify chemical changes in the soil in line with a theoretical maximum of 0.332 tons per hectare. We will discuss this approach in detail in Section 5.

Striving to optimize Public Engagement, Environmental Justice, and Social Benefits

Farmers and farming communities are one of the most marginalized people on the planet - they are subject to a huge amount of risk, work in extremely volatile pricing markets, and generally receive extremely low wages. The core of Tropicarbon's business model — providing our feedstock to farmers for free — aims to increase farmers' yields and lower their costs (source).

Tropicarbon is deeply committed to engaging with the local communities in which we work. We encourage local students and community members to participate in our ERW projects, by working alongside our team implementing devices, spreading rock and monitoring and recording. We organize free workshops and educational sessions to arm farmers with knowledge of ERW and its benefits. This approach not only supports sustainable agriculture but also enhances economic opportunities for these communities.

Summary

Tropicarbon is scaling ERW in Colombia, targeting megaton-scale CO_2 removal by 2030 at sustainable price levels. We aim to achieve this by advancing the scientific understanding of rock weathering kinetics in the tropics, developing novel feedstock blends, and enhancing MRV technologies. Simultaneously, we support local communities by providing free feedstock to farmers, reducing their costs and increasing yields as we strive to foster sustainable agriculture, economic development, and promote environmental justice.

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

Project Overview

In this field-scale project, Tropicarbon will deploy 4,400 tons of our 70% basalt, 30% peridotite rock powder blend on approximately 110 hectares of farmland. The objective is to remove 1,415 tCO2 from the atmosphere using Enhanced Rock Weathering within five years. With this project, we will collect valuable data on rock reaction kinetics in Colombia, carbon sink uncertainties, heavy metal implications, and impacts on soil biological activity. Additionally, this project will help us further our goal of developing scalable MRV technology for the broader ERW community.

Location and Scale

When selecting the location for this project, we aimed to combine Colombia's most ideal climatic environments with logistical feasibilities. We selected a region close to Monteria, located in the northwest of the country in the department of Cordoba. The region predominantly has acidic soil with pH levels of 5.2-5.8, which results in accelerated rock weathering rates (source). Reddish-orange oxisol structures are semi-clay, semi-sandy, which are optimal for rock weathering due to their increased ability to transport bicarbonates while avoiding secondary mineral formations. Additionally, annual precipitation volumes in excess of 1.400 mm and average temperatures above 27 degrees Celsius will even further accelerate weathering rates (source). The region offers a wide availability of agricultural lands, with primarily corn, banana, African palm and pasture crops. While located close to the Caribbean Sea, the deployment site is located close to small drainages, enabling us to undertake meaningful downstream river monitoring.

Another factor influencing our decision for Monteria as the project site was its close proximity to key partners. Monteria is only 61 km away from our partner basalt mine in the nearby town of Puerto Escondido, and it is only 137 km from our partner peridotite mine in Cerro Matoso. In this project, we will deploy 4,400 tonnes of our proprietary blend of 70% basalt rocks and 30% peridotite rocks. The rocks we source are a byproduct of industrial mines and quarries, meaning the reuse of an otherwise unused material. However, due to their large size of >3 inches, we must partner with a processing plan to grind these rocks to reach the desired granulometry and corresponding weathering rates (source). Our processing partner in Monteria, based within 10km to the deployment site, will therefore process the feedstock to our desired granulometry. We will deploy the feedstock with agricultural spreaders available in the region, which are typically used for limestone application. In line with suggestions by literature and previous field-scale experiments (source), amended feedstock will be incorporated into top soils with available tilling equipment after deployment. Deployment will cover an area of 110 hectares of farmland with various crops, including corn, banana, and pasture. All deployment sites feature flat topography and are easily accessible for tractors and spreading machinery, ensuring efficient and safe application of our feedstock.

[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.

Current Cost Breakdown & Approach to Meeting Frontier's Criteria

Project Cost: $440,210

- CapEx: $77,230
  - MRV hardware, construction & installation labor, includes contingency costs
- OpEx: $296,980
  - Feedstock, crushing, transport, application, operating labor, general admin
- Indirect costs: $66,000
  - MRV sampling, modeling

In the future, we see major cost saving and growth opportunities that can get us to the Frontier criteria of less than $100 per ton removed and approach the goal of 0.5 GtCO2 removed annually. Our growth levers will be partnering with key stakeholders to secure scalable feedstock supply and deployment space. Our cost reductions will come from improving logistics, furthering the development of MRV technologies, optimizing rock treatment and procurement, and implementing future co-revenue streams.

Securing scalable feedstock supply and deployment space

Scaling to gigaton levels at sustainable prices will require substantial volumes of feedstock and extensive agricultural land for deployment. We plan to secure large feedstock supply agreements with mines that provide residues in suitable granulometry and purchase rocks in bulk to reduce costs. Additionally, we aim to establish partnerships with major farmer associations like Agrosavia in Colombia and similar organizations in other countries as we expand. We will also collaborate with fertilizer distribution suppliers to enhance access to farmers in new locations, ensuring a broad and effective deployment network.

Improving Logistics

The largest cost driver in our business model is the transportation of rocks. Although the average transport distance for basalt and peridotite in this project is only 107 km (relatively low compared to prior Frontier ERW applicants) transportation remains a significant expense in this project.

To reduce these costs in the long-run, we aim to leverage Colombia's distributed network of mines and quarries and strategically locate future projects even closer to feedstock suppliers and crushing facilities. Developing a comprehensive data set on viable project locations near feedstock supplies will also be crucial in other countries of future operation. Additionally, we plan to secure large-scale cooperation agreements with regional logistics companies. These partnerships will drive costs down through more efficient route planning, bulk pricing agreements, larger vehicle capacities, and the ability to capitalize on idle return ride capacities. Our cofounder, Wilson Escobar, brings over 25 years of experience in Latin American logistics to this effort. His network, experience and reputation in the industry will continue to play a crucial role in our success in this area.

Innovating MRV Techniques

Both MRV CapEx and leachate water sampling efforts are significant cost factors for our project. MRV CapEx primarily includes hardware costs for soil water lysimeters and digital titration devices, as well as the cost to install them in the field. Based on experience from previous projects, we know that field-scale leachate water sampling requires a minimum of one lysimeter per hectare plus additional control locations. The installation and weekly sample collection from these lysimeters is labor intensive and requires initial instruction by supervisors.

As our understanding of weathering rates in tropical environments improves, we anticipate significant reductions in MRV costs. Data collected today will enable future modeling of weathering kinetics, allowing us to deploy monitoring devices at lower spatial frequencies, thus reducing both CapEx and sampling costs.

Our long-term vision is to automate bicarbonate alkalinity titration by integrating our lysimeter design with automated titration devices similar to existing off-the-shelf solutions (source). This advancement will enable cost-effective bicarbonate alkalinity monitoring in remote locations, even more significantly reducing both CapEx and sampling costs.

Finally, we are leveraging data we collect today to build the largest database on weathering rates in the tropics, which will drastically decrease C-sink uncertainties due to better understanding of weathering rates in a given environment. Currently, we discount our gross CDR estimations for field-scale projects based on these uncertainties. Further knowledge in this area will enable us to reduce this discount, leading to larger gross CDR, a decrease in the volume of feedstock required per hectare, and lowering overall transport expenses for sampling efforts.

Optimizing Rock Treatment and Procurement

Although Colombia has an extensive supply of rocks from mines throughout the country, the granulometry of this residual feedstock is sometimes unsuitable for rock weathering projects. For optimal weathering rates we apply rocks in particle sizes between 150-1,000μm (source), necessitating a crushing and processing step prior to application. Many rock suppliers lack this type of treatment facility, forcing us to process with expensive third-party facilities.

Partnering with mines that provide residues in suitable granulometry, and working with rock suppliers who have larger machinery for rock grinding will reduce processing costs and increase efficiency. Additionally, bulk procurement and increased rock storage near ideal deployment regions will further reduce costs. Finally, investing in mobile crushing facilities will further decrease processing and transportation costs.

Innovative Revenue Streams

Cost economics can be further improved by introducing secondary revenue streams from value created during our operations. We see opportunities in advising large-scale agricultural operators on yield optimizations from mafic rock application, ongoing soil property monitoring, and replacing traditional soil enhancers with more sustainable feedstocks like our rocks. Additionally, licensing our pore water sensor technology to Colombia's heavy industrial sectors which are subject to public intoxication regulations, such as agriculture, mining, crude oil, gas, and petrol recovery, will generate additional revenue streams.

How we quantify carbon removal

To quantify CDR in this project, we will be monitoring both dissolved aqueous product as well as mineralogical changes in soils. This project will be the largest of its kind to deploy field-scale, high-frequency monitoring of the aqueous/solid phases in the tropics.

We are developing and adapting technologies to measure CDR through the dissolved aqueous products in the meteoric water that infiltrates the soil and reacts with rock amendments and the solid phase (Fig. 2). First, we developed a lysimeter that allows us to collect the total volume of water which reacts with the rock powder in the soils, without disturbing agricultural activities. We are also implementing a technique to quantify the mineralogical changes that take place in the solid phase. These two *in-situ* techniques allow us to have two independent yet complementary ways to empirically quantify CDR as it takes place in the field. Figure 2 demonstrates an overview of our CDR quantification approach, and Section 5 of this application outlines our approach in detail.

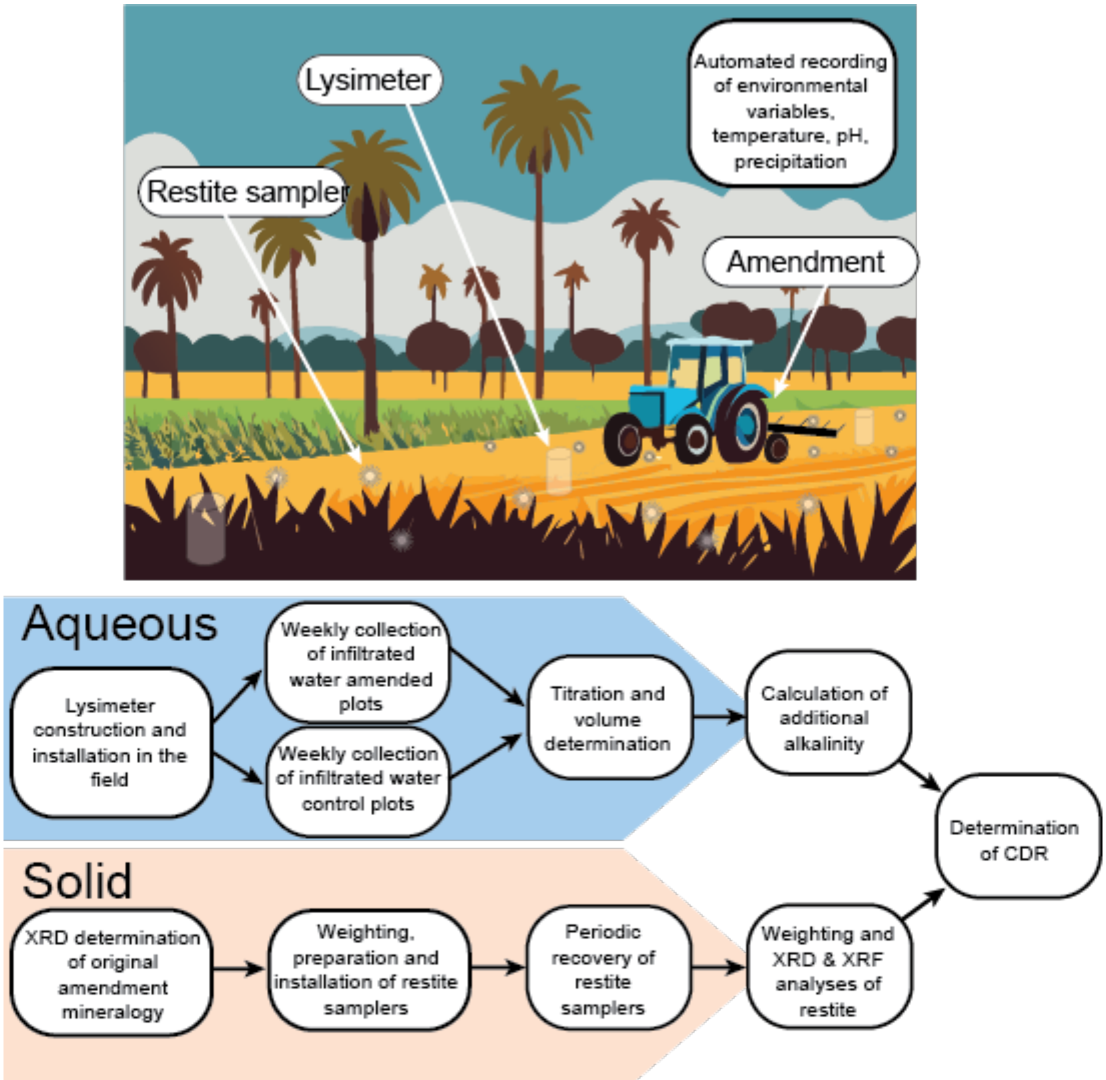

Figure 2: Schematic diagram of the components and work flow for the redundant determination of CDR.

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

Technical Risks

Uncertainty about actual CDR in field-scale

Uncertainties exist in the both weathering rates and potential CDR losses along the carbon sink pathway. Weathering rates can vary based on a number of factors, including differences in soil composition, interactions with organic carbon pools, pH levels, temperatures, and precipitation. Other technical risks include CDR losses from non-carbonic acid weathering (often induced by fertilizers), secondary mineral formation (e.g., clays) (source), terrestrial carbonate precipitation, plant cation uptake, evasion from streams and rivers (source), and ocean losses due to carbonic acid system equilibration (source) and counterfactual carbonate weathering sink (source).

To account for this uncertainty, we adopt a very conservative approach in how we discount the expected CDR (Section 5c). To address the risk, we will continuously monitor soil and leachate waters by analyzing small catchment riverine outlets and conducting baseline studies prior to feedstock application. We will monitor changes in pH and cation concentrations over time, ultimately enabling us to better understand and mitigate the variability in weathering rates and potential CDR losses.

MRV

Data reliability, measurement accuracy and reliable reporting also pose inherent risk in effectively assessing CDR. To mitigate these risks, we will utilize MRV methodologies that have been successfully employed in previous pilot projects in the same region. To ensure representative data collection, we will deploy lysimeter devices and restite samplers at a high spatial frequency of minimally one device per hectare, and add duplicate devices to ensure repeatability. For data integrity, we will implement the same number of monitoring samplers in control plots. This dual deployment strategy will enhance data accuracy and reliability (see details in section 5).

Project Execution Risks

Logistical Challenges

Transporting large quantities of rock to remote agricultural areas presents logistical challenges and can be costly. We mitigate this risk by partnering with local logistics companies who know the region and cultural dynamics. Tropicarbon co-founder Wilson Escobar's extensive experience and professional network in Colombian logistics will be instrumental in navigating these challenges efficiently, and will open doors for us as we work to optimize transport routes and reduce costs.

Operational Feasibility and Efficiency

The application of rock dust over large agricultural areas can be time-consuming and labor-intensive. For fast, cost-effective application, we will utilize agricultural spreaders, most commonly tractor vehicles used for limestone application to deploy our feedstock. Previous pilot projects in the region helped us build relationships with local spreading partners.

Ecosystem Risks

Heavy Metal Contamination in Soils and Waters

The application of ultramafic rocks can potentially introduce heavy metal trace elements, such as nickel and chromium, and asbestos into soils, posing a risk of contamination to crops and water sources. To address this, part of our MRV strategy will be to thoroughly test rock mineralogy for heavy metal contents before application. Our proprietary blend of 70% basalt and 30% peridotite (chemical characteristics) is specifically chosen to keep heavy metal contamination levels below United States thresholds (source). Estimated release rates should remain small, as studies with higher basalt application rates showed no notable sign of increased heavy metal contaminations in rock amended soils and leachate waters (source). We will nevertheless conduct baseline studies to understand the existing soil and water conditions before the project begins. Additionally, regular monitoring of soil and water quality will help us detect any sudden spikes in contamination levels.

Biodiversity

Changes in soil chemistry could affect local flora and fauna, potentially disrupting ecosystems. To mitigate this risk, we will select deployment sites with minimal ecological sensitivity and monitor the impact on local biodiversity through regular ecological surveys. We plan to collaborate with local environmental agencies to develop and implement biodiversity protection plans.

Health risks

Peridotite naturally contains some minerals of the asbestos group. To ensure no damage is done to local communities or our team on the ground, we will ensure our mining partners are avoiding rocks containing asbestos, as they are required by Colombian laws. We will mandate our partners use the appropriate protective equipment during any operation involving the mining, crushing and spreading of rock.

Other Risks

Political Risks

Political instability in Colombia poses a minor risk to the project's execution and continuity. Changes in government, regulatory policies, or social unrest in the region could disrupt project activities. To address this risk, we will engage with local and national government officials to build strong relationships and ensure compliance with all regulatory requirements. We believe that transparency works in our favor, and will ensure that all governmental bodies are aware and on-board with our projects. We will also engage heavily with local communities to gain their support of our projects, reducing the risk of disruption. Additionally, we will maintain flexibility in our project plans to quickly adapt to any political changes or unrest.

Community Acceptance

Lack of acceptance or opposition from local communities could hinder project implementation. To mitigate this risk, we will engage with local communities from the outset to build trust and support, while encouraging participation through the project lifetime. Communicating the benefits of the project, including economic opportunities and environmental improvements will be key. We will address any concerns transparently and involve community representatives in the planning and

execution phases. All of our environmental monitoring will be published.

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)*	1,305 tCO2eq (takes uncertainty and produced emissions into account)
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	5 years
Levelized cost (\$/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	\$337/tCO2eq
Levelized price (\$/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	\$380/tCO2eq (including 15% margin on direct costs)

[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).