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Carbon on the Coast: Creating a Suitability Framework to Inform Coastal Enhanced Weathering in California

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Carbon on the Coast

Creating a Suitability Framework to Inform Coastal Enhanced Weathering in California

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The Need for Carbon Dioxide Removal in California Climate Policy

The state of California, a leader of U.S. climate policy, set its most ambitious climate goal in the California Climate Crisis Act in September 2022 (Assembly Bill 1279, Muratsuchi, Chapter 337 of the Statutes of 2022). The Act requires the state to take drastic cuts to its greenhouse gas emissions and achieve carbon neutrality no later than 2045. Afterwards, the state must maintain net-negative emissions, meaning that the amount of carbon dioxide (CO₂) removed from the atmosphere each year must be greater than the amount emitted. In addition to fossil fuel phaseout and renewable energy integration, the state must also undergo intensive carbon dioxide removal (CDR) to meet these legally bound targets. CDR refers to a group of biotic and abiotic strategies that physically remove CO₂ from the atmosphere and store it durably for long-period timescales.

Although CDR technology is still largely in development, California has legally bound itself to meeting rigorous carbon removal targets. The California Climate Crisis Act calls for statewide removal of approximately 7 million metric tonnes of CO₂ annually by 2030, and 75 million metric tonnes annually by 2045. Meeting such targets will require significant public investment in CDR research and deployment, yet California does not possess a funding program dedicated specifically to CDR. While California's Greenhouse Gas Reduction Fund is capable of funding CDR projects, emerging CDR technologies must compete with more established climate innovations to receive these grants. A dedicated CDR funding program was proposed in SB 643 (2025-2026) but was not signed into law. If CDR is to be deployed at scale in California, the state will need to identify which removal technologies can produce the greatest benefit, mapping where these deployments could feasibly exist without jeopardizing the nearby environment, and opportunities to finance these projects that distribute the cost and benefits equitably.

CDR first evolved from the concept of geoengineering but has largely gravitated away from this foundation, becoming its own field of study in recent years. CDR strategies attempt to enhance the Earth's capacity to absorb and store atmospheric CO₂ for long-period timescales. There are various CDR strategies that mimic Earth's natural processes, and others that rely on engineered-based approaches to extract CO₂ and store it underground. In recent years, there has been growing attention around marine CDR because of the ocean's capacity to absorb roughly a quarter of anthropogenic CO₂ emissions each year (Friedlingstein et al. 2023). As Earth's largest active carbon sink for anthropogenic CO₂ emissions, many researchers are investigating whether the ocean's uptake of CO₂ could be accelerated with human intervention (Friedlingstein et al. 2023).

A popular marine CDR (mCDR) method focuses on adding alkaline or silicate minerals to seawater, due to a chemical reaction that occurs when these minerals dissolve in the ocean. When atmospheric CO₂ dissolves in seawater, it forms carbonic acid (H₂CO₃). This weak acid dissociates into a hydrogen ion and bicarbonate. Hydrogen ions increase ocean acidity, and this process is the foundation of ocean acidification. When minerals such as olivine or basalt are introduced into the water, they dissolve by reacting with these hydrogen ions, consuming them in this process and ultimately reducing ocean acidity. To compensate for this loss of hydrogen ions, more dissolved CO₂ or carbonic acid gets converted to bicarbonate, shifting the carbonate equilibrium from dissolved CO₂ to bicarbonate. This shift lowers the partial pressure of CO₂ in the surface ocean, meaning that the surface ocean now holds less CO₂ than the overlying atmosphere. This triggers an influx of atmospheric CO₂ into the surface ocean to balance out this ocean-atmosphere carbon equilibrium (Renforth & Henderson 2017). As long as there is a source of alkalinity, the same cycle will repeat itself, where CO₂ is converted to bicarbonate which can be stored in the ocean for thousands of years.

Researchers have begun exploring the potential of alkalinity enhancement on beaches, in a process known as coastal enhanced weathering (CEW). CEW involves spreading finely crushed alkaline or silicate minerals onto beaches. Wave action and nearshore currents carry these minerals offshore where they dissolve in seawater by reacting with hydrogen ions, reducing ocean acidity and shifting the carbonate equilibrium from dissolved CO₂ to bicarbonate. Causing an imbalance of CO₂ at the air-sea interface, atmospheric CO₂ is naturally drawn down into the ocean to stabilize this equilibrium. CEW, although promising in theory, requires specific oceanographic metrics to exist at these pilot locations to drive the carbon removal process—proper grain deposition, mineral dissolution, alkalinity transport, efficient ocean-atmosphere CO₂ exchange, and safe carbon storage.

Vesta, PBC is the first group to study CEW, with two active research projects in Duck, North Carolina and Southampton, New York (Vesta 2024). They deposit crushed up olivine on beaches for the stated purpose of removing carbon from the atmosphere, preventing sea level rise, reversing ocean acidification, and fighting coastal erosion. Olivine is a magnesium-iron silicate mineral that does not raise water pH itself but dissolves in seawater by consuming hydrogen ions, which increases ocean alkalinity and shifts the carbonate equilibrium toward bicarbonate (Oelkers et al. 2018; Foteinis et al. 2023). Vesta deposits the olivine sand onto beaches, similar to a typical beach nourishment project. Over time, the ocean carries the olivine grains into the surface layer of the ocean where they dissolve, triggering the chemical process that reduces ocean acidity and also causes a shift in the carbonate equilibrium from dissolved CO₂ to bicarbonate.

The Coastal Enhanced Weathering Carbon Removal Process

The carbon removal process associated with CEW is not a single event but rather a chain of physical and chemical processes. The following five steps outline the carbon removal pathway and identify the key oceanographic conditions that influence where along the California coast CEW is most likely to succeed.

Step 1 – Grain Deposition

The CEW process begins with the deposition of crushed silicate or alkaline minerals such as olivine, basalt, dunite, or serpentinite onto beaches or blended into beach nourishment sediment and/or dune restoration projects (Meysman & Montserrat 2017; Foteinis et al. 2023). These minerals have hydrogen-consuming capabilities, meaning that each unit of mineral dissolved removes acidity from seawater and shifts the carbonate equilibrium toward bicarbonate (Rimstidt et al. 2012; Oelkers et al. 2018). Sourcing these minerals matters greatly due to the energy expended in the process of grinding and transporting the minerals to their beach location. If the amount of energy expended in this process releases more carbon to the atmosphere than CEW can remove, the method fails as a CDR strategy. Grain size typically ranges from 100 to 1000 μm , with finer grains dissolving faster but consuming more energy in production, highlighting the fundamental tradeoff between grain size and energy expenditure (Rimstidt et al. 2012). In terms of physical deployment, the shoreline must be sandy and capable of receiving and retaining mineral amendments. The site must be compatible with beach nourishment infrastructure or coastal management equipment, meaning that it must be able to accommodate nourishment machinery. Sites with active beach nourishment or dune restoration programs offer practical entry points for CEW deployment, allowing for seamless integration rather than operating as a stand-alone activity.

Step 2 – Mineral Dissolution

Once finely ground, the silicate or alkaline minerals are deposited on the shoreline and ultimately washed into the surf zone by wave action. In near-shore coastal waters, the

mineral grains will dissolve and release magnesium and calcium, which consume hydrogen ions. This increases the alkalinity of the seawater, reducing ocean acidity at that location. The rate at which this dissolution occurs depends on a number of oceanographic metrics such as wave energy, seawater temperature, and pH, as well as grain size (Oelkers et al. 2018; Rimstidt et al. 2012). Wave energy is largely responsible for dissolution because wave-driven tumbling abrades the grains much faster than calm ocean conditions (Meysman & Montserrat, 2017; England et al., 2025). Olivine, for example, subject to continuous tumbling in seawater is able to dissolve 8 to 19 times faster than it would under stagnant conditions (Flipkens et al. 2023). Grain size has a significant impact on dissolution, as a larger grain will take much longer to dissolve and may sink below the surface before it can dissolve properly. As for sea surface temperature, the Arrhenius relationship predicts that for every 10°C increase in seawater temperature, the dissolution rate approximately doubles (Rimstidt et al. 2012). Seawater pH is also a predictor of dissolution rates, as a lower pH accelerates dissolution. Particularly on the California coast where upwelling is prominent, the seasonal influx of nutrient-rich, low-pH water up to the surface provides ideal conditions for accelerating dissolution.

Step 3 – Alkalinity Transport and Residence Time

Driving atmospheric CO₂ uptake requires the minerals to remain in near-shore, highly turbulent surface waters long enough for dissolution to occur. The first consideration to assess residence time is the slope of the beach, which is evaluated based on the assumption that shallower beach profiles should be prioritized for CEW, as steeper slopes may trigger rapid offshore advection during initial placement of minerals onto the beach. This idea is developed from the equilibrium beach profile theory (Dean 1977), and is treated as an assumption as no studies have directly measured beach slope as a residence time driver. There is an inherent tension worth addressing, as mineral dissolution requires high wave energy that is often associated with steeper beach profiles (as larger waves steepen beach faces through sediment transport). However, these steep slopes can trigger offshore advection of minerals before dissolution can

occur. In theory, CEW deployment sites should have a shallow beach slope with high wave energy, which represents conditions that are not always found together.

The second driver of residence time is nearshore current speed in the surf zone. High wave energy and active circulation at the surf zone tend to shorten surface residence time, as stronger currents will transport the minerals offshore before dissolution can occur. Additionally, the coastal geometry of the site location is of critical importance, as embayments or semi-enclosed ecosystems may struggle to dissolve these minerals due to lack of wave energy, making these areas largely unsuitable for CEW. There is a tension between dissolution and residence time worth noting: sites that possess high wave energy that support high dissolution may also have strong currents that limit the residence time of the minerals in the surf zone, preventing dissolution, then equilibration, and overall reducing the potential for atmospheric CO₂ uptake.

Step 4 – Ocean-Atmosphere CO₂ Exchange

The ocean-atmospheric CO₂ exchange is the most critical step for attaining net carbon removal. Once dissolution has occurred, and the alkalinity-enriched water has made its way to the coastal zone, the carbonate equilibrium has shifted from dissolved CO₂ to bicarbonate, lowering the partial pressure of CO₂ ($p\text{CO}_2$) in the surface water relative to the overlying atmosphere. According to the Revelle factor, the extent to which the partial pressure of CO₂ in the surface water drops per unit of alkalinity added depends on seawater chemistry. Colder waters rich in dissolved CO₂ like those present in the California Current System have a higher Revelle factor, meaning each unit of alkalinity drives a larger drop in partial pressure of CO₂, thus has more atmospheric drawdown potential. In the surf zone, breaking waves trigger higher amounts of gas transfer than open ocean, making the surf zone ideal for alkalinity release. Gas transfer efficiency is a complex, active area of research governed by many factors such as wind speed, wave energy, and mixed layer depth. Wind speed and wave energy promote turbulent mixing that enhances air-sea exchange. Mixed-layer depth affects gas exchange because a deeper mixed layer will dilute the alkalinity to fill the layer, whereas a shallower mixed

layer will concentrate the alkaline water near the surface. A shallower mixed layer would allow more potential for equilibration and gas exchange.

Step 5 – Carbon Storage and Safety

Once the atmospheric CO₂ has been drawn down, dissolved, and converted to bicarbonate, it remains in the ocean for tens of thousands of years before cycling back into Earth's natural carbon systems (Renforth & Henderson 2017). This durability is a principal advantage of CEW and mCDR strategies over land-based CDR. In terms of traditional enhanced rock weathering, a land-based CDR approach, carbon stored in soils can return to the atmosphere within decades through wildfire, land-use change, or drought, but bicarbonate dissolved in the ocean is not subject to any of these reversal pathways. There are, however, potential risks associated with alkalinity enhancement, mainly if too much alkalinity were to be added to the marine environment. When alkalinity is added to seawater that is already saturated with for example calcium or aragonite, or too much alkalinity is added at once, the carbonate system can be pushed past a critical threshold. When this happens, bicarbonate precipitates to solid calcium carbonate—a process known as runaway calcium carbonate precipitation triggered by reaching the aragonite saturation threshold (Moras et al. 2022; Suitner et al. 2024). This is problematic because the precipitation of bicarbonate cancels out the carbon removal process and removes alkalinity. Additionally, solid calcium carbonate is less stable than bicarbonate and can redissolve and eventually release CO₂ back into the atmosphere. Coastal environments with warmer waters, less wave energy, and high pH are more prone to precipitation and will ultimately influence the safety of these pilot projects.

Piloting Coastal Enhanced Weathering in California

The five factors that govern the CEW carbon removal chain are necessary for responsible deployment and given the specificity required, it is evident that CEW will not be successful on every section of coastline. The California coast, however, is uniquely well positioned to undergo CEW pilot projects. The seasonal upwelling that exists along the coast brings cold, carbon-rich water from depth to the surface of the ocean, providing the acidic conditions that allow for maximum mineral dissolution. The low surface pH from upwelling accelerates mineral dissolution and the high dissolved CO₂ concentration in the upwelled water allows the water to accommodate a large capacity of alkalinity to be added to the marine environment without pushing beyond the carbonate precipitation threshold (Feely et al. 2008; Bach et al. 2023). The California current's high Revelle factor means that each unit of alkalinity triggers a larger drop in partial pressure of CO₂, thus has more potential for atmospheric drawdown (Feely et al. 2018). The same processes that make the California coast vulnerable to ocean acidification make it the ideal candidate location for alkalinity enhancement through CEW.

The California coast spans roughly 1,600 km of coastline, and much of this area is sandy beach that can accommodate CEW pilot projects. Many of these beaches are already part of active beach nourishment programs, simplifying integration of CEW mineral amendments. With the existing coastal management infrastructure from the U.S. Army Corps of Engineers, state agencies such as the California Coastal Sediment Management Workgroup, and numerous coastal cities that maintain nourishment projects, California is uniquely equipped to pilot this mCDR strategy. While the state's mCDR portfolio has largely consisted of electrolysis and direct ocean capture from companies known as Equatic and Captura, both housed at the Port of Los Angeles, fitting CEW into the California mCDR landscape could serve as a legitimate, scalable mCDR strategy to help California reach its net-zero and net-negative goals.

The Challenges with Measurement, Reporting, and Verification

The central challenge with any mCDR strategy is knowing where to deploy and how to effectively monitor the success of these approaches—ensuring efficient carbon removal is occurring. Measurement, reporting, and verification (MRV) is widely regarded as the binding constraint on the credibility of mCDR. Since mCDR projects produce a chemical signal that must be detected against the natural background variability of the ocean carbonate system, researchers are tasked with separating anthropogenic influence from natural variability from things like seasonal upwelling and biological productivity that fluctuate regularly on the California coast. By understanding the oceanic drivers in local marine environments and utilizing existing oceanographic monitoring infrastructure, these datasets can be adapted to identify the most suitable areas to monitor and validate carbon removal processes in the coastal ocean. A perspective such as this would allow researchers to see where deployment makes most sense, and where monitoring can be effective and accurate.

The Isometric Ocean Alkalinity Enhancement (OAE) protocol is the first carbon-registry MRV protocol for ocean-based alkalinity enhancement. This combines direct chemical measurements and verifies ocean circulation models to help estimate the carbon drawdown that occurs with alkalinity enhancement (Isometric 2024). However, this protocol was developed for alkalinity enhancement through coastal outfalls and point-source discharges—not for beach-scale weathering. As no current protocol exists for CEW deployment, MRV is all the more important to get right. CEW deployments are most capable of being adequately monitored where the alkalinity signal can be tracked against background noise. This could be at sites with high dissolution rates that generate detectable signals and/or those with moderate to long surface residence times that allow the alkalinity signal to accumulate, shift the carbonate equilibrium, and trigger drawn down. Proximity to existing oceanographic monitoring infrastructure or to autonomous total-alkalinity sensors is crucial as well. Site selection and monitoring feasibility are two aspects of the same problem, and can be used to inform each other to support mCDR siting decisions.

A collection of relevant physical and chemical oceanographic data, as well as ecological and regulatory constraints, does not exist in a form usable for mCDR deployment decisions. The California Ocean Protection Council's 2025 informational item for mCDR development highlighted the gap in spatial data that would be necessary to support siting decisions, representing the principal gap facing California mCDR development (OPC 2025). The strong site dependence of CEW in terms of physical, chemical, ecological, and regulatory conditions creates an urgent need for a suitability screening tool capable of determining where along the California coast CEW deployment may be viable. With this in mind, this project combines oceanographic drivers, as well as ecological and regulatory factors, to develop a framework to assess site suitability for CEW pilot projects along the California coast, enabling researchers and policymakers to identify the locations where CEW has its best chance of both capturing atmospheric CO₂ and being properly monitored to demonstrate that success.

The Coastal Enhanced Weathering Suitability Scoring Framework

The CEW suitability framework separates the California coast into 1-km segments and assesses the suitability of each segment based on the relevant oceanographic, ecological, and regulatory data at that site. The framework is structured in two tiers.

Tier 1 – Eligibility Gate

Tier 1 serves as an eligibility gate, which classifies a segment of the coast as eligible if it meets certain hard constraint requirements. These five conditions are primarily concerned with avoiding regulatory stress and permitting barriers. Acting as a screening tool, Tier 1 streamlines the process of determining suitable sites for CEW pilot projects. To ensure compatibility, a segment must first have a sandy shoreline type (beach, dune, or developed beach), and be compatible with nourishment infrastructure. Wetland and estuarine segments do not pass Tier 1 because alkaline mineral grains cannot easily dissolve in near-shore waters given the lack of wave energy. Rocky and cliff-backed coastal segments do not offer the sandy beach face that mineral deposition requires, as minerals cannot be effectively placed or retained without a sandy substrate. Next, the segment must be outside of a California Department of Fish and Wildlife (CDFW) no-take or restricted-activity marine protected area (MPA) and outside critical habitat for endangered species listed on the Endangered Species Act or Marine Mammal Protection Act that prohibit sediment addition. Finally, the segment will be ruled as ineligible if there is kelp canopy covering more than 10% of the 100-m seaward buffer or an eelgrass habitat present within 500m of the segment. This buffer reflects the requirements of the California Environmental Quality Act (CEQA) no-net-loss policy that would trigger environmental review for any activity nearby mapped submerged aquatic vegetation (NMFS CEMP 2014). Segments that are deemed ineligible segments are retained in the dataset but depicted in a thin grey line on the map with no assigned score. If a segment satisfies the criteria for Tier 1, the segment moves on to be evaluated under Tier 2 conditions.

Tier 2 - Physical Suitability Score

Tier 2 assesses the physical conditions necessary for productive carbon removal in the coastal environment. This framework was adapted from Guo et al. (2025), who developed a four-metric passive tracer approach for measuring alkalinity enhancement in the open ocean. This project used dye-release simulations over a 30-day period, across ten shelf sites in the Atlantic Ocean. This current framework builds off of Guo's structure but adjusts the approach to match the conditions relevant for beach-scale CEW. Eligible segments are evaluated based on four subscores that correspond to one physical step in the CEW carbon removal chain. The four subscores consist of dissolution, residence time, efficiency, and safety. Dissolution assesses the wave energy, temperature and pH of the specific site to assess how fast the grains will dissolve in seawater at that site. Residence time is evaluated based on the beach slope at the site as well as nearshore currents that assess how long the minerals are likely to remain in the surf zone. Efficiency measures how much carbon removal actually occurs before the alkaline plume is swept offshore where equilibration can't efficiently occur. The final subscore is storage, which looks at the risk of runaway aragonite precipitation, which would cancel out the alkalinity addition and reverse the carbon removal process. All oceanographic variables are computed as long-term climatological means over their respective record periods. They are then z-scored by removing the California coastal mean and dividing by the standard deviation. The z-scored variables are then combined within each sub-score, and finally the four sub-scores are averaged with equal weights to produce one composite score.

Dissolution

Dissolution refers to the speed at which the alkaline or silicate minerals dissolve in the surface water, thereby increasing the alkalinity of the seawater. To assess dissolution, oceanographic drivers such as significant wave height (H_s), sea surface temperature (SST), and seawater pH are weighed and computed as the following:

$$\text{dissolution_z} = 0.60 \times H_s_z + 0.25 \times \text{SST_z} - 0.15 \times \text{pH_z}.$$

The dominant driver of dissolution is significant wave height, weighted positively at 60%. Wave action is the principal justification for deploying enhanced weathering on beaches rather than in the open ocean with little to moderate wave action. Significant wave height was sourced from the Coastal Data Information Program (CDIP) Monitoring and Prediction (MOP) system using the 2000–2022 long-term mean of quality-controlled records. Each segment midpoint is assigned the period-mean H_s of its nearest MOP station; segments far from any MOP station are imputed to the regional mean and are flagged accordingly.

The second driver is SST, which is weighted positively at 25%. A higher SST causes increased dissolution through standard Arrhenius kinetics—where increased temperatures speed up reaction time. SST was sourced from the NASA Jet Propulsion Laboratory Multi-scale Ultra-high Resolution (MUR) Level-4 sea surface temperature analysis, which provides SST at 1-km spatial resolution. For each segment, the long-term annual mean is computed by averaging the 2003–2024 monthly climatology and interpolates the result to the segment midpoint. SST is weighted at 25% and is included in this sub-score because of the variation of temperature along the California coast. Warmer waters persist in Southern California and cooler persist in Northern California, making SST a strong factor that differentiates sites relative to one another.

The third driver is seawater pH, which has a negative weight at 15%. This is due to the fact that seawater with a lower pH has more hydrogen ions available for minerals to use in their dissolution process, which accelerates dissolution (Rimstidt et al. 2012; Oelkers et al. 2018). Thus, the negative coefficient rewards segments with lower pH. Seawater pH is interpolated from CODAP-NA West Coast Ocean Acidification cruise data via inverse-distance weighting. Seawater pH is interpolated to each segment from the Coastal Ocean Data Analysis Product for North America (CODAP-NA v2021), which is a compilation of West Coast Ocean Acidification cruises that measures carbonate chemistry data using inverse-distance weighting. The weight assigned to pH is the smallest of the three drivers because the pH range across the California coast produces the least differences between segments when compared to wave action and sea surface temperature.

One significant driver that is not incorporated into the dissolution sub-score is mineral grain size. While smaller grains dissolve faster in seawater and are therefore more ideal for dissolution, the grinding of rock down to extremely fine grain sizes is extremely energy intensive. This represents the largest source of CO₂ emissions in the CEW deployment chain, and Foteinis et al. (2023) estimate that grinding olivine to a 1 µm grain size has a carbon footprint of approximately 223 kg CO₂-equivalent per tonne of olivine. This reality could eliminate the net-negative emissions outcome the CEW project is intended to deliver, making this a crucial area of study that will determine if CEW functions as a genuine CDR strategy in practice.

Residence Time

Residence time quantifies how long the grains will persist in the surf zone, giving them time to dissolve before being flushed offshore. The residence time sub-score also creates a physical tension with the dissolution sub-score, as the same wave energy regime that accelerates mineral dissolution tends to coincide with stronger surf zone circulation that may in fact advect minerals offshore quickly, shortening residence time. This tension is a prime example as to why the four sub-scores are separated to represent specific steps in the pathway, rather than combining all steps into a single physical score. Residence time is a combination of two equally weighted drivers:

$$\text{residence_z} = 0.50 \times \text{beach_slope_z} - 0.50 \times \text{current_z}$$

Beach slope is the first condition to assess. A shallower beach slope is ideal for CEW because it allows for a wider, persistent swash and surf zone, which retains the minerals in shallow water and increases the time available for dissolution. A steeper slope risks advecting the minerals offshore to depth, where they may not dissolve as rapidly and eventually settle on the sea floor. Beach slope is derived from the NOAA Digital Elevation Model (DEM) Mosaic (NOAA NCEI). For each segment, elevation is sampled along a shore-normal transect from 0 to 500m offshore, with slope computed as the depth change between the shoreline and the 500m point divided by horizontal distance.

Slope values are given positive weight because shallower segments produce z-scores closer to zero or positive, while steeper segments produce more negative z-scores. No CEW literature uses beach slope as a residence time driver, but the physical basis is well established in the equilibrium beach profile theory (Dean 1977).

The second driver is nearshore surface currents, which control the speed at which the minerals may be advected offshore. More moderate currents will increase the time in which the minerals can dissolve in the surf zone, whereas faster currents will swiftly advect the minerals offshore before dissolution can occur. Current speed is taken from the SCCOOS HF (high-frequency) radar surface current dataset. While the HF radar product is the most spatially resolved continuous surface current observation available for the entire California coast, the nearest valid HF radar cell to a given shoreline segment typically sits 1 to 9 km offshore, measuring inner-shelf flow rather than the wave-driven surf zone current that transports minerals at the deployment site itself. Until there is accurate, surf zone current data available, the statewide HF radar dataset is used as a screening approximation tool.

Efficiency

Once dissolution has occurred, the efficiency sub-score quantifies how much atmospheric CO₂ is ultimately drawn down from the enriched alkaline water and sequestered in the ocean as bicarbonate. This measures the step in the CEW carbon removal chain responsible for ocean-atmosphere CO₂ equilibration and CO₂ drawn down, as well as the detectability of the alkalinity signal for monitoring purposes (He & Tyka 2023). This sub-score is computed as a combination of two drivers:

$$\text{efficiency_z} = (\text{wind_z} - \text{MLD_z}) / 2$$

This formula is motivated by air-sea CO₂ equilibration physics. The timescale required for an alkalinity-enriched surface water mass to equilibrate with the atmosphere scales as $\tau_{\text{eq}} \propto \text{MLD} / k$, where MLD is the surface mixed layer depth and k is the air-sea gas transfer velocity (He & Tyka 2023). Gas transfer velocity scales approximately as $k \propto$

u^2 , where u is wind speed at 10m above the sea surface (Wanninkhof 2014). Combining these relationships, τ_{eq} scales as MLD / u^2 , meaning that both higher wind speed and shallower mixed layers shorten the equilibration timescale. This allows for a larger fraction of alkaline water to trigger atmospheric CO₂ removal before the water gets advected below the mixed layer or to depth. To reflect this, the two drivers have opposite signs to favor wind speed but penalize a large mixed layer depth.

Wind speed governs the amount of atmospheric CO₂ that transfers across the ocean-atmosphere interface at the surface of the water. Strong wind speed causes turbulence at the surface which produces near-surface mixing, triggering gas transfer. Wind speed was sourced from the CCMP v3.1 climatology (Cross-Calibrated Multi-Platform wind vector analysis) dataset and interpolated to each coastal segment midpoint. Wind speed serves as a proxy for gas transfer velocity k , following Wanninkhof (1992), in which $k \propto u^2$.

The second driver is mixed layer depth, which is the depth of water in the well-mixed, upper ocean that exchanges CO₂ with the atmosphere. The minerals dissolve and increase the water's alkalinity, which eventually disperses throughout this layer rather than staying concentrated at the surface. The depth of the mixed layer controls indicates volume of water in which the alkalinity plume gets diluted (He & Tyka 2023). A shallower mixed layer will allow for a concentrated alkalinity plume closer to the surface that may equilibrate more efficiently with the atmosphere. Conversely, a deeper mixed layer would allow the alkalinity to dissolve in a larger body of water, lengthening the time it takes for equilibration and reducing overall exchange. This is the reason for the negative weight for MLD. This data is derived from the HYCOM 91.2 global ocean reanalysis (Naval Research Laboratory).

The efficiency sub-score does not include significant wave height, despite it being an ideal representation of gas transfer. Significant wave height contributes through gas transfer velocity, as breaking waves accelerate air-sea equilibration and trigger significant CO₂ exchange in the surf zone (Brumer et al. 2017; Deike & Melville 2018). It is not included in the sub-score because it is already weighted at 60% in the Dissolution

sub-score. Counting significant wave height a second time would risk overestimating its capacity to govern this carbon removal chain. By using wind and MLD to calculate efficiency, it focuses on the surface gas-transfer physics that operates independently from wave energy.

Another relevant factor for this process that was not included in the sub-score is the Revelle factor, which is the ratio of the fractional change in seawater $p\text{CO}_2$ to the fractional change in dissolved inorganic carbon (Sarmiento & Gruber 2006; Bach et al. 2023). It determines how much CDR can be achieved per unit of alkalinity increased by mineral dissolution. The Revelle factor was not included because its variability along the California coast is relatively low compared to other variables in the framework, therefore including this data does little for distinguishing sites relative to one another.

Storage

The storage sub-score is quantified by evaluating the risks or unintended consequences associated with alkalinity amendments in the marine environment, and ultimately assesses the carbon storage potential of a site. The sub-score assesses the risk of runaway calcium carbonate precipitation, which is a process where calcium ions react with bicarbonate in the ocean to form solid calcium carbonate. This process releases CO_2 back into the water, which could be outgassed back into the atmosphere. This essentially reverses the carbon storage pathway because the carbon that was stored as dissolved bicarbonate is now converted to solid CaCO_3 and partly released as CO_2 . Sites that sit well below this carbonate chemistry threshold can absorb more alkalinity before precipitation becomes a risk. Storage is assessed based on a combination of three drivers:

$$\text{storage_z} = -0.50 \times \Omega_\text{ar_z} - 0.35 \times \text{SST_z} + 0.15 \times \text{CUTI_z}$$

The first driver is aragonite saturation state ($\Omega_\text{ar_z}$), which is the physical quantity that governs the precipitation threshold, calculated from dissolved inorganic carbon (DIC) and total alkalinity (TA). High aragonite saturation means that the seawater is

naturally closer to the precipitation threshold, due to warmer, stratified surface water in which calcium carbonate solubility is reduced. The negative coefficient of the aragonite precipitation metric penalizes high aragonite saturated seawater. Ω_{ar_z} was sourced from the Coastal Ocean Data Analysis Product for North America (CODAP-NA v2021; Jiang et al. 2021).

The second driver is sea surface temperature, also possessing a negative weight to penalize higher temperatures. Sea surface temperature possesses a negative weight because warmer water reduces the safe TA addition limit substantially. Suitner et al. (2024) shows that the safe total alkalinity addition limit is more than three times larger at 5 °C than at 30 °C, because warmer water reduces CaCO_3 solubility. SST is taken from the NASA JPL MUR L4 SST analysis at 1-km resolution, the same product used in the dissolution sub-score.

The Coastal Upwelling Transport Index (CUTI; Jacox et al. 2018) is the third driver for storage, possessing a positive weight. This is the measurement of upwelling intensity along the coast of California that delivers cold, carbon-rich water from depth to the surface water. This process lowers the aragonite saturation level and increases the carbonate buffering capacity by replenishing the water with high amounts of DIC. Sites that have stronger seasonal upwelling transport benefit by having a larger defense against runaway precipitation than sites with modest upwelling conditions. This increases the natural buffering capacity that absorbs added alkalinity without crossing the precipitation threshold.

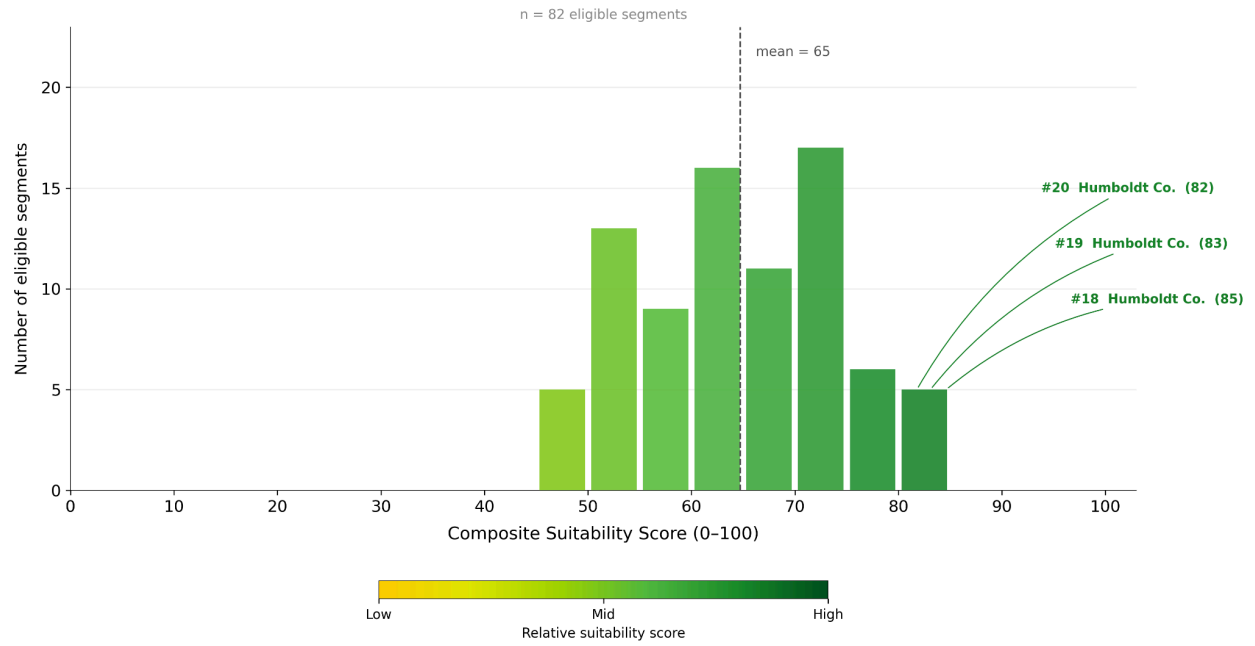
Suitability Findings

To score each coastal segment, the four sub-scores are averaged into a single composite score scaled from 0-100 using min-max normalization. This means that a score of zero represents the lowest-scoring eligible segment and 100 represents the highest-scoring eligible segment along the California coast. It is worth emphasizing that this suitability scoring framework measures segments relative to each other and does not provide any absolute biogeochemical values.

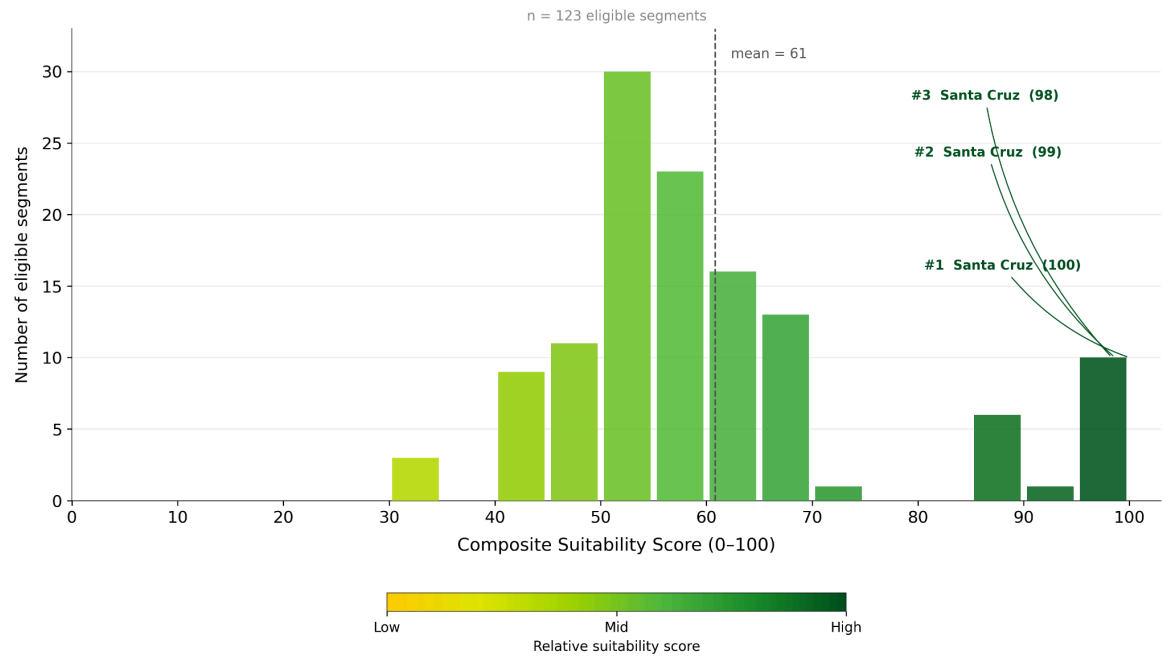
Based on this weighting scheme, the highest ranking coastal segment is located in Santa Cruz, specifically a shoreline near Cowell and Seabright Beach. This result is primarily due to the significant wave height that dominates the coastal region, with each Santa Cruz segment consistently scoring high due to ~ 6m mean wave heights. This high-performing driver outweighed the less-than-ideal drivers that existed in the Santa Cruz region, particularly the moderately elevated aragonite saturation levels in the region and moderate SST. Within the top-ranking Santa Cruz sites, the rankings were largely determined by differences in beach slope and current speed, which comprise the Residence Time sub-score.

The top-scoring Northern California site was Humboldt County, which had a composite score of 84.6. This segment's high rank is attributed to its low aragonite saturation levels and cold SST, which produced the stronger storage sub-score in the entire dataset at 90.9. This is likely due to the seasonal upwelling conditions associated with strong winds. In Southern California, the highest-scoring site was a segment of the coast near Point Conception in Santa Barbara County, possessing a composite score of 75.7. This high ranking is attributed to the region's shallow mixed layer and strong wind speeds, which combined produced the highest efficiency sub-score at 97.4. The lowest-ranking eligible sites were concentrated along the Malibu and Ventura coastlines in Southern California, due to low wave heights, warm SST, and high aragonite saturation levels that comprise the region. These metrics are non-ideal for CEW deployment under this framework, but are technically still eligible sites for deployment.

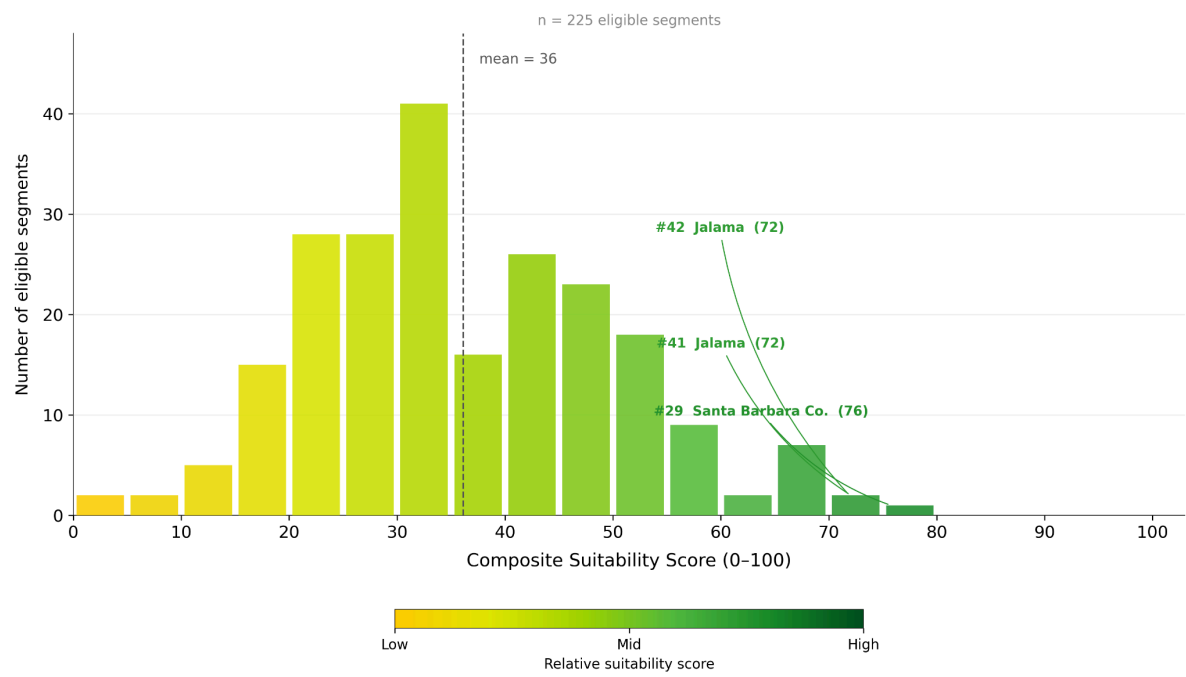
CEW Physical Suitability — Northern CA



CEW Physical Suitability — Central CA



CEW Physical Suitability — Southern CA



Limitations

The most significant limitation in this research project is the data used to measure the CEW carbon removal chain. The physical oceanographic datasets that drive the four suitability sub-scores were not built to measure this specific carbon removal chain, and many of them are too far offshore. They broadly measure other oceanographic conditions to inform weathering forecasting, ocean acidification monitoring, upwelling patterns etc. It is not that this data cannot be adapted to inform CEW site suitability; but the reality is that this suitability framework is based on proxies. This is acceptable for a screening tool whose purpose is to rank sites relative to each other, but should not and cannot be substituted for in-field measurements more tailored to measuring the specific CEW carbon removal chain. Such measurements would be necessary to support any formal pilot proposal at any given coastal segment.

A second limitation is the use of only four sub-scores to quantify a complex carbon removal chain. Narrowing this process down to four steps only captures a subset of the physical, chemical, and ecological processes that govern CEW carbon removal processes and outcomes. The complete carbon removal chain likely contains factors such as mineral grain transport and burial dynamics, fluctuations in biological productivity that govern local $p\text{CO}_2$ and DIC, seasonal variability of every oceanographic driver, and the influence of extreme events and climate variations such as ENSO that can enhance or suppress upwelling conditions. The framework also omits non-physical dimensions of suitability that significantly impact deployment feasibility and likelihood. Factors like community and tribal consent, impacts on tourism and local commerce, sediment supply economics, and lifecycle emissions accounting each have immense influence over CEW being implemented at a specific coastal site.

Recommendations for Implementation

The limitations of this project do not undermine its usefulness in evaluating site suitability along the coast; they do, however, provide limits as to what the framework can and cannot answer. The suitability map is not a pathway to deployment—it is a tool that can be used to identify the necessary steps to take to better understand this carbon removal process. Transitioning from site suitability into a permitted, monitored, and credible CEW pilot project requires three capacities that California does not yet possess at the scale required:

- 1) In-field measurements at candidate sites,
- 2) An MRV protocol designed for coastal enhanced weathering, and
- 3) A streamlined permitting pathway specific for mCDR projects.

Recommendation #1

The most fundamental limitation of the suitability map is the fact that the data sources used were not built to measure carbon removal processes in the surf zone. Several of the datasets sample conditions well offshore of the deployment zone, such as HF radar at 1 to 9 km and CODAP-NA carbonate-chemistry cruises at 5 to 50 km. Using these inputs to measure processes that occur at the shoreline relies on the assumption that offshore conditions are a defensible proxy for surf zone conditions. While this may be acceptable for ranking sites relative to one another, it does not support absolute claims about CDR efficiency at any given site. Recognizing that in-field measurements are necessary for understanding the carbon removal process of CEW, there must be steps taken to obtain direct field observations of carbonate parameters, nearshore currents, mineral source compatibility, and seasonal variability. California's major coastal research institutions are well-positioned to conduct this work—Scripps Institution of Oceanography in particular operates much of the analytical and observational infrastructure such a program would require. Coordinating existing capabilities around a CEW-specific research project would work to address the gaps in MRV protocol at a level of confidence that any future pilot proposal will require.

Recommendation #2

Building off of recommendation 1, this next proposal seeks to develop a specific MRV protocol for CEW. While carbon market registries have released ocean alkalinity enhancement MRV protocols, there is no current protocol designed specifically for beach-scale, passive, mineral-based deployment that CEW calls for. The protocol would specify baseline requirements for deployment monitoring such as tracking dissolved CO₂, nearshore surface currents, mineral dissolution rate verification, and a method to concretely track the influence of alkaline amendments against the natural variability of the ocean that already experiences shifts in alkalinity through upwelling and other various oceanographic processes. A CEW-specific MRV protocol developed collaboratively between registries, research institutions, and project developers would provide the standardized measurement and verification framework that any California CEW pilot will need for deployment. Once a defensible methodology is established, this would greatly reduce the barriers to entry for future pilot projects.

Recommendation #3

This recommendation seeks to emphasize an important consideration of CEW implementation that isn't discussed thoroughly throughout the project—the need for permitting. The introduction of new materials into the marine environment is subject to rigorous permitting under state and federal law, and alkaline mineral amendments could be classified as discharge of a pollutant. These interventions could trigger review under the Clean Water Act, the London Protocol, the Rivers and Harbors Act, the Marine Protection, Research, and Sanctuaries Act, the Endangered Species Act, the California Coastal Act, the California Environmental Quality Act, and potentially more depending on the size and scale of the CEW project. No state agency is tasked with handling mCDR projects, thus the project could be administered across several agencies such as the U.S. Army Corps of Engineers, the U.S. Environmental Protection Agency, USFWS, NMFS, the California Coastal Commission, CDFW, the State Lands

Commission, the relevant Regional Water Quality Control Board, and the host city or county.

Additionally, there is no established permitting framework that governs mCDR pilot projects. The first-of-its-kind National Pollutant Discharge Elimination System (NPDES) permit was secured for Ebb Carbon's Project Macoma, which was an ocean alkalinity enhancement pilot project in the state of Washington (Ebb Carbon 2025; Ecomagazine 2025). Vesta's coastal enhanced weathering pilot in Duck, North Carolina required permits under the federal Clean Water Act (administered by the U.S. Army Corps of Engineers) and North Carolina's Coastal Area Management Act (administered by the North Carolina Department of Environmental Quality) (Vesta 2024). A streamlined permitting framework, developed through interagency cooperation, would allow subsequent California CEW projects to be based on consistent guidelines rather than needing to start from scratch. This recommendation is likely the most complex, as it involves consistent regulatory and interagency coordination. Without this change, however, the first two recommendations are functionally useless; field-validated measurements and MRV protocols can only be established by doing these actual pilot projects, which involves first going through these complex permitting pathways.

Conclusions

The state of California has codified some of the most ambitious goals for carbon neutrality, and meeting these rigorous standards for carbon dioxide removal is unlikely without the proper pathways. Coastal enhanced weathering may be one of the most promising mCDR candidate strategies the state could deploy at various coastal beaches up and down the coast. But the question of where deployment projects should occur along the 1,600 km coastline has, until now, not been widely discussed or identified. This report aimed to develop a tool to help researchers and policymakers identify where along the California coast could CEW realistically work. This project developed a two-tier suitability framework to identify this knowledge gap, utilizing publicly available oceanographic datasets while taking ecological and regulatory precautions. This framework actively pursues a carbon removal pathway broken down into four phases or sub-scores known as dissolution, residence time, efficiency, and storage. Each of these phases maps on to a measurable phase in the carbon removal pathway, and this ultimately assesses a sites' suitability for deploying CEW at that location.

This framework does not determine locations where CEW should be deployed, but rather gives context as to what segments or coastal regions perform adequately based on the 4-phase pathway. However, the data relied upon to provide these contexts were not built to measure this specific carbon removal pathway. Thus the next step in this project would be to take in-field measurements of the relevant oceanographic drivers responsible for influencing the phases of this carbon removal pathway, perhaps at top-ranked segments. Direct measurements of carbonate chemistry, surf zone dynamics, and seasonal baseline variability would provide more exact context that other data fails to capture. Through this field work, alongside the development of specific MRV protocol for verifying carbon removal and streamlined permitting for implementation feasibility, barriers to entry for CEW deployment would be substantially reduced. This would attempt to close the gaps between this suitability map and verified, monitored, and permitted CEW pilot projects that California's CDR commitments will eventually require. Therefore, the creation of this suitability map is a starting point for addressing

knowledge gaps, uncertainty and barriers to entry, in an effort to position California as a state capable of deploying well-informed and legitimate CEW projects at scale.

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