Kodama Systems

Carbon Dioxide Removal Purchase Application

Fall 2022

General Application - Prepurchase

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

Company or organization name

Kodama Systems, Inc. + Yale Carbon Containment Lab

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

Sonora, CA + New Haven, CT

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

Jimmy Voorhis (Kodama), Justin Freiberg (CC Lab)

Brief company or organization description

Kodama deploys robotics to create fire resilient forests and scale biomass carbon removal

The CC Lab is a non-profit, interdisciplinary R&D group accelerating carbon containment methodologies

1. Project Overview

a) Describe how the proposed technology removes CO_2 from the atmosphere, including as many details as possible. Discuss location(s) and scale. Please include figures and system schematics. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar technology.

Kodama Systems, in partnership with the Yale Carbon Containment Lab (CC Lab), will pilot dry wood vaults which contain mechanically-thinned woody biomass residues resulting from forest restoration in regions of severe wildfire risk. If demonstrated to be safe and effective during our pilot, at scale this approach can:f

- Deploy carbon removal at costs approaching $60/tonne CO_2e in the near term
- Remove substantial fuel loads from forests while offsetting or eliminating removal costs

Opportunities and Risks Associated with Thinning Residue Utilization

Forest thinning treatments are effective at reducing the risk of large tree mortality and landscape conversion in forests at increasing risk of high-intensity wildfire (Liang et al, 2018). These thinning treatments are most effective when byproducts (residues) are removed from forests. New processes or technologies that valorize residues for their inherent energy, carbon, or product potential can offset residue removal costs, increasing the rate and scale of thinning treatments (Cabiyo et al, 2021). While long-term prospects for construction products and biofuels are compelling, there are hurdles to project development over the next decade. The largest hurdle is obtaining bank financing for centralized, high-capex projects (>$100MM). Bankable projects typically require 20-year feedstock supply agreements, which are difficult to obtain when the source of biomass is at risk of megafire and public agencies which manage forestlands (e.g., the U.S. Forest Service) have little precedent for long-term agreements.

Given these constraints, Kodama sees the need for decentralized, low-capex residue utilizations that enable short transport distances (i.e., <100 miles). Wood vaults in deserts and rangelands located near forests can serve as a 'baseline' utilization, valorizing residues for carbon dioxide removal (CDR). The vaults can scale up to meet forest management offtake needs, or sunset regionally if new technologies develop that provide similar outcomes at lower cost. Simultaneously, wood vaults incentivize Kodama to innovate and reduce feedstock transport costs to the benefit of all other residue utilizations.

Premise of Carbon Removal in Biomass Vaults

Carbon dioxide (CO_2) is removed from the atmosphere naturally during photosynthesis. Plants store most removed carbon in various structural compounds (cellulose, hemicellulose, lignin) which together constitute biomass. Carbon in biomass is vulnerable to release back to the atmosphere if biomass combusts or decomposes. In principle, vaulting biomass can prevent combustion and dramatically reduce agents of decomposition (e.g., fungi, termites) from acting on the biomass and releasing the carbon it contains. Climate and environmental conditions external to the vault are critical to performance, as factors which promote the growth of decomposers (e.g. water, nutrients) may enter the vault over time if the sealing is compromised.

We highlight that wood vaults are a subset of biomass vaults. Previously, clay-lined wood vaults (Carbon Lockdown Project, Carbon Sequestration Inc) and brine storage wood vaults (EBS, now InterEarth) have been proposed to Stripe and Frontier.

Kodama's differentiating innovations from previous biomass burial proposals are: 1) vault designs that control the risk of methane emissions by default, 2) integrated feedstock handling from source-to-storage, and 3) a mass balance approach to vault performance monitoring using proven, off-the-shelf technologies.

The Elephant in the Room: Methane Emissions

Decomposition of cellulosic biomass in anaerobic environments leads to production of equimolar volumes of CO_2 and methane (CH_4) through a four-step reaction chain beginning with hydrolysis, when cellulolytic bacteria secrete extracellular enzymes to convert insoluble cellulose and hemicellulose to soluble sugars. Since CH_4 has much higher climate forcing than CO_2, other biomass burial projects have received concerns about the potential for methane emissions. Thus, CH_4 emissions are the proverbial elephant of biomass burial CDR approaches. The concern around methane emissions is so great that the recent Puro.earth Woody Biomass Burial Methodology lists the detection and destruction of methane generated as one of its eligibility requirements (Puro.earth, 2022).

Unlike other forms of cellulosic biomass, softwoods exhibit a characteristic which limits the activity of anaerobic decomposers. The association of softwood-type lignin with cellulose and hemicellulose creates a physical barrier to enzymatic activity, significantly reducing the bioavailability of organic carbon. This limits overall softwood carbon losses to decomposition in anaerobic settings, as evidenced by a broad range of research topics including biofuels (Matsakas et al, 2015), bioreactors (Ximenes et al, 2019; Wang et al, 2011), landfills (Ximenes et al, 2014; Wang et al, 2013), and natural storage of wood in sedimentary systems (Lee et al, 2019). As a result of this recalcitrance, expected methane generation yields are low. Across the studies cited, total CH_4 yields ranged from 0 to 6.8 grams CH_4 per kg softwood, similar to the 4.9 grams CH_4 per kg observed during biomass combustion in wildfires (Liu et al, 2017).

In an arid wood vault, low CH_4 yields means low generation over a long time. Therefore, CH_4 and CO_2 will diffuse through a cover at low flux. Flux is how much mass passes through a given area over a given time. Kodama models indicate annual average CH_4 fluxes of 1 to 2 grams CH_4 per m^2 of cover per day in large-scale facilities, which have more wood under a given surface area and represent our highest-flux scenario.

Instead of constructing a chemical or physical barrier to prevent or block CH_4 fluxes, Kodama relies on naturally occurring methanotrophic bacteria in an evapotranspirative (ET) cover to control methane emissions. Oxidation rates of 52 to 102 grams CH_4 per m^2 per day have been measured in earthen covers at municipal solid waste landfills (Chanton et al, 2009), and there is evidence for complete oxidation at fluxes below 8 grams CH_4 per m^2 per day (Morris et al, 2018). Applying conservative estimates, expected generation rates within a wood vault are 4x to 100x lower than oxidation rates, indicating that functionally all methane produced from wood decomposition would be fully oxidized rather than released to the atmosphere.

Proposed Pilot Details

We will pilot two vault approaches in Mineral County, Nevada. Wood feedstock will be sourced from a fuels-thinning treatment which will begin in Q2 2023 near the town of Mammoth Lakes in eastern California. The vault types are:

- Small diameter boles (tree trunks) stored in an unlined vault. We project this to be the lowest cost vaulting approach adaptable to any sufficiently arid environment with nearby feedstock. A portion of the net CDR from this vault is on offer to Frontier.
- Slash (branches and needles), stored in a confidential vault type (see supplement).

Figure 1: *The forest-to-vault conveyor. Small diameter forest residues are mechanically thinned from overstocked, high fire risk areas. They are processed and loaded on logging trucks, transported <100 miles to vaults in arid locations, and buried in shallow geologic storage.*

Vault Construction

A thinning contractor will gather all material to a central landing (a common forest operation), and Kodama will process and load it for transport to the vault facility. Small diameter boles and tree tops will be delimbed, aggregated, and shipped whole to the vault site on a logging truck outfitted with a “turkey rack” trailer. Slash will be processed and loaded into possum-belly chip trucks and shipped to the vault site while green. Material removed will consist of Jeffrey and lodgepole pine.

Kodama’s vault will be constructed on land owned by Kodama in Mineral County, NV. Excavation and trucking will be contracted with local businesses.

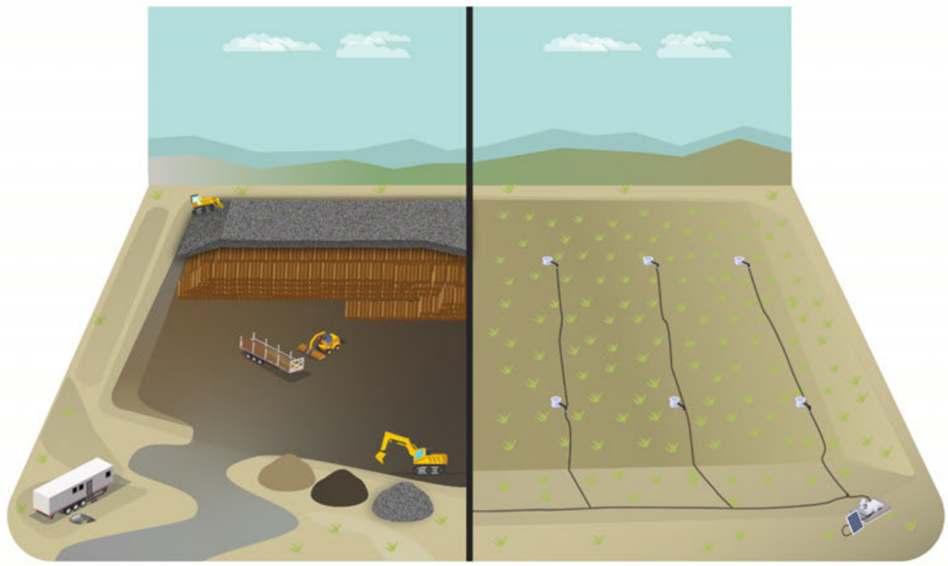


Figure 2*: Pilot vault conceptual model during operations (left) and closure monitoring (right).*

Excavation of the vault will consist of preserving different soil horizons to rebuild soil structure later during cover construction. First, vegetation is removed from the surface and stockpiled nearby. The topsoil horizon is excavated and stockpiled near the edge of the vault pit. Next, the deeper soil layers are excavated and stockpiled separately, and a flat subgrade is established at the bottom of the pit.

We note that soil organic carbon (SOC) is a key consideration of site selection. While some organic soils can have >10% SOC, the arid environments of the Lahontan Salt Scrub Basin and the Tonopah Sagebrush Foothills of Mineral County, Nevada, are likely all less than 1% SOC. Aeration of different soil horizons will expose these previously-stable pools of carbon to oxygen and decomposing agents. We will minimize time of exposure and plan to measure the SOC and soil inorganic carbon (SIC) prior to replacing the material in the ground.

On arrival onsite, the biomass from wood thinning is weighed on a calibrated truck scale and a statistically representative number of samples are collected. Samples will be shipped to a lab to measure bulk moisture content and carbon content. The log trucks drive directly into the pit and material is unloaded in progressive rows by a loader.

When log rows are finished to their final height, an excavator and bulldozer work in concert to build the cover in four layers. Gravel, either imported locally or screened from soil removed from the excavation, is layered in over the top of the logs to form a working platform and to infill any gaps between log rows. Next, a geotextile is unrolled across the graded gravel surface. Lastly, a two-layer evapotranspirative soil cover is constructed over the vault using the excavated materials by placing deeper, low carbon fine grained soil under topsoil, and is vegetated with forbs and shrubs found in the local ecosystem. The topsoil is amended with gravel, and over time naturally develops a 'desert pavement' surface that resists wind and water erosion.

The vault and the overlying cover are designed to be congruent with the desert landscape; after closure it will look like a low lying, sagebrush-dotted mound, approximately 50m on each side and 7m tall. Hydrologic isolation of the underlying vault is enabled by natural vegetation harvesting all the available water in the cover. The site receives an annual average rainfall of 4 inches per year.

Our Monitoring Approach Closes the Mass Balance

Some previous wood vault monitoring approaches aimed to measure CH_4 and CO_2 concentrations within, not outside of vaults. We're taking a different approach. Prior to burial, we measure the total mass of each truckload of wood and sample for carbon and moisture content. After the vault is covered, we will install instruments to measure CO_2 and CH_4 fluxes at various points on the vault surface. These instruments operate remotely with small power demand and provide hourly measurements of background and wood-vault fluxes. This enables Kodama and the CC Lab to monitor vault performance without boots on the ground. By combining flux measurements with soil characterization and monitoring, we will understand how carbon is changing within the system and close the vault mass balance.

Addressing Key Approach Criteria and Pathway Uncertainties

We address both Frontier's key approach criteria and the biomass burial pathways uncertainties listed on page 7 of the Fall 2022 RFP throughout this application, and we believe we meet all Frontier criteria. For our comprehensive treatment of transport, logistics, and associated costs and emissions, we direct the reviewer's attention to Kodama's LCA model included within the TEA spreadsheet.

Kodama would like to address biomass opportunity cost directly, as we do not seek to displace other uses. We believe in a future where residues are used to make high-value products such as biofuels and construction materials. However, challenges to financing centralized projects (i.e. biofuels and construction materials production facilities) will persist as long as forests remain at risk of megafire. Residue piles remain a persistent, unsolved, and hazardous problem for communities and agencies. Kodama can tackle this problem via wood vaults while building the transport and logistics technologies necessary to service higher residue end-uses.

b) What is the current technology readiness level (TRL)? Please include performance and stability data that you've already generated (including at what scale) to substantiate the status of your tech.

A wood vault is an aggregation of several technologies. Due to the uncertainty in putting all the components together in a full system, we view the overall TRL at 5. Critical components of vault systems which are well-proven include:

- Evapotranspiration Covers are TRL 9 and industry best-practice for shallow geologic storage of a wide variety of materials in arid areas.
- CH_4 and CO_2 Soil Gas Flux Monitoring Equipment are TRL 9. Several companies (LiCOR, Picarro, Los Gatos Research) make widely-tested, reliable greenhouse gas flux monitoring equipment which resolve CH_4 and CO_2 fluxes at detection limits sufficient to measure vault performance relative to background fluxes accurately over decades.

Kodama's TEA assumes cost reductions in delimbing, truck loading, unloading and stacking. These cost reductions come from a combination of low-hanging operational improvements (e.g. a revised trailer design to hold biomass) and semi-automation to reduce FTE requirements. Robotics in forest applications is currently

TRL 6, and Kodama will have a TRL 7 teleoperated forestry machine by the end of 2022.

Models of wood decomposition, which are largely empirical, are TRL 5. Although studies performed in anaerobic bioreactors (lab) and landfills (field) consistently indicate that softwoods are highly resistant to decomposition, these studies are limited in the array of species investigated. Kodama is currently running feedstock-specific anaerobic decomposition tests, and we will continue to improve decay models for project planning, tracking, and credit issuance purposes.

The CC Lab designed and deployed several fully replicated field experiments at 10 total sites in the U.S. in mid-2020 to quantify the effects of wood species, feedstock form (e.g., chips, slash, and whole logs), climate and soil types, and burial depth on rates and modes of wood decay, as well as carbon losses. Excavations of 2-year burials are currently underway, and additional excavations will occur at years 4 and 6. This experimental work will be peer-reviewed, published, and shared.

c) What are the key performance parameters that differentiate your technology (e.g. energy intensity, reaction kinetics, cycle time, volume per X, quality of Y output)? What is your current measured value and what value are you assuming in your nth-of-a-kind (NOAK) TEA?

We've estimated the NOAK cells based on site-specific scaling factors and conservative decomposition models. Details at the right indicate expected values and our reasoning.

Key performance parameter	Current observed value (units)	Value assumed in NOAK TEA (units)	Why is it feasible to reach the NOAK value?
Average Daily CH_4 Flux	N/A	1.3 g m^{-2} day^{-1}	In our decay models, we use conservative estimates of methane generation to estimate fluxes (i.e. we apply CH_4 yields from experiments designed to maximize generation by pulverizing wood to increase reactive surface area, then spiking it with moisture, nutrients, and bacteria). We expect lower fluxes because we'll bury whole logs, which have lower reactive surface area, in a dry, nutrient- and bacteria-poor environment.
Average Daily CO_2 Flux	N/A	4.6 g m^{-2} day^{-1}	(same as above, except for CO_2)
CH_4 Oxidation %	35 - 100% (from literature)	95%	At the average generation rates we observe, there is literature evidence for complete CH_4 oxidation (100%). Our average generation rates would need to increase over 6x to risk incomplete oxidation. 95% is a reasonable conservative factor.

d) Who are the key people at your company who will be working on this? What experience do they have with relevant technology and project development? What skills do you not yet have on the team today that you are most urgently looking to recruit?

Kodama and the CC Lab have collaborated since July 2021. While Kodama tackled feedstock supply chains, assembled preliminary vault designs, and developed life-cycle and techno-economic analysis of vaults, the CC Lab investigated CH_4 and CO_2 measurement and monitoring design applicable to vaults, conducted field trials of wood decomposition, and assessed wood vaults through a social and environmental justice lens. Together, we've assembled a world-class team to bring our vault pilot to life.

Jimmy Voorhis, Kodama's Head of Biomass Utilization and Policy, has researched biomass burial carbon removal in-depth for over a year and conducted on-the-ground research on biomass processing, handling, and transport. Previously he worked as a mining geochemist building systems-wide mass and water balances for mining clients across North America, and developed a drone-based MRV solution to assess water quality in mine pit lake environments. He holds a MSc in Earth Science from Dartmouth.

Craig Benson, an Engineering Advisor to Kodama, is an international authority on containment systems for a broad variety of materials and wastes and is one of the foremost international experts on ET covers. His expertise includes municipal solid waste, hazardous waste, coal combustion residuals, mining and mineral processing wastes, and low-level radioactive waste. Craig served as Dean of Engineering at the University of Virginia and in various leadership roles at the University of Wisconsin-Madison before entering emeritus status. He is a Professional Engineer and member of the National Academy of Engineering.

Mort Barlaz, a Scientific Advisor to Kodama, is a foremost expert on biological refuse decomposition who pioneered the use of life-cycle analysis in solid waste management. He was named as a 2021 American Association for the Advancement of Science Fellow for his "distinguished contributions to the field of environmental engineering, particularly for advancing understanding of solid waste engineering and related fundamental biological and chemical processes." He is a Distinguished University Professor at North Carolina State University.

Justin Freiberg, Managing Director at the CC Lab, has entrepreneurial experience in carbon dioxide removal with a biochar company - Encendia Biochar - that he co-founded more than a decade ago as well as previous work at Yale in commercializing sustainability-oriented ideas and technologies.

Sinead Crotty, Project Manager at the CC Lab, applies her expertise in both experimental design and execution across a variety of projects at the CC Lab, helping to ensure that experimental research at the Lab connects to the scaled implementation needs of practitioner partners. She has looked extensively at forest systems across the U.S., and has led the CC Lab's work on understanding the mechanisms of wood decomposition.

Dean Takahshi, Founder and Executive Director of the CC Lab, applies the principles and lessons from his more than three decades of work at the Yale Investments Office to his work in building and guiding the CC Lab. Dean has decades of experience in partnership with large timberland investment management organizations.

Jana VanderGoot, Affiliate to the CC Lab, has been focusing work on the siting and design of projects that could reduce the rate of wood decomposition. She is a licensed architect, landscape designer, and Associate Professor of Architecture at the University of Maryland School of Architecture, Planning and Preservation. Jana's teaching, research and practice center at the intersection of design and environment and include urban ecological planning, non-toxic building processes and materials, and climate adaptation.

Merritt Jenkins, Kodama's CEO, is a serial entrepreneur with a technical background in robotics and agriculture. Previously he co-founded Pattern Ag, a venture-backed soil analysis company and led a robotics team at the indoor farming company Plenty. He holds an MBA from MIT and a MEng in Robotics from Carnegie Mellon.

Matt Verminski, Kodama's Head of Technology, is building Kodama's team and technologies. Previously, he led the Desktop Metal engineering team and was part of the initial team at Kiva Systems (acquired by Amazon

in 2012). He holds a MS from MIT. We are seeking a rangeland ecologist to craft our revegetation plan and are in discussions with candidates via the CC Lab and Dr. Benson.

e) Are there other organizations you're partnering with on this project (or need to partner with in order to be successful)? If so, list who they are, what their role in the project is, and their level of commitment (e.g., confirmed project partner, discussing potential collaboration, yet to be approached, etc.).

Partner	Role in the Project	Level of Commitment
National Forest Foundation	Partner coordinating thinning treatment, feedstock supply, and informing counterfactuals	Developing specific partnership details
Northern Nevada Development Authority	Support community engagement and facilitate introductions to government entities as needed for the project in NV	Confirmed project partner
Whitebark Institute	Support community engagement and facilitate introductions to stakeholders near Mammoth Lakes, CA	Confirmed project partner
Yardstick	Partner for soil carbon analysis; reviewing sampling plan to support robust characterization and measurement	Confirmed project partner

f) What is the total timeline of your proposal from start of development to end of CDR delivery? If you're building a facility that will be decommissioned, when will that happen?

We plan to break ground in Q3 2023, at the same time the thinning treatment begins. Enough feedstock will be available to fill and close the vault by Q4 2024, when monitoring and revegetation will begin.

g) When will CDR occur (start and end dates)? If CDR does not occur uniformly over that time period, describe the distribution of CDR over time. Please include the academic publications, field trial data, or other materials you use to substantiate this distribution.

We consider CDR to occur at vault closure plus one year to account for a pile burning storage counterfactual, which we describe in the Biomass Supplement.

h) Estimate your gross CDR capacity over the coming years (your total capacity, not just for this proposal).

Year	Estimated gross CDR capacity (tonnes)
2023	3,741 (150 acres thinning treatment serviced)
2024	Pilot assessment period - no CDR delivered

2025	50,000 (first portion of 1 large landscape-scale treatment)
2026	200,000 (remainder of 1 large landscape-scale treatment, 12.5k acres total)
2027	600,000 (3 treatments, 30k acres)
2028	1,200,000 (6 treatments, 75k acres)
2029	3,000,000 (12 treatments, 150k acres)
2030	6,000,000 (25 treatments, 300k acres) (>500K acres thinned in aggregate by 2030)

i) List and describe at least three key milestones for this project (including prior to when CDR starts), that are needed to achieve the amount of CDR over the proposed timeline.

	Milestone description	**Target completion date** (eg Q4 2024)
1	Land Purchase	Q4 2022
2	Special Use Permit Approved	Q1 2023
3	Nevada Department of Environmental Protection Class III Permit Approved	Q3 2023
4	Vault Closed	Q4 2023
5	Counterfactual Executed + CDR Delivered	Q4 2024

j) What is your IP strategy? Please link to relevant patents, pending or granted, that are available publicly?

Kodama is taking a systems approach to forest restoration and sees wood vaults as a tool to increase the pace and scale of forest restoration, driving business to Kodama's forest restoration service.

Direct defensibility of wood vault designs is challenging from an IP perspective (especially low-cost designs) but there are ways to build a competitive moat:

- Be first to market on data collection
- Acquire land (or options to acquire land) in optimal locations for wood vaults (close to forest, meets aridity thresholds)
- Streamline the process of delimbing and loading small-diameter tree boles, which is a non-trivial portion of total cost
- Innovate in forest trucking and biomass haulage
- Establish forest thinning operations in the eastern Sierras (of which there are very few) to build supply chain defensibility

k) How are you going to finance this project?

Our first project will be financed with venture capital. Kodama recently raised a $6M funding round led by Congruent Ventures, Breakthrough Energy Ventures, and others. We do not plan on exclusively using venture capital to finance future projects, but it is necessary for a first-of-a-kind project. Our goal for a first-of-a-kind project (50K+ tonnes CO_2e of CDR) is to use a combination of ex ante purchase commitments, debt, and venture capital.

We anticipate that any follow-on project of 50K+ tonnes CO_2e of CDR can be financed almost entirely through debt. It is very common for waste management projects to be financed through green bonds, and we anticipate that wood-based carbon storage will have a lower risk profile than traditional waste management projects.

l) Do you have other CDR buyers for this project? If so, please describe the anticipated purchase volume and level of commitment (e.g., contract signed, in active discussions, to be approached, etc.).

We do not have other CDR buyers lined up, but have started discussions with another potential purchaser. We are happy to discuss this with Frontier.

m) What other revenue streams are you expecting from this project (if applicable)? Include the source of revenue and anticipated amount. Examples could include tax credits and co-products.

We do not expect to generate any other revenue streams from this project.

n) Identify risks for this project and how you will mitigate them. Include technical, project execution, ecosystem, financial, and any other risks.

Risk	Mitigation Strategy
Risks to our people and partners	
Health and Safety	• Will implement project risk controls for working around heavy machines, driving, etc. • Will with contractors with a proven track record of safety and willingness to review, modify, and implement our Health and Safety plan • Will implement a daily stand up to discuss risks and controls before work starts
Social and legal risks	
Community Resistance	• Engaging in collaborative planning process with host communities and partner organizations
Difficulty obtaining permits	• Obtained checklist of permit requirements; in close contact with permitting agencies in both Mineral County and NV Dept. of Env. Protection
Physical risks to vault sites	
Methane emissions	• ET cover designed for complete emissions oxidation • CH_4 fluxes monitored at high resolution in six locations on vault surface
Fire (after/during operations)	• Burial depth to 2.3 m; subsequent development of anaerobic environment means no O_2 available for combustion in vault • Rapid internment of wood minimizes site • Fuel load control plan implemented on vault site • Rocks and strike surfaces marked as sparking risks • Designated fire-wise team member onsite during all machine operating hours
Erosion (wind and	• Vegetation on ET cover anchors soils

water)	• Gravel amended in topsoil to create 'desert pavement' effect • Sloped sides with gentle grade minimizes runoff velocity
Rain event prior to vault closure after wood emplaced	• Watch weekly forecasts for rain events • Tarp emplaced wood stacks if rain forecast • Allow drying of any standing water prior to vault closure
Climate risks	• Design for influence of extreme rain and wind events using localized downscaled projections under likely RCPs
Ecosystem Risks	
Revegetation Challenges	• Involve ecological experts in arid ecosystems, especially those well versed in restoration of sagebrush shrub ecosystems, in the planning and deployment of vegetation plantings • Engage in active discussions about the success of the restoration activities and allow for evolution of restoration strategies as informed by the science
Financial Risks	
Contractor Availability	• Engage contractors during permitting stage to ensure contractors are available to complete work
Overruns	• Produced detailed cost estimate based on real contractor, engineering costs, and conversations with permitting agencies • Included contingencies in project budget

2. Durability

a) Describe how your approach results in permanent CDR (> 1,000 years). Include citations to scientific/technical literature supporting your argument. What are the upper and lower bounds on your durability estimate?

Unlined vaults do not rely on isolating wood entirely from the outside environment. Rather, the focus is on creating a stable and dry environment within the vault using natural principles to manage the ingress of moisture and oxygen. Then, we rely on the inherent recalcitrance of wood maintained under these conditions for durable carbon storage.

There is precedent for this approach. Shallow geological storage under earthen vegetated evapotranspirative (ET) covers is considered a best-practice for disposing of a variety of materials including mine tailings, low-level radioactive waste, and contaminated soils. Many storage facilities have a design life of 1000 years, though analogous evidence suggests they can be effective for at least 13,000 years (Bjornstad & Teel, 1993).

Given the well-understood design philosophy of and impressive performance data of existing ET covers (Apiwantragoon et al, 2015; Benson and Bareither, 2012; Albright et al, 2010), we have high confidence that cover integrity, and therefore vault environment, will be maintained for millennia in the absence of intentional human disturbance. Key properties of ET covers (see Figure 3) include:

- Gravel amendment in the surface soils forms a naturally resistant 'desert pavement' which minimizes wind and water erosion
- Native vegetation prevents percolation of water into deeper layers by scavenging and transpiring water stored in the cover soils, so contained materials stay dry

- The soil cover absorbs and stores water, providing a favorable environment for vegetation growth and microbial activity, including oxidation of CH_4, while creating a barrier for gradual diffusion of CH_4 into the zone of oxidation near the surface
- Biota barriers constructed with gravel and cobbles can prevent burrowing of animals and insects (not shown in Figure 3)

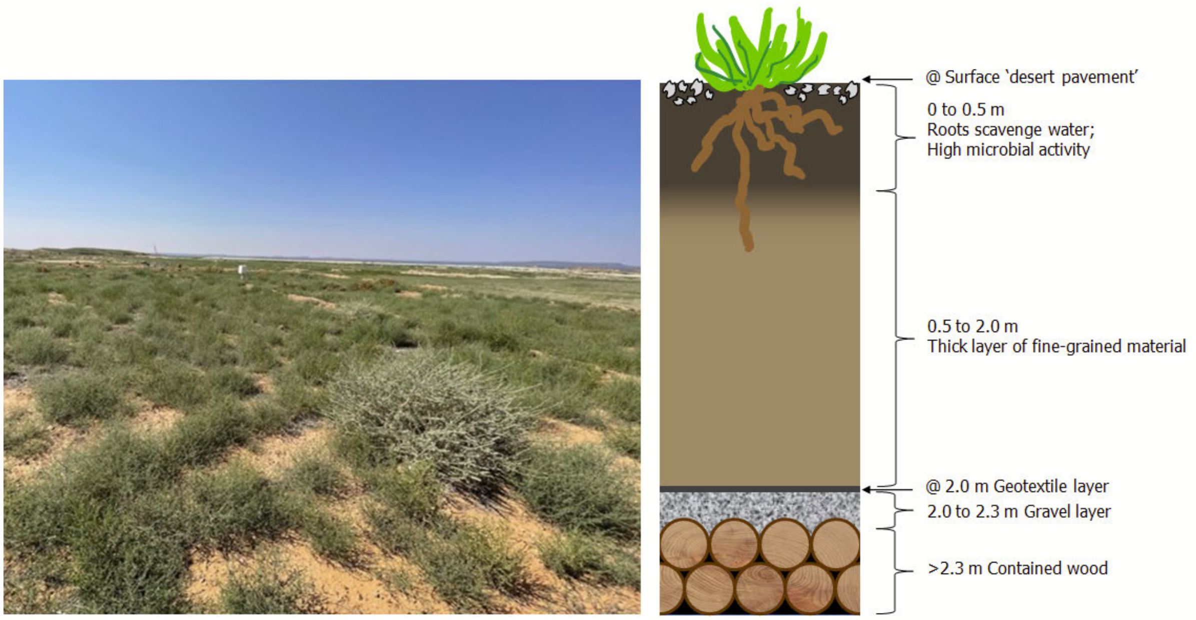


Figure 3*: (Left) An ET cover over a uranium tailings facility in Monitcello, Utah. (Right) Conceptual cross section of a vault ET cover.*

To address the durability of wood storage, we performed a sensitivity analysis using our LCA model to determine the variability in net CDR at 1000 years. With cleaner machines, good cover performance, and using carbon losses associated with softwoods, we can achieve 95% carbon removal efficiency. Using conventional machines, poor cover performance, and worst-case decomposition losses, we can achieve 60% removal efficiency.

b) What durability risks does your project face? Are there physical risks (e.g. leakage, decomposition and decay, damage, etc.)? Are there socioeconomic risks (e.g. mismanagement of storage, decision to consume or combust derived products, etc.)? What fundamental uncertainties exist about the underlying technological or biological process?

Two durability risks are biological activity on biomass (low-to-medium risk) and intentional disturbance of vault sites (low risk).

Biological activity risks include:

- Fungi, including white and brown rots (Basidiomycetes), are efficient wood decomposers which can break down softwood-type lignin. However, they are obligate aerobes which require water to grow. Soft rots, another grouping of fungi, are slower and metabolically less efficient decomposers, and may be found in low-oxygen environments. Since we will maintain an anoxic environment in the vault, we rate this as low risk. Furthermore, this risk could be mitigated by adding a soluble carbon source (e.g. sugar) which would drive rapid consumption of residual oxygen prior to vault closure.
- Termites are also efficient wood decomposers which create CH_4 during wood digestion, but they are

also aerobic organisms. We've corresponded with termite experts who indicated they are unlikely to burrow deeper than the top meter of the 2.5m cover. We rate this as low risk.

- Anaerobic bacteria have been shown to act on wood, but carbon losses for softwoods ranged from 0 – 2% of total carbon mass for various softwood species under conditions designed to accelerate anaerobic decomposition (i.e. ground biomass with maximum reactive surface area, high moisture, optimal temperature, nutrient addition, and methanogenic consortia added, see Q1a for references). The conditions in a wood vault in an arid environment are far from optimal (low moisture, no nutrients, low or no methanogenic microbes).

Ultimately, maintaining wood in whole-log form will confer maximum resistance to decay by minimizing the surface area available for decomposition. Structural changes within the wood (e.g. cracking through drying, or compression of the wood by overburden pressure) may expose additional cellulose and hemicellulose to degradation over time.

At the surface, the structural stability provided by minimally degraded, interlocking logs will ensure long-term support for the cover. Modest deformation of the wood mass is unlikely to affect cover performance, as ET covers are made of fine-grained materials which deform evenly without compromising containment.

Intentional disturbance of vault sites is also a risk, especially if biomass becomes significantly more valuable in the future. We view this as unlikely and therefore low risk.

3. Gross Removal & Life Cycle Analysis (LCA)

a) How much GROSS CDR will occur over this project's timeline? All tonnage should be described in **metric tonnes** of CO_2 here and throughout the application. Tell us how you calculated this value (i.e., show your work). If you have uncertainties in the amount of gross CDR, tell us where they come from.

Gross tonnes of CDR over project lifetime	Gross CDR = 3741 tonnes CO_2e (see Biomass Supplement for counterfactual discussion)
Describe how you calculated that value	Total Mass = 4500 short tons (4082 tonnes) Moisture Content = 50% on wet basis % Carbon of bone dry wood = 50% Mass Fraction CO2/C = 44/12 $Total\,Mass\ *\ MC\ *\ \%C_{bone\,dry}\ *\ MF\ =\ Gross\,CDR$

b) How many tonnes of CO_2 have you captured and stored to date? If relevant to your technology (e.g., DAC), please list captured and stored tons separately.

YCCL has conducted smaller scale log, chip, and wood cookie burials at 10 sites distributed around the U.S. These experiments were deployed in 2020 and are being excavated currently to assess decay. Kodama and YCCL have not constructed large-scale vaults of any wood to date.

c) If applicable, list any avoided emissions that result from your project. For carbon mineralization in concrete production, for example, removal would be the CO_2 utilized in concrete production and avoided emissions would be the emissions reductions associated with traditional concrete production. Do not include this number in your gross or net CDR calculations; it's just to help us understand potential co-benefits of your approach.

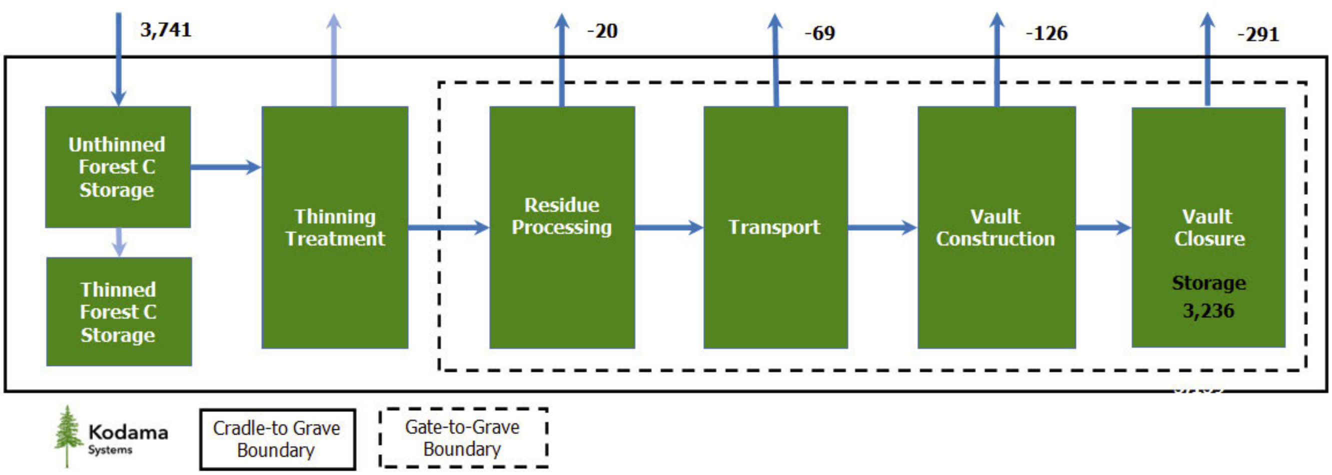
Biomass burial CDR approaches that leverage waste feedstocks are inherently avoided emissions projects, so the majority of CDR happens as a result of creating a different future for the biomass versus the counterfactual scenario. We've outlined out counterfactual details in the Biomass Supplement.

Additionally, even when it is assumed material is pile burned on a project, a thinned acre of overstocked forestland in the western U.S. yields an average ecosystem carbon benefit (also called "avoided wildfire emissions") totalling 9 tonnes CO2e (Fargione et al., 2018). This benefit is due to the reduced statistical likelihood of a high-intensity, "stand-replacement" wildfire. Kodama's proposed vault will store biomass removed from 150 to 300 acres of wood, depending on the per-acre yield. Kodama's proposed wood vault will contribute to avoiding an additional 1350 to 2700 tons of CO2e.

d) How many GROSS EMISSIONS will occur over the project lifetime? Divide that value by the gross CDR to get the emissions / removal ratio. Subtract it from the gross CDR to get the net CDR for this project.

Gross project emissions over the project timeline *(should correspond to the boundary conditions described below this table)*	505 tonnes CO2e
Emissions / removal ratio *(gross project emissions / gross CDR–must be less than one for net-negative CDR systems)*	505/3741 = 13.5%
Net CDR over the project timeline *(gross CDR - gross project emissions)*	3236 tonnes CO2e

e) Provide a process flow diagram (PFD) for your CDR solution, visualizing the project emissions numbers above. This diagram provides the basis for your life cycle analysis (LCA).



f) Please articulate and justify the boundary conditions you assumed above: why do your calculations and diagram include or exclude different components of your system?

We claim the gate-to-grave emissions as part of our project. We include residue processing, transport, vaulting, and vault C storage as part of the project, and exclude the thinning treatment emissions, since we are not conducting the thinning as part of the project.

g) Please justify all numbers used to assign emissions to each process step depicted in your diagram above. Are they solely modeled or have you measured them directly? Have they been independently measured? Your answers can include references to peer-reviewed publications, e.g. Climeworks' LCA paper.

All of Kodama's LCA assumptions are documented in the TEA spreadsheet, in sheets to the left of the Frontier TEA (highlighted in green). Broadly:

- All forest machine fuel use and cost estimates were based on a review of a thinning partner's operating expenditures
- Processing, loading, transport, and unloading rates were determined from Kodama's in-forest research on machines handling small diameter feedstocks
- Excavation machine fuel use was determined from literature values
- CO_2e for fuel use was based on EPA estimates and equipment type (diesel for heavy equipment; gas for scope 3 driving)
- All Scope 3 driving assumed a 125 mile one-way travel distance, 21 mpg vehicle (consistent with a light duty pickup), and 10 hour workday

Process Step	CO_2(eq) emissions over the project lifetime (tonnes)	Describe how you calculated that number. Include references where appropriate.
Residue Processing	20 tonnes CO2e total Scope 1: 18 tonnes Scope 3: 2 tonnes	Scope 1: ● Processor emissions were based on total runtime required to process feedstock mass Scope 3: ● Processor operator driving emissions
Transport	69 tonnes CO2e total Scope 1: 63 tonnes Scope 3: 6 tonnes	Scope 1: ● Loading and unloading emissions were based on total runtime required to handle feedstock mass ● Transport emissions were based on 83 mile one-trip transport distance from treatment area to site, and literature value for logging truck fuel economy Scope 3: ● Loader operator and trucker driving emissions
Vault Construction	126 tonnes CO2e total Scope 1: 71 tonnes Scope 3: 55 tonnes	Scope 1: ● Excavator and bulldozer emissions were based on total volume of excavation, cover soil, and gravel earthmoving required and hourly capacity ● Embodied emissions of gravel and geotextile were based on mass required and estimates from aggregate mining and geotextile production, and required trucking for delivery ● Estimated SOC and SIC oxidation losses which could occur during disturbance Scope 3: ● Excavator and bulldozer operators driving emissions ● Biannual monitoring visit driving emissions for 30 years ● 10 round trip flights from Denver to Reno and 10 round trip flights from New York to Reno ● 30 tons of CO2e was added to the total for the

		amortized impact of all machines used to develop the pilot, plus the production emissions associated with the flux chambers and solar array used for monitoring.
Vault Closure	291 tonnes total Scope 1: 291 tonnes	Scope 1: • Decomposition emissions were calculated using a first order decay equation based on EPA's LandGEM model, (Section 2.2.1 in SI from Wang et al. 2021) run for 1000 years • We use a decay constant consistent with slowly degrading waste in an arid environment (k=0.02) and a methane generation potential consistent with the high end of softwood generation potential (adjusted value from Matsakas et al. 2015, corresponding to a 2% C loss) • We calculate an equimolar volume of CO_2 emission based on CH_4 generation, consistent with byproducts of anaerobic decomposition of cellulose • We apply a CH_4 oxidation factor of 85% to the total mass of CH_4 generated, and add the oxidized fraction to overall CO_2 emissions, though we note microbial assimilation in the soil cover and partitioning to the SOC stock is possible • We assume a 100-year CH_4 GWP of 36 for residual methane emission

4. Measurement, Reporting, and Verification (MRV)

Section 3 above captures a project's lifecycle emissions, which is one of a number of MRV considerations. In this section, we are looking for additional details on your MRV approach, with a particular focus on the ongoing quantification of carbon removal outcomes and associated uncertainties.

a) Describe your ongoing approach to quantifying the CDR of your project, including methodology, what data is measured vs modeled, monitoring frequency, and key assumptions. If you plan to use an existing protocol, please link to it. Please see Charm's bio-oil sequestration protocol for reference, though note we do not expect proposals to have a protocol at this depth at the prepurchase stage. (<300 words)

Kodama's basis for monitoring involves three phases:

Pre-burial data collection: Prior to biomass burial, and during pit excavation, we will randomly select 6 locations consistent with the eventual flux chamber locations, and 6 locations randomly across the pilot spatial extent. At each location, we will characterize SOC and SIC at multiple depth profiles, to the maximum depth of excavation (3 m). At these locations, we will then take core to 3m depth, and take physical samples at each soil horizon. Physical samples will be sent to an independent lab recommended by our analytical partner Yardstick.

Closure Monitoring: We will divide the vault cover into six 500 m^2 areas and install automated soil gas flux chambers on the surface of each area to measure CO_2 and CH4 fluxes. Fluxes will be measured both above the vault and on disturbed ground adjacent to the vault (>20m laterally away to ensure no leakage from buried samples) to capture background patterns.

Flux measurements rely on stationary chambers on the vault which collect and relay surface emissions to a central unit (optical feedback-cavity enhanced absorption spectroscope), which measure the CO_2, CH_4, and H_2O concentrations at a known volume, as well as environmental temperature and pressures. The systems use these parameters to resolve fluxes from the soil cover (g/m2/hour), which will be collected at hourly intervals. The unit is remotely operated, solar-powered, and relays data via cellular telemetry.

We use vault fluxes, background fluxes, and monitoring surface areas to calculate the total emissions from the vault and soil cover. Then on an annual basis, Kodama will continue to measure the total biomass on the surface of the vault and take annual measurements of cover soil carbon content, to account for the effects of soil carbon storage and vegetation growth on the vault.

Kodama will terminate the closure monitoring period and begin the post-closure monitoring phase when two criteria are met:

- the vault cover vegetation pattern reaches a stable state consistent with surrounding vegetation patterns as determined by annual monitoring of species distribution and coverage on the cover relative to comparative analogs in the surrounding landscape,
- While vegetation is reestablished, we will collect annual data on SOC, SIC, and primary productivity in each of the 12 plots measured in Phase I until stocks stabilize, and,
- CH_4 and CO_2 concentrations measured from all flux chambers are at background concentrations for more than one year.

We expect revegetation to occur after 5 to 10 years and emissions and SOC/SIC stock stabilization to occur after 20 to 40 years.

Post-closure monitoring: Kodama will monitor vault elevation and vegetative cover using high-resolution satellite imagery (1m or greater resolution) for 20 additional years on a quarterly basis. If no substantial change is observed during this period, we will continue annually thereafter. High-resolution remote monitoring is an area of rapid innovation. Kodama may explore avenues to deed vault sites into rangeland trusts, which would pass on these monitoring responsibilities.

b) How will you quantify the durability of the carbon sequestered by your project discussed in 2(b)? If direct measurement is difficult or impossible, how will you rely on models or assumptions, and how will you validate those assumptions? *(E.g. monitoring of injection sites, tracking biomass state and location, estimating decay rates, etc.)*

For the development of the pilot plan, we quantified durability based on a detailed carbon balance and decay model relying on generalized softwood decay rates derived from our review of the landfill and biofuels literature. We estimated the durability ranges outlined in Q2a, 60% to 95%, using these models and the likely high and low end ranges of key parameters with input from our advisors. Currently we are running pilot feedstock-specific biochemical methane potential tests, which are batch experiments to measure maximum feedstock biodegradability. We will use these results to further refine our empirical models.

For the pilot itself, we plan to measure carbon stored and fluxes directly, then quantify the durability based on the amount of CO_2e contained versus the amount emitted from the vault and the amount retained in soil, corrected for a conservative global warming potential factor for any emissions. Once we observe no further decay emissions from the vault, we will assume the carbon will be durably stored unless disturbed.

c) This tool diagrams components that we anticipate should be measured or modeled to quantify CDR and durability outcomes, along with high-level characterizations of the uncertainty type and magnitude for each element. We are asking the net CDR volume to be discounted in order to account for uncertainty and reflect the actual net CDR as accurately as possible. Please complete the table below. Some notes:

- In the first column, list the quantification components from the Quantification Tool relevant to your project (e.g., risk of secondary mineral formation for enhanced weathering, uncertainty in the mass of kelp grown, variability in air-sea gas exchange efficiency for ocean alkalinity enhancement, etc.).
- In the second column, please discuss the magnitude of this uncertainty related to your project and what percentage of the net CDR should be discounted to appropriately reflect these uncertainties. Your estimates should be based on field measurements, modeling, or scientific literature. The magnitude for some of these factors relies on your operational choices (i.e., methodology, deployment site), while others stem from broader field questions, and in some cases, may not be well constrained. We are not looking for precise figures at this stage, but rather to understand how your project is thinking about these questions.
- See this post for details on Frontier's MRV approach and a sample uncertainty discount calculation and this Supplier Measurement & Verification Q&A document for additional guidance.

Quantification component Include each component from the Quantification Tool relevant to your project	**Discuss the uncertainty impact related to your project** Estimate the impact of this component as a percentage of net CDR. Include assumptions and scientific references if possible.
Storage	We weigh loads of woody biomass directly using a calibrated truck scale, and will sample each load for carbon and moisture content. Our feedstock is small-diameter Jeffrey and lodgepole pine boles that have been delimbed. Because of the homogeneity of the feedstock and our ability to accurately measure it, we rate the overall storage uncertainty as Very Low (<1%).
Leakage (i.e. Fugitive Emissions)	There are two components to consider here: uncertainties in losses to decomposition and uncertainty in monitoring. Our decay models account for a likely loss of approximately 2% of total wood carbon interred. Kodama is in the process of running Biochemical Methane Potential tests on our feedstocks, which will indicate its maximum anaerobic degradability and further refine our decay models. A very conservative factor for wood carbon loss in landfills is 10% (Table 3, IPCC, 2019). We monitor emissions from storage directly and nearly continuously, at environmentally relevant detection levels using reliable, field-proven instrumentation (e.g. LiCOR systems are capable of resolving CO_2 concentrations at a precision of 1.5 ppm at 400 ppm, and CH4 concentrations at a precision of 0.25 ppb at 2 ppm). We plan to segment the vault cover into areas and use the flux measurement as representative of the larger area. This is a reasonable assumption because geotechnical, textural, and vegetative properties will be consistent across the cover, so we don't expect emissions 'hotspots' to form as may happen with other vault designs (e.g. in arid environments, there is high risk of a clay vault type cover cracking and creating preferential flow paths for CH_4 escape). Based on the uncertainty in wood decomposition models and discounting that we can't measure the entire vault surface with this approach, though we can multiple representative sites nearly continuously, we rate the total uncertainty in

Quantification component Include each component from the Quantification Tool relevant to your project	**Discuss the uncertainty impact related to your project** Estimate the impact of this component as a percentage of net CDR. Include assumptions and scientific references if possible.
	leakage as Medium (5 to 20%).
Feedstock Storage Counterfactual	If thinned small-diameter trees and tops are not within the economic radius of a biomass power plant, they generally have one of four fates. In order of likelihood, these four fates are: pile burning, biomass decay after chipping and spreading, piles burning in wildfire, or biomass decay after sitting in piles. We have modeled the pile burning and sit-and-decay counterfactuals and found the long-term results to be similar. Our models are described in the Biomass supplement. Biomass removed from this thinning project has no end use, and will likely be combusted in an air-curtain burner outside the forest, chipped and spread, or piled to decay. Since there is no difference in CDR profiles between these end members (all end up with CO_2 returned to the atmosphere), but there is difference in timing, we rate the uncertainty in the Feedstock Storage Counterfactual as Medium (5-20%).
Feedstock Use Counterfactual	Our partner told us feedstock has no end uses. We rate the uncertainty in the Feedstock Use Counterfactual as Very Low (<1 %).
Indirect Land Use Change	We believe a successful pilot would bolster broad federal and state commitments to increase thinning treatments on at-risk forestland across the Western U.S. and potentially lead to a new avenue for mineland reclamation. This project is unlikely to lead to indirect land use change. We welcome input on this topic from reviewers.
Materials	We calculated the fuels to power our machines to move wood, soil, and produce gravel onsite, and considered the embodied carbon of the geotextile used in the cover. Instead of digging into the LCA of each piece of equipment and attempting to amortize the embodied carbon of the equipment to be used in the project, we assumed a 30 tonne impact CO_2e for all embodied emissions (under 'vault construction' in our LCA). Based on this analysis, we consider material impacts to be Low (1-5%).
Energy	We will install a small solar panel and battery to run our flux analytical system and flux chambers, and will use a small amount of compute power for long term monitoring and data analysis. Therefore, we consider energy impacts to be Very Low (<1%).
Storage Monitoring and Maintenance	We are conducting this pilot on private land owned by Kodama, which will be permitted and bonded as required under Nevada State Law. Well-designed ET covers have been shown to be effective and low-maintenance over long time horizons in similar environments. However, it is possible we need to conduct some unplanned cover maintenance in the future beyond what's listed in our MRV plan, so we rate uncertainty in Storage Monitoring and Maintenance as low (1-5%).

d) Based on your responses to 4(c), what percentage of the net CDR do you think should be discounted for each of these factors above and in aggregate to appropriately reflect these uncertainties?

Based on the above, we propose discounting the net CDR amount by 28%; we provide no discount for uncertainty in the total storage, the feedstock use counterfactual, and energy because we these will be well constrained and therefore we have low uncertainty. We don't understand the potential for indirect land use change in our case, and welcome the Frontier technical reviewers' feedback here.

We recommend the following allocations for the discount factor:

- **Leakage - 10%**: We apply a very conservative 10% discount to the net CDR in case there is higher decay than we anticipate. This discount brings our 'effective' contained carbon losses to 10% of our gross CDR.
- **Feedstock Storage Counterfactual - 12%**: After pile burning or decay, a residual fraction of biomass remains unburnt or undecayed, and contained carbon may partition to SOC, or back to biomass, instead of returning to the atmosphere. We choose a 12% discount on this parameter because it's a reasonable estimate for residual carbon storage after pile burning or decay in piles. We assume these are boundary conditions for the counterfactuals. However, our counterfactuals are simple and do not consider second-order impacts, which could improve the balance towards the project. See the Biomass supplement for further discussion.
- **Materials - 1%**: We account for the carbon emissions from producing gravel onsite in our LCA. However, if additional gravel is required beyond what we can produce, or if a cheaper option is available offsite, it may make more sense to source it elsewhere. We apply a 1% discount in case this happens, based on our calculations CO_2e associated with loading and trucking gravel from a local producer.
- **Storage Monitoring and Maintenance - 5%:** Kodama will own the project land and apply progressively more remote monitoring methods. We believe we've accounted for monitoring emissions appropriately but add a 5% discount as a buffer.

e) Will this project help advance quantification approaches or reduce uncertainty for this CDR pathway? If yes, describe what new tools, models or approaches you are developing, what new data will be generated, etc.?

Yes, the project will help advance quantification approaches for biomass burial projects generally. Our contributions are outlined in the MRV section in Q4a, but briefly:

- We plan to measure initial wood mass buried, continuous CO_2 and CH_4 fluxes from the vault, and annual soil carbon stock changes. Together, these measurements enable mass balance closure. The data we generate will present the most accurate picture of a wood vault system to date.
- Kodama is performing detailed feedstock analysis for each species, including density, carbon content and biochemical methane potential. Many of these fundamental properties are not widely published or replicated in the literature, and represent key inputs to decay and storage models.
- Upstream of our biomass utilization focus, Kodama is a forest robotics company. Some of the problems we are considering include inefficient feedstock processing, manual loading, and high biomass transport costs. We are honing in on several opportunities to improve efficiency of forest residue supply chains.

f) Describe your intended plan and partners for verifying delivery and registering credits, if known. If a protocol doesn't yet exist for your technology, who will develop it? Will there be a third party auditor to verify delivery against that protocol or the protocol discussed in 4(a)?

Today there is no protocol for wood vaults which precisely fits our vault type. If selected for a Frontier pre purchase, Kodama and YCCL will review existing protocols and prepare a new protocol which is a precise fit. We are ready to suggest capable auditors to Frontier.

5. Cost

We are open to purchasing high-cost CDR today with the expectation the cost per tonne will rapidly decline over time. The questions below are meant to capture some of the key numbers and assumptions that you are entering into the separate techno-economic analysis (TEA) spreadsheet (see step 4 in Applicant Instructions). There are no right or wrong answers, but we would prefer high and conservative estimates to low and optimistic. If we select you for purchase, we'll work with you to understand your milestones and their verification in more depth.

a) What is the levelized price per net metric tonne of CO_2 removed for the project you're proposing Frontier purchase from? 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), but we will be using the data in that spreadsheet to consider your offer. Please specify whether the price per tonne below includes the uncertainty discount in the net removal volume proposed in response to question 4(d).

$610/tonne including the uncertainty discount

b) Please break out the components of this levelized price per metric tonne.

Component	Levelized price of net CDR for this project ($/tonne)
Capex	$294/tonne
Opex (excluding measurement)	$205/tonne
Quantification of net removal (field measurements, modeling, etc.)[1]	$111/tonne
Total	$610/tonne

c) Describe the parameters that have the greatest sensitivity to cost (e.g., manufacturing efficiencies, material cost, material lifetime, etc.). For each parameter you identify, tell us what the current value is, and what value you are assuming for your NOAK commercial-scale TEA. If this includes parameters you already identified in 1(c), please repeat them here (if applicable). Broadly, what would need to be true for your approach to achieve a cost of $100/tonne?

Parameter with high impact on cost	Current value (units)	Value assumed in NOAK TEA (units)	Why is it feasible to reach the NOAK value?
Transport Distance	83 miles	60 miles	There are many suitable locations for wood vaults that are within 60 miles of

[1] This and the following line item is not included in the TEA spreadsheet because we want to consider MRV and registry costs separately from traditional capex and opex.

			forest edges. The broader challenge here is navigating the regulatory and permitting environments.
Truck Load + Unload Time	110 minutes	20 minutes	Conventional forestry trucking requires long load and unload times today. Kodama is evaluating ways of drastically reducing loading and unloading times and improving overall trucking efficiency.
Relative Volume per Area	1	2.5	Larger facilities can have a greater volume/area ratio, which drastically improves all costs based on area, including excavation and cover. How tall we can go will depend on fluxes observed in the pilot.
MRV Costs	$41/tonne	$2/tonne	After we constrain our first few projects with flux chambers, we anticipate being able to deploy other monitoring approaches, such as eddy covariance towers, which have overall lower costs.

d) What aspects of your cost analysis are you least confident in?

Kodama's capital cost estimate is Class II, so there are still cost unknowns. These include the following:

- Diesel fuel price is difficult to predict a year from now
- Excavation costs include a buffer for several steps of material transport within the site, and these costs won't be fully known until engineering design is complete

Other costs with lower confidence include employee comfort requirements (e.g. type of mobile office trailer on-site), and monitoring costs. Monitoring costs are modeled to be biannual over 30 years. Kodama anticipates that labor costs will increase, but so will opportunities for fully remote sensing.

e) How do the CDR costs calculated in the TEA spreadsheet compare with your own models? If there are large differences, please describe why that might be (e.g., you're assuming different learning rates, different multipliers to get from Bare Erected Cost to Total Overnight Cost, favorable contract terms, etc.).

Kodama's own models roughly match the CDR costs calculated in the TEA spreadsheet. There are a few differences:

- Our pilot facility doesn't include the same magnitude of project contingencies because the project is relatively simple.
- Our model accounts for EPC services, so the TEA spreadsheet double-counts Kodama's cost of EPC services, which we discount in the offer.
- The Kodama team did not model a learning rate but rather specific scenarios (e.g. revised trailer design, automated truck loading, etc.). Frontier's learning rate approximately matches the future scenarios modeled.

f) What is one thing that doesn't exist today that would make it easier for you to commercialize your technology? (e.g., improved sensing technologies, increased access to X, etc.)

Two things would transform the economics of dry wood vaults:

- Modification to California policy enabling wood vaults to either be categorized separate from landfills, or an SB1383 waiver allowing delimbed softwoods to be interned. Streamlined regulations on wood vaults in California would enable Kodama to build facilities <60 miles from thinning projects, which would enable storage costs <$50/ton CO2e.
- Material transport will account for about 40% of the total cost of a FOAK facility and ~10% of Scope 1 emissions. Autonomous trucks running on low carbon fuels (e.g. biomethane, hydrogen) or electricity would be a significant cost lever.

6. Public Engagement

In alignment with Frontier's Safety & Legality criteria, Frontier requires projects to consider and address potential social, political, and ecosystem risks associated with their deployments. Projects with effective public engagement tend to:

- Identify key stakeholders in the area they'll be deploying
- Have mechanisms in place to engage and gather opinions from those stakeholders, take those opinions seriously, and develop active partnerships, iterating the project as necessary

The following questions help us gain an understanding of your public engagement strategy and how your project is working to follow best practices for responsible CDR project development. We recognize that, for early projects, this work may be quite nascent, but we are looking to understand your early approach.

a) Who have you identified as relevant external stakeholders, where are they located, and what process did you use to identify them? Please include discussion of the communities potentially engaging in or impacted by your project's deployment.

We've identified three stakeholder groups for the project.

First, the communities which will be directly impacted by the project. We identified these groups by looking at a map of the project area:

- We seek to build the vault on land in Mineral County, NV, outside the town of Hawthorne.
- There are three residential communities between the thinning site and our proposed vault site (Lee Vining, Mono City, and Hawthorne Heights Mobile Home Park). During vault construction, approximately 160 truck trips will occur on paved roads past these communities.
- The closest residence to our proposed vault site is ⅔ mile southeast. The closest town is over 1 mile away to the east.
- Mammoth Lakes, NV sits just south of the thinning treatment area.

Second, the regulatory bodies and agencies which we need permits from:

- The Mineral County government issues Special Use permits for parcels within their jurisdiction.
- The Nevada Department of Environmental Protection, Bureau of Sustainable Materials Management (NDEP-BSMM) issues operating permits for disposal sites within Mineral County.

Third, the project coordinators for the thinning treatment:

- The National Forest Foundation which is coordinating the 500-acre thinning project and retaining thinning contractors on the ground.

- The Whitebark Institute of Interdisciplinary Environmental Sciences, which is leading the NEPA planning process for the remaining 50,000 acres.

b) If applicable, how have you engaged with these stakeholders and communities? Has this work been performed in-house, with external consultants, or with independent advisors? If you do have any reports on public engagement that your team has prepared, please provide. *See Project Vesta's community engagement and governance approach as an example and Arnestein's Ladder of Citizen Participation for a framework on community input.*

There are community engagement standards in place required for permit issuance. It is our priority to understand how a vault will be perceived in the host community, and by other communities impacted by its construction.

We began our engagement at the state level, by thoroughly understanding the permitting requirements for a wood vault under NDEP-BSSM's regulatory structures. We had several calls with permitting agents to outline the footprint of the facility, our feedstocks, and the level of monitoring we plan to conduct. NDEP personnel recommended we engage Mineral County officials to better understand county-level permitting requirements.

We engaged with the Mineral County government via the Northern Nevada Development Authority, a state designated non-profit focused on economic development, and had an initial conversation with the Head of the Planning Department and District Attorney. We continue to engage with the Head of Planning during the Special Use permit application process. As part of the process, and the NDEP permit application process, we will send letters to community members who may be impacted by the vault site and development, and if concerns arise during this process, we will host an in-person community Q&A session and address them.

In November, we anticipate giving a presentation on wood vaults to the Mammoth community at an event hosted by the Whitebark Institute, and facilitating feedback on the approach after the presentation.

c) If applicable, what have you learned from these engagements? What modifications have you already made to your project based on this feedback, if any?

The most important lesson we learned is to speak to local planning commissions early on, which often understand the priorities of the communities they serve. This has been critical in helping us find suitable pilot sites and building support for our project.

One surprise has been a strong interest across the board in pairing wood vaults with mine reclamation projects. As part of our FOAK facility roadmap, we are prioritizing understanding the permitting and regulatory modifications required for a mine reclamation project in NV. We'd love to connect with folks knowledgeable of BLM and USFS policies around mine reclamation.

d) Going forward, do you have changes to your processes for (a) and (b) planned that you have not yet implemented? How do you envision your public engagement strategy at the megaton or gigaton scale?

We feel our public engagement strategy has served us well this far, and aren't planning changes to our process. At the megaton and gigaton scale, we will need to hire a team dedicated to community engagement and project permitting, and would love to partner with utility solar and/or conservation interests to plan appropriate end uses for vaults.

7. Environmental Justice[2]

As a part of Frontier's Safety & Legality criteria, Frontier seeks projects that proactively integrate environmental and social justice considerations into their deployment strategy and decision-making on an ongoing basis.

a) What are the potential environmental justice considerations, if any, that you have identified associated with your project? Who are the key stakeholders? Consider supply chain impacts, worker compensation and safety, plant siting, distribution of impacts, restorative justice/activities, job creation in marginalized communities, etc.

Moving large volumes of wood to burial sites may increase trucking through particular communities, including communities with environmental justice concerns. Increased traffic raises a number of issues that could directly affect communities: increased particulate matter in the air, decreased air quality, and decreased road safety.

Regarding air quality, the forest thinnings associated with this project are projected to lower the risk of severe wildfire, which will in turn lower the levels of PM in the air associated with these fires.

While we don't project our wood burial projects to have any water quality issues associated with them, there is a long history of disadvantaged communities being affected by substandard drinking water. The project we have planned has minimal risk of impacting water quality. It is located in an area with 4 inches of annual average rainfall, our ET cover will prevent water from reaching the wood mass, and the depth to groundwater is > 100 feet. There is low risk of leachate generation, and also a low risk of groundwater interaction. Still, we will prepare a water quality model during permitting to demonstrate this.

This system could enable job creation in communities in forests and desert areas – from thinning operations to vaulting operations. There is the potential for seasonal jobs associated with thinning and forest restoration could be coupled with burial operations, to create full time, year round opportunities.

b) How do you intend to address any identified environmental justice concerns and / or take advantage of opportunities for positive impact?

We intend to integrate environmental justice data into our operating systems using EJ screening tools (i.e., Environmental Protection Agency EJSCREEN, Department of Energy Disadvantaged Communities Reporter Tool) and GIS mapping analysis for our region of interest. Data analysis will be performed in close consultation with community stakeholders to ensure environmental burdens to communities with environmental justice concerns are adequately characterized and minimized. For instance, in planning the routes by which our woody feedstock will make its way towards the vault sites, we can use Justice40 and EPA EJ GIS maps (as well as careful community-level planning beyond those maps) to minimize air quality and increased traffic impacts to communities.

Biomass power plants are often located in low-income communities and have a non-negligible impact on air quality. For this reason, some biomass power plants face litigation and risk of closure, threatening jobs. Biomass vaults provide an alternative material end-use which could preserve employment of similar roles (e.g. heavy equipment operation for feedstock handling).

[2] For helpful content regarding environmental justice and CDR, please see these resources: C180 and XPRIZE's Environmental Justice Reading Materials, AirMiners Environmental and Social Justice Resource Repository, and the Foundation for Climate Restoration's Resource Database

As our systems scale, it will be important that any potentially impacted communities understand and share in the upside of these projects, both in terms of job creation and reduced wildfire risk. To accomplish this, community-level engagements will be planned and executed, such as the meetings outlined in Q6b.

We want to partner with indigenous communities. Tribes have been proactively managing wildfire risk for 10,000+ years. There is increasing focus among large conservation organizations and the USFS to include indigenous practices and practitioners in forest thinning and wildfire prevention treatments. We believe recognizing historic land stewards and involving them upstream of wood vaults could be a central pillar of our environmental justice platform. We welcome feedback on pathways to positive engagement here.

8. Legal and Regulatory Compliance

a) What legal opinions, if any, have you received regarding deployment of your solution?

We've talked to regulators in California, Nevada, and Colorado regarding the deployment of wood vaults. Currently, this form of CDR falls under waste disposal regulations federally and at the state level. Federal regulations set minimum standards, but states are generally permitting authorities. There are many types of 'waste' that fall outside of federal waste disposal regulations; including mining, radioactive, CO2 injection, etc. It is likely a change in this regime such that wood vaulting is no longer a form of 'waste disposal' would require state, if not federal action. However, there are several jurisdictions we can operate in under waste disposal regulations, and this is not a barrier to deployment in the next five years.

b) What permits or other forms of formal permission do you require, if any, to engage in the research or deployment of your project? What else might be required in the future as you scale? Please clearly differentiate between what you have already obtained, what you are currently in the process of obtaining, and what you know you'll need to obtain in the future but have not yet begun the process to do so.

For the pilot, we require two permits. First, we require a special use permit from Mineral County, Nevada to allow use of the parcel of private land we're pursuing for a Class III Disposal site. We also require a permit from the state of Nevada Department of Environmental Protection, Sustainable Materials Management Bureau to build and operate a Class III disposal site. We are engaged with both agencies and are in the process of obtaining these permits.

In the future, to deploy in other states, we will need to pursue additional Special Use permits and Class III-equivalent permits from local and state agencies in the appropriate jurisdictions, unless there are changes to federal or state carbon management policies which explicitly allow for wood burial as a form of CDR. We are happy to discuss the intricacies of wood vault deployment across new jurisdictions with interested parties, especially those who have substantial forest residue supply issues.

c) Is your solution potentially subject to regulation under any international legal regimes? If yes, please specify. Have you engaged with these regimes to date?

We are not aware of any international legal regimes which apply to our proposed solution.

d) In what areas are you uncertain about the legal or regulatory frameworks you'll need to comply with? This could include anything from local governance to international treaties. For some types of projects, we recognize that clear regulatory guidance may not yet exist.

One example of a regulatory framework we have uncertainty around is California's Short-Lived Climate Pollutant Reduction Strategy (SB 1383). It classifies wood as an organic material and requires diversion away from land disposal sites under the assumption that it will decay and produce substantial volumes of methane. We've communicated with senior stakeholders at the state level who agree wood burial is a viable form of CDR, and folks in the firefighting community who have expressed a clear preference for vaulting over pile burning. It is likely an advocacy effort will be required to enable wood vault development in California, and hence we are initially deploying systems in Nevada.

e) Do you intend to receive any tax credits during the proposed delivery window for Frontier's purchase? If so, please explain how you will avoid double counting.

We do not intend to receive tax credits during the proposed delivery window for Frontier's purchase. We are evaluating tax credit opportunities with scaled facilities, but we will not receive tax credits for this first facility.

9. Offer to Frontier

This table constitutes your **offer to Frontier**, and will form the basis of contract discussions if you are selected for purchase.

Proposed CDR over the project lifetime (tonnes) *(should be net volume after taking into account the uncertainty discount proposed in 4(c))*	820 tonnes
Delivery window *(at what point should Frontier consider your contract complete? Should match 1(f))*	December 2024 (Vault closed for one year, plus one year delay for pile-burning counterfactual to kick in)
Levelized Price ($/metric tonne CO_2) *(This is the price per tonne of your offer to us for the tonnage described above)*	$610/tonne CO_2e

Application Supplement: Biomass

Feedstock and Physical Footprint

1) What type(s) of biomass does your project rely on?

Kodama's project relies on unmerchantable forest biomass removed during forest thinning treatments, which is typically pile-burned as a disposal mechanism.

The CC Lab has previously utilized data provided by the U.S. Forest Service's Forest Inventory and Analysis (FIA) Program to estimate the locations, quantities, and accessibility of these biomass pools (https://nickdahl.shinyapps.io/WoodyBiomassApp/). The interactive application allows for any user to select states of interest, wildfire hazard potential (by county), as well as biomass pool restrictions (including distance to road, management prescription, etc.). The tool returns data detailing the total amount of biomass available by county and state that fits the search parameters, and can give a sense of various fractions available from FIA data.

2) How is the biomass grown (e.g., kelp) or sourced (e.g., waste corn stover)? Do you have supply agreements established?

Woody biomass grows naturally in the forest. We are determining partnership details with the National Forest Foundation, who is leading the thinning project to produce it. When we described that we would be interested in transporting 4000 tons of material they replied "we can guarantee that amount of material." Kodama understands biomass removal is not part of the thinning budget so any removal we can provide will be additional.

We plan to establish supply agreements for larger vaults. However, it's important to point out that biomass vaults are especially compelling as a tool in scenarios where long-term, large-scale supply agreements are challenging to obtain, such as on US Forest Service projects.

3) Describe the logistics of collecting your waste biomass, including transport. How much carbon emissions are associated with these logistics, and how much does it cost? How do you envision this to evolve with scale?

Thinning treatments in the Western U.S. remove 15-30 green short tons of residual biomass per acre, not including merchantable logs and lumber. Typically, this material is aggregated from multi-acre units by yarding all material to a landing, then processing whole trees while sorting merchantable material, i.e. branches and needles, from non-merchantable material, i.e. damaged stemwood, small diameter material, tops, and slash (branches and needles).

Kodama is developing workflows to process materials slightly differently. By sorting and delimbing tops, we can shift the material classes to three: sawlogs, small diameter and low-value logs, and slash (branches and needles), which we treat separately at landings.

For this project, we will focus on small diameter logs. Our costs and emissions for every step are described in detail in our LCA/TEA.

4) Please fill out the table below regarding your feedstock's physical footprint. If you don't know (e.g. you procure your biomass from a seller who doesn't communicate their land use), indicate that in the table.

	Area of land or sea (km^2) in 2022	**Competing/existing project area use (if applicable)**
Feedstock cultivation	E.g. 1 km^2 (floating kelp array) OR N/A (procuring waste biomass)	We do not cultivate, but rely on forest thinning projects. Estimates vary from 15 to 30 short tons/acre, which equates to 150 to 300 acres of thinning for this project. We assume 20 short tons/acre for 225 acres of thinning.
Processing	E.g. 0.1 km^2 (boat yard, manufacturing facility) OR 0.5 km^2 (manufacturing facility for mobile biochar plants)	Material processing happens at forest landings and coincides with forest operations, likely <5 acres total, which are restored post-thinning.
Long-term Storage	E.g. N/A (uncertainty in final state of kelp) OR 2 km^2 (ag fields in which biochar is deployed)	The total disturbed vault area will be 0.7 acres.

Capacity

5) How much CDR is feasible globally per year using the biomass you identified in question 1 above? Please include a reference to support this potential capacity.

Kodama's carbon storage calculations focus on four developed regions of the world where wildfire risk is significant: United States, Canada, Mediterranean Europe, and Australia. Kodama's calculations assume an 80% net CDR removal efficiency, which is Kodama's estimate for a pilot facility. The total storage opportunity for vaulting woody biomass from forest thinning is 0.35 to 1.1 GT of CO2e per year. Kodama anticipates that its CDR methods will eventually be applicable to other regions of the world beyond these.

Region	**Carbon Storage Opportunity**		**Reference**
	Low	**High**	
United States	259 MT CO2e	388 MT CO2e	Oak Ridge National Laboratory, 2016
Canada	33 MT CO2e	201 MT CO2e	Gronowska et al. 2009
Mediterranean Europe	27 MT CO2e	339 MT CO2e	FAO, 2018; Verkerk et al, 2019
Australia	32 MT CO2e	214 MT CO2e	Crawford et al., 2015
Total	**351 MT CO2e**	**1,142 MT CO2e**	

n.b. Thinning residues are approximately 60% small diameter boles and 40% slash, though estimates vary.

Additionality and Ecosystem Impacts

6) What are applications/sectors your biomass feedstock could be used for other than CDR? (i.e., what is the counterfactual fate of the biomass feedstock)

We've considered both storage and use counterfactuals.

For the storage counterfactuals, if the feedstock remains in the forest after thinning, there are four likely scenarios: pile burning by hand, decay after chipping and spreading, piles burning in wildfire, or decay after sitting in piles. We've modeled the pile burning and decay counterfactuals, and believe these are representative end-members which bound the other scenarios. Figure 4 shows what our CDR looks like over time against the counterfactuals, versus the outcome of our FOAK scenario.

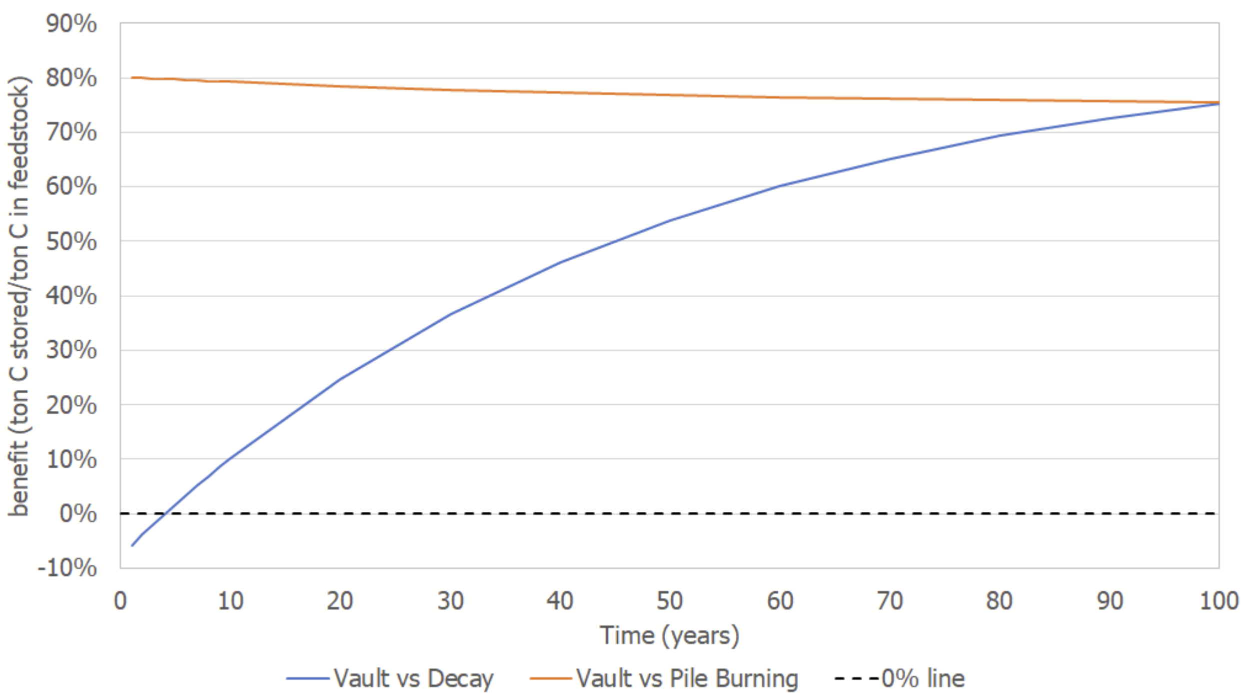


Figure 4: *A comparison of the benefits of vaulting versus counterfactual scenarios of decay and pile burning over time.*

The effect of pile burning decreases over time due to decay losses from the vault, whereas the decay counterfactual starts negative because of the project emissions. We use literature values for both the pile burning ([Hardy, 1998]) and decay counterfactuals (Section 1.2.1.2 in SI for [Cabiyo, 2021]). These counterfactual scenarios do not consider the following:

- Second order effects of pile burning (e.g. decay of burned materials, soil carbon impacts, etc.)
- Assessment of additional stock losses if decaying material burns in wildfire
- The influence of emissions besides CO_2 which may occur in pile burning or decay

The use counterfactual is arguably more complex. For this project, we've been told the feedstock is unmerchantable and there are no competing uses. For future projects, we anticipate there are uses which may be higher value than biomass burial. However, we contend that even compared with CDR solutions which generate multiple co-products (e.g. wood-to-hydrogen producing pure H_2, CO_2, and wood ash), wood vaults could be cost-competitive ([Woodall and McCormick, in review]). Kodama is implementing wood vaults as a low-tech 'baseline' CDR as a clear alternative to pile burning. We believe it will help us build efficient residue supply chains and improve the economics of other utilizations.

From the perspective of building a healthy business, it's worth discussing long-term credit issuance. Biochar projects today are selling credits without counterfactual execution, so we believe there is plenty of near-term demand for ex ante credits. In the future, with a myriad of use and storage counterfactuals, we don't know what will be attractive in the market. In a future where direct air capture plus geologic storage is much cheaper, we believe we'll have to compete on an ex post basis. We invite feedback from the Frontier reviewers and other knowledgeable individuals on our counterfactual discussion, as this is a critical point for all biomass-based CDR pathways to solve.

7) There are many potential uses for waste biomass, including avoiding emissions and various other approaches to CDR. What are the merits and advantages of your proposed approach in comparison to the alternatives?

The scale and immediacy of wildfires in the American west and the needed amount of forest thinning, requires appropriately sized and scoped solutions, that fit within project timelines. In 2022, the U.S. Forest Service published a Wildfire Crisis Strategy that calls for 50 million high-priority acres to be treated over 10 years, out of 450 million acres in the Western U.S. With a successful pilot deployment, our solution is ready to scale to meet this need:

- Many proposed technologies for dealing with waste biomass will not be deployable in the near term (<5 years). Given results tracking with our projections at the pilot scale, we can deploy a FOAK facility delivering 225,000 tonnes CO2e removed within 5 years.
- Unlike higher CAPEX facilities, we can work on short term supply agreements that scale to project size.
- Our approach is easy to deploy and faces a clear path to innovation. We primarily rely on widely available construction and forestry equipment, which we are currently modifying for teleoperation.
- The majority of our Scope 1 emissions come from fuel use, and we have effectively no Scope 2 emissions. Unlike more energy intensive forms of CDR, we will not compete with the deployment of renewables towards decarbonization, and we can decarbonize our own operations quickly further as drop-in fuels or H_2 becomes cheap and widely available.
- There is near-zero water risk associated with the projects, as we don't require water for any of our processes.
- Vaulted wood may be a viable reclamation tool where legacy open-pit mines are near forests, which could reduce vault excavation costs and emissions and enable rangeland restoration. However, we note mine reclamation projects will involve additional regulatory, operational, and material challenges, and must be approached opportunistically and on a site-specific basis. We welcome conversations with mining operators planning for closure and federal agencies (USFS, BLM) on this point.

8) We recognize that both biomass production (i.e., growing kelp) and biomass storage (i.e., sinking in the ocean) can have complex interactions with ecological, social, and economic systems. What are the specific, potential negative impacts (or important unknowns) you have identified, and what are your specific plans for mitigating those impacts (or resolving the unknowns)?

Environmental concerns have been raised about this biomass burial broadly, and while many don't apply to our specific solution, we have made plans to mitigate and minimize those that do. In certain cases, we will be researching them further as needed. Some of these concerns include:

- The operations associated with widespread forest thinning adversely impact the ecology of forests, specifically soil carbon stocks and the spread of invasive vegetation. This concern deserves much more research. It can certainly be agreed that megafires are adversely affecting forest ecosystem health, and that this solution offers one way to lower that risk. At Kodama, we are aware of slight modifications to forestry equipment systems used in thinning treatments (e.g. using tracks instead of tires) or different system configurations ((e.g. whole-tree versus. cut-to-length) may offer different end results. Prior to developing our own research agenda in this area, we are conducting a literature review to better understand forest carbon impacts and identify key knowledge gaps.

- The tops, branches, and needles contain the most nutrients in trees. Their repeated removal over time would likely lead to substantial ecosystem impacts. We do not plan to conduct multiple thinning treatments in one area, so we look at this as low-risk. If our solution expands to offtake from repeated thinnings in plantation-style forests in the Southeastern or managed logging lands in the Western U.S., we will take a close look at this.
- Removing vegetation and disturbing soils disrupts desert ecosystems, and recovery of desert vegetation and soil structure can be slow. Several studies suggest that while revegetating sagebrush and similar ecosystems, planting seedlings or cut-shrubs can be far more successful (Davies et al, 2013) than reseeding, and can provide brush ‘islands’ that eventually become seed sources that accelerate recovery of associated vegetation, fauna, and ecosystem structure (Longland and Bateman, 2002). We will consult local experts from the USGS and academic institutions to prioritize the most effective restoration planting strategy.