Resolution Without Revolution

Green Capitalism, Ecological Management, and the Carbon Dioxide Removal Industry in the United States

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Abstract:

Carbon dioxide removal (CDR) is quickly moving from mere imagination to material reality. As I write, billions of dollars are flowing into this nascent industry from government, philanthropy, and venture capital; this thesis thus attempts to grasp history as it flies. By employing a Marxist theoretical approach, including concepts like the real subsumption of nature and the spatiotemporal fix, I draw a nuanced illustration of the political economy of carbon dioxide removal in the United States. By mapping the organizations and investment flows that constitute the US CDR industry, I show that the industry is both already substantial and less connected to fossil capital than one might think. Instead, I found that tech and finance are the key capitalist economic sectors driving the US CDR industry through their purchases of high amounts of removals from suppliers and through investment spread throughout the industry. By really subsuming atmospheric nature via CDR, I posit, the tech and finance sectors are able to address the crisis in capitalism's ecological background conditions of possibility without needing to directly challenge the hegemony of fossil capital. They can instead strive for negative emissions and "net-zero" while postponing the devaluation of fossil assets, a defensive spatiotemporal fix that preserves existing lucrative accumulation strategies. The tech and finance sectors are *for solving the ecological crisis* (**not** *against fossil fuels*) and can be said to be pursuing a green capitalist project to manage the crisis towards capital's ends.

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Abbreviations

AR6: The Sixth Assessment Report of the IPCC (2022)

ARPA-E: Advanced Research Projects Agency - Energy

BECCS: Bioenergy Carbon Capture & Storage

BiCRS: Biomass Carbon Capture & Storage

CCS: Carbon Capture & Storage

CDR: Carbon Dioxide Removal

CEO: Chief Executive Officer

CO_2: Carbon Dioxide

COP: Conference of the Parties, part of the UNFCCC

CTO: Chief Technology Officer

CZI: Chan Zuckerberg Initiative

DAC: Direct Air Capture

DAC Hubs: United States Regional Direct Air Capture Hubs Program

DCFP: Douglas County Forest Products

DOE: US Department of Energy

EOR: Enhanced Oil Recovery

ESG: Environmental, Social, and Governance

FECM: United States Office of Fossil Energy and Carbon Management

Gt: Gigatons

IAM: Integrated Assessment Model

IIJA: Infrastructure Investment and Jobs Act (2021)

IPCC: Intergovernmental Panel on Climate Change

IRA: Inflation Reduction Act (2022)

MCJ: My Climate Journey

MRV: Monitoring, Verification, and Reporting

Mt: Megatons

NET: Negative Emissions Technology

NCS: United States National Climate Strategy

NGO: Nongovernmental Organization

R&D: Research & Development

SNA: Social Network Analysis

SRM: Solar Radiation Management

UCLA ICM: University of California-Los Angeles Institute for Carbon Management

UNFCCC: United Nations Framework Convention on Climate Change

USG: United States Government

VC: Venture Capital

Resolution Without Revolution:

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> Carbon dioxide removal is finally having its moment. … Carbon dioxide removal is key to restoring our climate. This is an all-hands on deck moment. We can, and we will, save our planet.
>
> **Secretary Jennifer Granholm,**
> **US Department of Energy, July 2022**

1. Introduction

Amidst the Northern hemisphere's second hottest summer in recorded history, a member of the Biden Administration's Cabinet hopped onto a Zoom call in July 2022 to speak at the world's first Carbon Negative Summit. Jennifer Granholm, head of the US Department of Energy, led a virtual coming together of the top minds across industry, government, academia, and environmental NGOs to discuss a recently introduced priority to deal with what the president was calling a "climate emergency": carbon dioxide removal. Unlike the recently defeated Trump Administration, everyone in the room "listened to the science" of planetary heating and was beyond squabbling over its merits – climate change was real and was getting worse, the question was now what to do about it. Decarbonization was the obvious priority, but what if it was impossible, or too slow, or just too expensive? Even worse, what if we are already beyond certain tipping points? How do we fix the crisis then? Enter carbon dioxide removal (CDR).

The technology capable of separating CO_2 from mixed sources is much older than the Biden Administration's recent recognition. One form has been used since the 1920s to cleave CO_2 from natural gas at industrial refineries, and the air recycling units on spacecraft are similar too. What is different about carbon dioxide removal is its purpose: to separate CO_2 from ambient air in order to bring down excess CO_2 concentrations and reduce global warming. It is worth noting up front that CDR is different from a similar process known as carbon capture and storage (CCS). Although CDR and CCS employ overlapping technologies, the CCS process is focused on limiting the carbon content of gasses as they are emitted. Thus, CCS can reduce the amount of carbon emissions that reach the atmosphere while CDR removes, or subtracts, CO_2 that is already there. While CCS is also currently being discussed as a climate tech solution, especially by the fossil fuel industry, this study sets CCS aside in favor of a deeper examination of CDR.

Carbon dioxide removal is quickly moving from mere imagination to material reality. No longer confined to the hypothetical scenarios of climate models, one of the aims of this study is to illustrate the emerging materiality of the US CDR industry, including its organizations, funding flows, and technological capabilities. I will show that the US CDR industry is real, growing, and potentially poised to play an important role in US climate politics in the decades to come. Drawing on tools from political ecology, critical CDR social science, and ecological Marxism, this research will discuss how we might make sense of the recent arrival of “the carbon dioxide removal moment.”

2. Aim, Justification, and Research Questions

This thesis is well placed as a project within Human Ecology because of how the topic embodies intersections of culture, power, and sustainability. Culture is here defined as "the diversity and plurality of life…guided by different world-views, priorities, belief systems and making sense of the world" (Crang, 1998, p2-3). For my working conceptualization of power, I utilize Brazilian social theorist Rodrigo Nunes's distinction between power-to (*potentia*) and power-over (*potestas*) to orient my thinking (Nunes 2021). *Potentia* is apparent when individuals or groups have the capacity to act on the world as they wish (to have efficacious practice) and have the capacity to resist being unwilling subjects of others' change (to have resiliency against coercion). *Potestas* is the power that seeks to undermine these capacities in others. Throughout this thesis I remain sensitive to dynamics of power through these two concepts. Sustainability here is taken up in the spirit of the Brundtland Commission; sustainable activity or development is activity that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987 p. 24). Within these three concepts, carbon dioxide removal can be placed at the nexus:

- The way that various groups – governments, climate professionals, CDR suppliers, purchasers, and investors – conceptualize negative emissions is a product of **Culture**, their ideological underpinnings and priorities;
- **Power** – how actors exercise capacity for *potentia* and build *potestas* through the CDR industry, using rhetorical promises, investment flows, or state mechanisms;
- **Sustainability** – how carbon dioxide removal is put forth as a means of saving the planet from runaway climate catastrophe, and what this means in light of the complexities of culture and power that inflect it.

With these concepts in mind, I employ a Marxist approach to formulate an understanding of the US CDR industry. My aim in this thesis is to grasp how carbon dioxide removal functions in the United States as a *necessary* condition of the present conjuncture, so as to enable attempts to anticipate what futures it might bring about. In other words, my aim is to understand how carbon dioxide removal fits into our world – and why it fits that way – in order to help us foresee what the future holds. Our world is *contingent*, the opposite of predetermined; the future is open and the past need not have happened the way it did. But by examining the conditions, dynamics, qualities, and forces that make the world what it is and not something else, we can come to understand the historical context that co-constitutes everything. The past *did happen* a certain way, and history has infinite reverberations in the present. Nothing is intelligible as somehow separate from these historical reverberations. There being a carbon dioxide removal industry in the United States is a product of such reverberations. My limited contention here is merely that by studying the substance and mechanisms of US CDR we can prepare ourselves for a coming interval that is potential but not-yet, indeed perhaps even intervene it in.

While occasionally touching on global CDR developments, I limit the scope of this thesis to the United States. My focus on the US is a product of two factors: data reliability and positionality. First, I have greater confidence about my data's reliability for the US than for the world as a whole. Given that *cdr.fyi* – one of my primary data sources – is English-language and has a founding team located in the Global North (Sweden, UK, and US), there is a risk that non-English CDR transactions are underrepresented. There is evidence, for example, of a substantial CDR industry in China (Smith et al. 2023) but there are zero China-based suppliers listed in *cdr.fyi*.[1] Since my research abilities are restricted to English, I am unable to investigate such data lacunae and admit that non-US claims have less reliability. Second, I have lived the vast majority of my life in the United States, studied American history and politics in a higher education setting, and have a partial yet intuitive understanding of the ways political economy in the US functions. My personal characteristics as a researcher thus position me to explore the US as one important site within an emerging global industry. Taken together, these factors make an exploration of the US – rather than the global – CDR industry the most efficacious for this study.

From this aim and delimitation, I derived the following research questions:

1. What organizations, carbon credit transactions, and investment flows constitute the US CDR industry?
2. What might be the logic underlying the development of the US CDR industry?

I would also like to emphasize here that this thesis is attempting to grasp history as it flies, so to speak; to write about developments that happen very fast from the vantage point of the present. The US CDR industry is still coming into being even as my fingers strike the keys. But developments are already slipping the bounds of common expectation – fossil fuel companies seem to be less involved than many presuppose, for example – and thus deserve our attention.

[1] According to Smith et al. (2023), China is by far the leader in CDR research. This assertion is supported by the fact that China leads all CDR-related patent claims and that more CDR research originates in China (32%) than in any other state (US is second at 9%). The authors lament the limited data availability regarding Chinese CDR.

3. Background

3a. Negative Emissions

I begin with the seemingly contradictory concept of "negative emissions." "Emissions" is a word commonly used to describe the release of CO_2 into the air, as in "carbon emissions." Carbon emissions, whether from industry, agriculture or another source, *add* carbon to the atmosphere and can in this sense be considered *positive*. The concept of "negative emissions" appears as the inverse of positive emissions, or as a phrase to signal the *subtraction* of some CO_2 from the atmosphere to be stored someplace elsewhere. Various techniques of doing such subtraction are called "negative emissions technologies" (NETs). The broader activity of subtracting, or removing, CO_2 from the atmosphere and then durably storing it is called carbon dioxide removal (CDR).[2] Conceptually, "negative emissions" has merit as a mathematical identity. It is not that simple, however. Considering the massive amounts of CO_2 emitted in the past 200 years, coupled with the still-growing annual addition to that existing cache, moving from business-as-usual to a world with substantial negative emissions appears to be at a minimum a prodigious undertaking without precedent, if not a hubristic chimera. How did this prospect come to acquire such resonance among climate policymakers? Critical in this matter is the work of the Intergovernmental Panel on Climate Change (IPCC).

The IPCC's Working Group III, tasked with summarizing the state of – and prospects for – climate change mitigation, systematically included large-scale carbon dioxide removal in the body's sixth round of assessments, published in 2022 (IPCC 2022). This report states rather plainly that the global emissions pledges made prior to COP26 are insufficient for achieving the goals of the Paris Agreement; the planet "will *likely* exceed 1.5ºC during the 21st century" (IPCC 2022 p. 19). In order to "return warming to 1.5ºC by 2100 with a likelihood of 50% or greater," the report states that global emissions will have to be cumulatively net-negative to the tune of 380 gigatons[3] of CO_2 between 2050-2100 (IPCC 2022 p. 19; see also Malm & Carton forthcoming). This scenario (temperature overshoot between 0.15-0.30C with a return to 1.5ºC by 2100 through CDR) nevertheless still assumes "rapid acceleration of other mitigation efforts across all sectors after 2030" (IPCC 2022 p. 19), a task that has proven exceptionally difficult in the three decades since the UNFCCC was formed (Stoddard et al. 2021). Keeping warming

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[2] These two terms (NETs and CDR) are very similar and are often conflated. I will primarily use CDR in this thesis because it is more widely used in the United States.

[3] A gigaton is equivalent to one billion metric tons. Around 37 gigatons (Gt) of CO_2 is emitted globally every year.

below 1.5ºC thus "*requires* the large-scale deployment of negative emissions technologies" alongside systematic global decarbonization (Minx et al. 2018 p. 1, emphasis mine; see also Pues 2022 p. 5; Sandalow et al. 2021 p. vi; Terlouw et al. 2022 p. 1701).

It is worth briefly considering how NETs have become such an IPCC-endorsed panacea. Up until the release of the fourth Assessment in 2007, the integrated assessment models (IAMs) used to model climate trends in IPCC reports were consistently stabilizing CO_2 concentrations at levels much higher than what would later become the Paris Agreement's goals. When the 2ºC target received political substantiation,[4] modelers were asked to get us there; in order to do so, and while almost always operating under assumptions that remain mostly obscure to their readers (Rivadeneira & Carton 2022), modelers concocted results in which negative emissions were made crucial for their models' functioning (Tavoni & Socolow 2013). The inclusion of large-scale negative emissions technologies in IAMs not only reduced costs by postponing expensive mitigation further into a discounted future, but also introduced a debt mechanism into carbon budgets whereby expended carbon might be repaid later (Carton 2020). NETs have since come to occupy crucial places in the future trajectories modeled by the IPCC – first in its report on reaching 1.5ºC (2018) and again in AR6 (2022) – an effect of which has been "to normalize and mainstream the idea that negative emissions are both feasible and necessary" (Carton 2020 p. 39; Beck & Mahoney 2018). The IPCC "is an important player in making futures, not just foreseeing them" (Beck & Mahoney 2017 p. 313).

One potential future in the making is one where mitigation – the reduction of carbon emissions – is wholly or partially discouraged thanks to the availability of negative emissions. Indeed, questions over possible mitigation deterrence, or "*the prospect of reduced or delayed emissions reduction resulting from the introduction or consideration of another climate intervention*" like CDR are never very far from CDR debates (Markusson et al 2022 p. 2, emphasis in original; see also Markusson et al. 2018; Carton et al. 2020; McLaren et al. 2021). Why, the negative emissions concept prompts us to ask, is it such a big deal to emit when the CO_2 can come back out later? The prospect of future large-scale carbon dioxide removal, the

[4] The 2ºC temperature target was originally proposed by economist William Nordhaus in 1975 as a reasonable target for humanity to achieve; it was a back-of-the-envelope calculation that has little basis in climate science (Nordhaus 1975).

thinking goes, coupled with a series of equivalency assumptions[5] appear on the surface to provide cover for continuing some emissions.[6] However, these equivalency assumptions do not hold up under scrutiny and often obscure important implications as when, for example, low-probability/high-impact “catastrophic” outcomes become more likely when carbon was emitted and removed rather than left in the ground (Kemp et al. 2022). The net result may be equivalent in the abstract (carbon in the ground) but so much has changed in the process. When understood this way, fears over mitigation deterrence appear well-founded. Mitigation deterrence would not necessarily need to be an intentional phenomenon either. Global capitalism tends toward cost-minimization and the accumulation of surplus value, and the “mute compulsion” of economic power makes certain decisions – such as investing in large-scale CDR instead of decarbonization – appear rational despite consequences like mitigation deterrence (Mau 2023). Unfortunately, an exploration of the validity of CDR-related mitigation deterrence is outside the scope of this thesis, but I flag these debates for the interested reader.[7]

To conclude the discussion of negative emissions, I note that none of the proposed negative emissions technologies currently exist at climate relevant scale (Smith et al. 2023). Their inclusion in global trajectories entails substantial risks, including the potentials of mitigation deterrence (they could delay cutting emissions) and biophysical infeasibility (they might not work). These risks are unevenly borne by future generations; if NETs fail to materialize, it is the present who will benefit from the continuation of emissions and the future who will suffer from more severe climate impacts (Shue 2017). And if one goes digging into the specifics, colonial inequalities are frequently perpetuated – as when land used for NETs in the Global South is claimed by the Global North to justify its disproportionately higher energy use (Dooley et al. 2022; Hickel & Slamersak 2022). No recent phenomenon, the “long history of carbon removal” (Carton et al. 2020) illustrates that the uncritical default approaches to addressing ecological crises tend toward the entrenchment of existing structural inequities. If

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[5] Assumptions such as: fossil-combusted carbon is equivalent to carbon captured in biotic ecosystems or in chemical sorbents; emissions in the Global North are equivalent to offsets in the Global South; emissions now and removals later are equivalent (Carton et al. 2021).

[6] Examples of so-called “hard-to-abate”, or difficult to decarbonize, emissions that are frequently invoked for CDR justification are concrete production, aviation, and agricultural emissions. For critiques of the concept and its use in justifying questionable CDR offsets, see Buck et al. (2023).

[7] For an excellent analysis of the structural dynamics compelling mitigation deterrence see Carton et al. (2023); for a well-formulated disagreement see Jebari et al. (2021).

policymakers find large-scale carbon dioxide removal to be necessary, despite consideration of its potential shortcomings, these risks and legacies must be grappled with.

3b. Carbon Dioxide Removal Technologies

While carbon dioxide removal names the intentional process of capturing and sequestering CO_2 from the atmosphere toward the goal of negative emissions, it does not presume a certain means of achieving this feat. The question of how to do so is left open for engineers, scientists, and financiers to figure out. As one might expect, there are multiple carbon dioxide removal methods, indeed what some might call a dizzying variety of proposals that can leave one unsure of how to separate the flashy hype from the quietly plausible. In this thesis, I consider five carbon dioxide removal method categories: mineralization, direct air capture, ocean CDR, biochar, and biomass methods. **Figure 1** shows these five methods' representation among active CDR suppliers in the US. In this section, I will illustrate in some detail what I am referring to when I talk about these carbon dioxide removal methods before turning to a brief discussion of the biophysical (in)feasibility of carbon dioxide removal at scale.

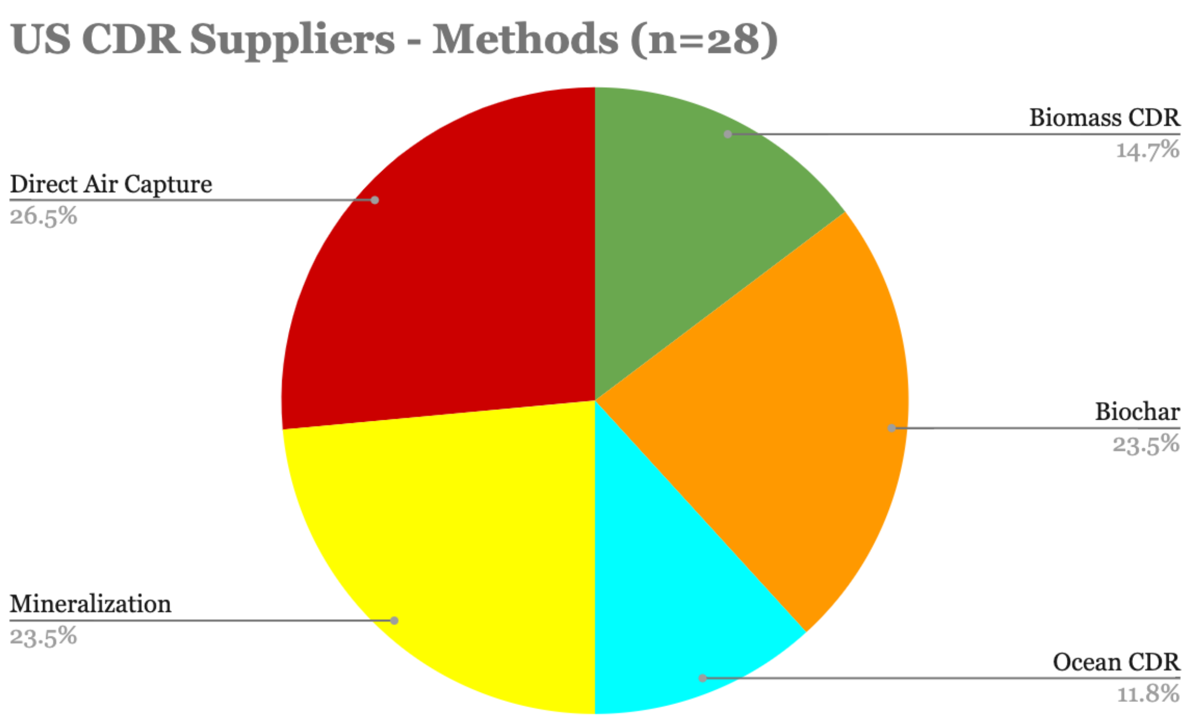

Figure 1. US CDR Suppliers - Methods

One method or technique for removing carbon is known as *mineralization*, whereby CO_2 is captured from the atmosphere via a reaction with minerals to form solid carbonates (Dipple, Keleman & Woodall 2021). Alkaline minerals are ideal, and can be naturally occurring or found in waste products from industrial processes or mining. Mineralization is a natural process that happens without any necessary human interference (Schuiling & Krijgsman 2006). However, such a process occurs at geological timescales; engineered mineralization is thus a CDR method to speed it up so as to sequester more CO_2. The most common engineered mineralization approaches are to "weather" alkaline materials by passing CO_2-enriched fluid or gas through them, or to initiate a cognate process with geologic formations by injecting the CO_2-enriched fluid or gas underground. Some sources further differentiate these two processes, the former being "enhanced weathering" and the latter being "mineralization"; I collapse this distinction under the umbrella "mineralization" in the spirit of simplicity. Mineralization is the CDR method of choice for at least sixteen global CDR suppliers, including eight who are US-based such as Heirloom, CarbonBuilt, and Vesta.

Direct air capture (DAC) removes carbon via machines outfitted with chemical sorbents, materials designed to chemically bind with only CO_2 molecules. In this method, ambient air passes through the DAC machines where it comes into contact with CO_2-reactive chemicals; the CO_2 binds with the capture agent while nitrogen, oxygen, and other atmospheric gasses pass through (McQueen & Wilcox 2021). After a sorbent becomes saturated, high-purity carbon is recovered by breaking the chemical bonds (using heat, pressure, or a chemical reaction). The CO_2 is then compressed into a gas or liquid form suitable for sequestration. This description necessarily entails some simplification, as there are various ways of doing the above. Indeed, direct air capture technology remains in its "infancy," and the research and development on sorbent chemistry, process technology, and manufacturing has not yet settled on a single set of best practices (Erans et al. 2022 p. 1396). DAC is the method utilized by nine US CDR suppliers and by some of the most well-known suppliers globally, such as Switzerland's Climeworks and Canada's Carbon Engineering. It is also the method the US Government appears to be supporting most explicitly upon naming their massive $3.5B investment into CDR the "Regional Direct Air Capture Hubs" program.

Another category encompasses methods that enroll the oceans for the purposes of carbon dioxide removal, henceforth referred to as *ocean CDR*. There is again a range of distinctions to be made within this category – between kelp cultivation, ocean alkalinity enhancement, coastal blue carbon, etc. – that I collapse in this thesis for simplicity reasons. What unites these methods is their manipulation of oceanic chemistry and/or ecosystems so as to generate a heightened uptake of CO_2 from the atmosphere (Renforth & Kolosz 2021; Troxler 2021). As an example, US-based supplier Running Tide deploys ocean CDR by catalyzing widespread kelp growth – this process removes CO_2 during kelp photosynthesis, and stores it when the biomass sinks into the deep oceans. There are at least five ocean CDR suppliers operating today with Running Tide, SeaChange, Captura, and Ebb Carbon based in the US and Planetary operating from Canada.

Biochar is a carbon-rich, organic product created when biomass is burned in an oxygen-free environment, a process known as pyrolysis. The charred biomass – biochar – degrades at a slower rate than ordinary organic material, and thus keeps carbon absorbed by plants during photosynthesis out of the carbon cycle for an extended duration. Applied as a soil amendment, biochar has many helpful properties, including microbial stimulation, increased soil-water retention, improved nutrient availability, and limited susceptibility to plant disease (Belmont et al. 2021). Utilized as a carbon dioxide removal technology, it may promote an increased uptake of carbon in soils (and, as such, is one tool in the wider "soil carbon sequestration" toolkit) in addition to the enhanced durability it provides decomposing biomass (Paustian et al. 2021).[8] By tons actually removed from the atmosphere, biochar is the leading carbon dioxide removal method in the US by a wide margin, with suppliers like Wakefield Biochar and Douglas County Forest Products each having proven sequestration totals of more than 10,000 tons. Indeed, biochar leads globally with research outpacing all other methods (50% of CDR publications in 2021 were about biochar) and as the method with the most tons removed of all-time (87%) (Smith et al. 2023; CDR.fyi 2022).

The fifth and final CDR method this thesis touches upon is *biomass*, or the utilization of biological material to remove CO_2 from the atmosphere. This method category is intentionally broad, collapsing method variations like Charm Industrial's bio-oil (liquified agricultural

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[8] Soil carbon sequestration, along with afforestation and reforestation, are beyond the scope of this thesis for several reasons: i) the *cdr.fyi* data lists no suppliers with those CDR methods and ii) it is extremely difficult to measure carbon dioxide removal at the ecosystem scale, thus making it difficult to establish additionality and apply independent MRV practices to these methods at this time. CO_2 is indeed removed via these practices, but I set them aside for now.

residue) with Living Carbon's genetically modified photosynthesis (a trait prompts the plant to increase carbon uptake) and Kodama Systems' wildfire prevention practices (thinning forest cover and burying, not burning, the cuttings). Biochar is another specific example of a biomass CDR method. Until recently, the most popular carbon dioxide removal method in policy discussions was known as BECCS – bioenergy carbon capture and storage – and on the surface this method appears to belong under my biomass heading (Belmont, Jacobson & Sanchez 2021). However, I set aside BECCS for two reasons. The first is that the main dataset that I am working with excludes BECCS suppliers.[9] The second reason is that the US Government is moving away from using the BECCS terminology and framing, preferring instead the acronym BiCRS for biomass carbon removal and storage.[10] BiCRS is broader than BECCS, and can be considered a synonym for the more accessible "biomass CDR methods" deployed here.

It would be irresponsible not to flag the ongoing debates over the potential biophysical (in)feasibility of carbon dioxide removal technologies at scale. To start, it is not clear that the amount of carbon dioxide removal conjured through IPCC models is practically possible; the energy and land use involved would displace so many essential human activities as to render the whole undertaking absurd. Let's take direct air capture (DAC) as an example: DAC machines require an enormous amount of energy to operate (Realmonte et al. 2019). Given that fossil fuel-run DAC is counterproductively carbon emitting, renewable energy – wind turbines, solar farms, etc. – would need to be summoned to keep the carbon vacuums running. But one study calculated that it would require 3500 terawatt hours to remove 1 Gt CO_2 via DAC, equivalent to the entirety of 2017 US energy use (Sekera & Lichtenberg 2020).[11] This was a single study, but more accurate figures are hard to come by: the study's authors "found no analyses of a full-scale, renewables-powered DAC process based on a full life cycle … and including embodied

[9] My dataset (*cdr.fyi*) excludes BECCS on the basis of its energy production dimension. Their reasoning: if one is burning biomass for energy, the CO_2 is not being directly sequestered; if it is then captured upon burning, as the CCS part of BECCS implies, then this process is closer to point-source carbon capture than carbon dioxide removal from ambient air. I disagree with this framing. The whole BECCS process - from growing plants to sequestering the CO_2 – may indeed still be CDR, and on this point I part ways with the creators of the dataset. That this thesis does not include BECCS CDR suppliers is an admitted shortcoming.

[10] The reasoning for this change can be found in a 2021 report written for DOE: ""BECCS" is too limited and has the wrong emphasis. BECCS starts with the word "bioenergy," but some processes that use biomass to remove CO_2 from the atmosphere do not involve bioenergy. Furthermore, when bioenergy is combined with carbon capture and storage (CCS), the removal of carbon from the atmosphere—not the production of energy—will often be the most valuable part of the process. (Most biomass has high carbon value but poor energy value)" (Sandalow et al. 2021).

[11] This number excludes crucial upstream (sorbent manufacture; steel and cement production; construction) and downstream (transportation and sequestration of the captured carbon) processes, making 3500 terawatt hours a conservative estimate.

emissions and emissions from chemicals (e.g., sorbent) manufacture" (Sekera & Lichtenberger 2020 p. 14).[12] Indeed, the 2023 report on the *State of Carbon Dioxide Removal* identified a general lack of lifecycle emissions accounting as a glaring omission for CDR more generally, not just DAC (Smith et al. 2023, ch 6). We simply do not yet know if these technologies actually function as carbon negative at scale, although some experts have seen enough to call DAC "an energetically and financially costly distraction" until renewable energy is more widespread (Chatterjee & Huang 2020 p. 1). Biomass-based methods have better answers to the energy question, but themselves falter in other respects – one of which is land use.[13]

Discussions of land in the context of large-scale CDR can appear equally as daunting as the renewable energy requirements. *The Land Gap Report* (Dooley et al. 2022) tallied up all of the land claims made by countries' biological carbon dioxide removal pledges and found that it added up to 1.2 billion hectares, equal to the world's food producing base. That is, countries' paper commitments to addressing climate change rely significantly on turning massive amounts of land currently used for feeding the world – whether through industrially managed monocrops or local agroecological farms – into land primarily dedicated to capturing carbon, co-benefits aside. Land transformed for the purpose of carbon dioxide removal risks withdrawing or modifying it from other, perhaps more immediately critical uses, such as subsistence farming or animal grazing, potentially perpetuating hunger and fuelling land-based inequity[14] (Bluwstein & Cavanagh 2022; McElwee 2022; Sen & Dabi 2021).

Once the carbon is removed from the atmosphere it must then be transported to a suitable storage site and sequestered there – and this carbon infrastructure promises to make serious land demands too. Indeed, in the US it already is. Around 5,000 miles of carbon pipelines currently exist in the US, mostly in Texas and Wyoming; according to a report by Princeton University, 65,000 miles of carbon pipelines would be required to meet the Biden administration's carbon sequestration goals (Larson et al. 2021). These pipelines would run across vast tracts of the continental US, appropriating formerly private landholdings in the name of the public good. Land seizure to build such pipelines is already facing resistance. In Iowa, for example, local

[12] Before the DAC plants even come online, the colossal chemical manufacture of sorbents needed to capture the carbon would likely emit a sizable carbon load (Realmonte et al. 2019).

[13] Biochar requires only modest energy use and can be compatible with agricultural uses of the same land. However, this more promising CDR method faces an important challenge when it comes to durability (See Discussion).

[14] Not to mention the pressure coming from the warming itself, as the need for agricultural land comes into conflict with the shrinking of zones amenable to food production .

property owners are allying with environmental groups skeptical of the pipelines to resist eminent domain claims (Douglas 2022; Wittenberg 2022).

This brief sketch is only meant to illustrate the contested materiality of some of the claims made in the name of the necessity of carbon dioxide removal. Overall, the scientific literature on carbon dioxide removal does not sufficiently address questions of energy use, land use, or biophysical impacts at scale, instead biasing research toward questions of a more abstract economic nature (Sekera & Lichtenberg 2020; Dooley at al. 2022).

3c. Global CDR Trends

The global CDR industry has undergone rapid and exponential growth across a variety of indicators over the past few years. In June 2019, less than 150 tons of carbon dioxide removal had been sold and delivered – purchased by insurance company Swiss Re, supplied by Finnish biochar company CarboFex. By March 2023, less than four years later, over 774,000 tons had been purchased by 143 distinct buyers across 812 transactions. Much less than that had been physically removed from the atmosphere ("delivered"), a point that we will return to shortly. Purchasers ranged from giants of international finance (JP Morgan Chase, UBS Financial, Blackrock), to Silicon Valley standards (Microsoft, Stripe), to retailers and manufacturers (H&M Group, Audi). All publicly paid for carbon to be taken from the atmosphere by a suddenly materializing entity: the carbon dioxide removal supplier.

Carbon dioxide removal suppliers are the entities tasked with actually deploying a CDR method and overseeing the removal of CO_2 from the atmosphere. They are often smaller companies, start-ups or other early-stage enterprises, with high proportions of engineers, chemists, and other scientists on staff. When a corporation like Swiss Re approaches a CDR supplier, as in the example above, that corporation "purchases" carbon dioxide removal from the supplier who "sells" it to them – in essence, the supplier receives money from the corporation, deploys their CDR method, and the corporation walks away with a "product", usually a certificate that says that the corporation is credited for sequestering a certain amount of CO_2. In an age of carbon footprints, green public relations, and environmental, social, and governance (ESG) investing, that certificate is indeed worth something. A key dynamic to keep in mind, however, is that there is almost always a delay between the corporation's purchase of an amount of CDR and the suppliers biophysically removing that CO_2 from the atmosphere. When the suppliers get around to biophysically removing the CO_2, we say that the CDR transaction has been "delivered." Until then, the suppliers have merely "sold" a promise to remove CO_2.

The global list of carbon dioxide removal suppliers stands at 84, according to *cdr.fyi*; however, only 69 have sold at least one ton of carbon dioxide removal.[15] The remainder are presumably still in development, to be called upon in the near future. The 69 active suppliers are based across North America, Europe, Australia, Israel and Brazil with the US having the single most active suppliers at 29 (42%).[16] These active global suppliers utilize the same variety of methods examined in section 2b, but in differing proportions than the US (**Figure 2**). Biochar is more common at the global level than in the United States with thirty-two suppliers accounting for 46.4% of the total, while biomass CDR, ocean CDR, and direct air capture are less common globally than in the US.

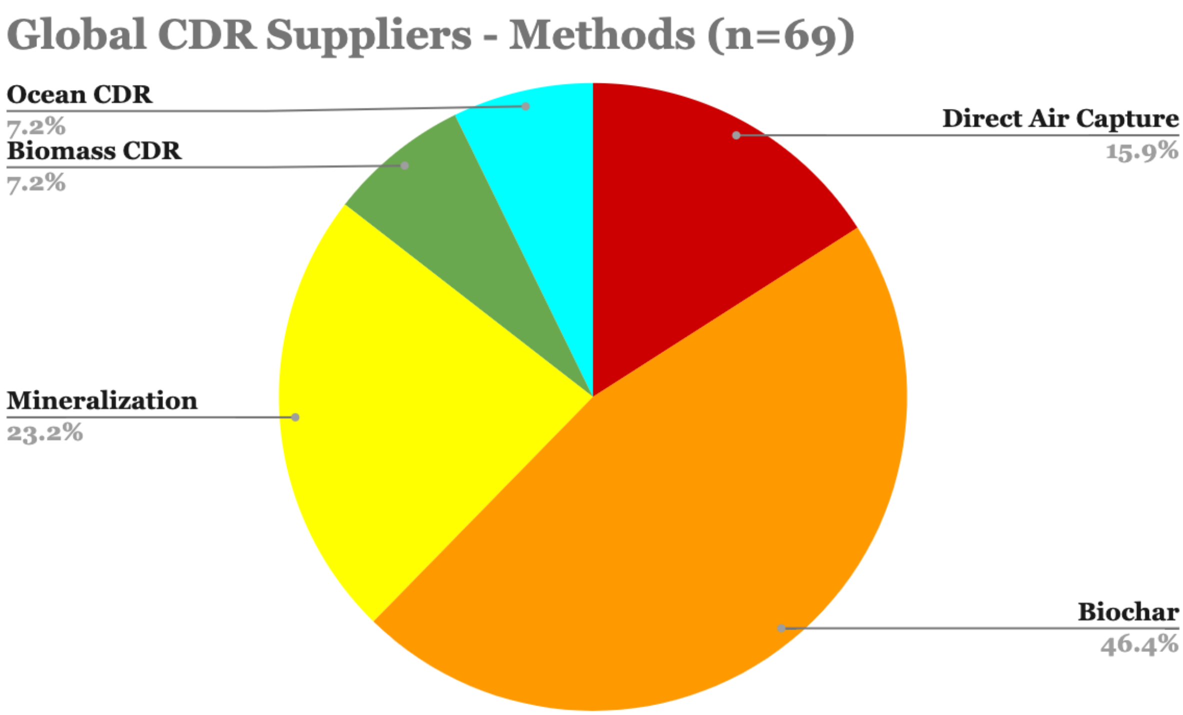

Figure 2. Global CDR Suppliers - Methods

[15] Data on global CDR suppliers (name, location, method, tons sold and tons delivered) can be found in **Appendix A**.
[16] The other 40 suppliers are located in the following countries: Canada (6), Australia (5), Germany (5), United Kingdom (5), Sweden (4), Switzerland (3), France (2), Denmark (2), with Austria, Brazil, Finland, Ireland, Israel, Norway, Romania and Spain at one each.

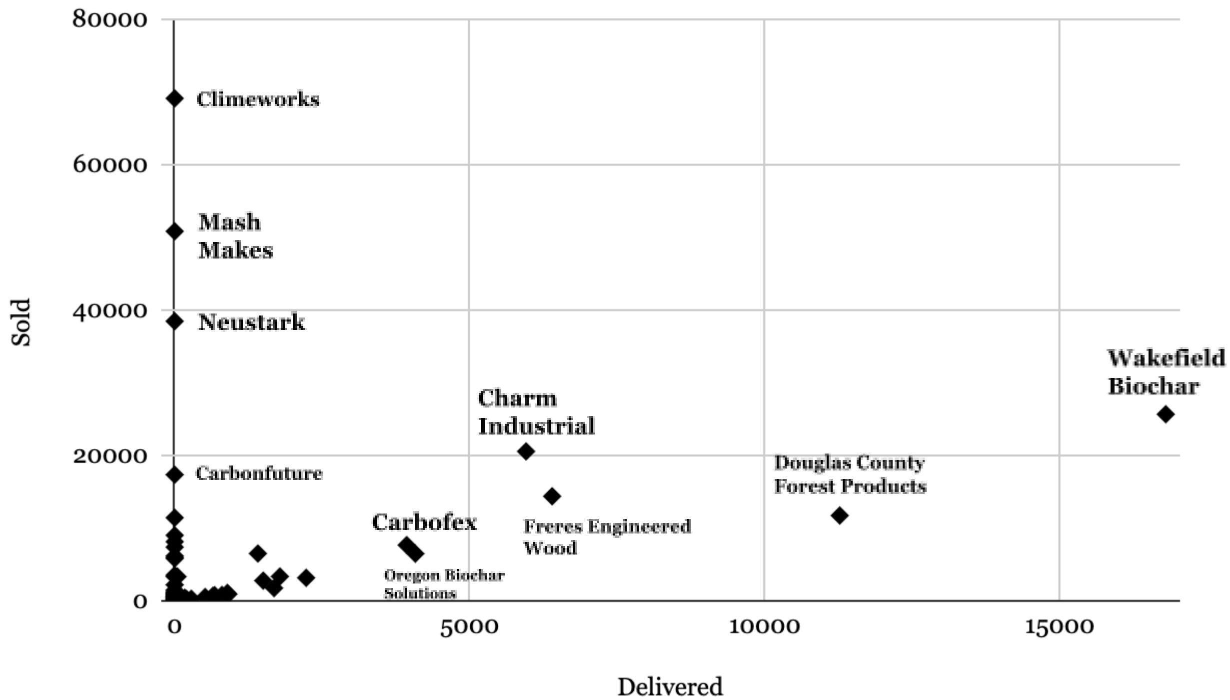

Figure 3. Global CDR Supplier Hype Index

69 CDR suppliers have sold at least one ton of carbon dioxide removal, but how much have they actually delivered? In other words, how much of these removal transactions remain promissory hype, and how much CO_2 has been biophysically removed from the atmosphere? Using data from *cdr.fyi*, I plotted these two variables – tons sold and tons delivered – against one another to create something called a Hype Index (**Figure 3**).[17] The Hype Index allows us to visually distinguish between the CDR suppliers that have high delivery totals from those who merely have high sales totals. Switzerland's Climeworks, for example, has sold more than 69,000 tons of carbon dioxide removal but as of writing has not confirmed the deliveries of any specific purchases.[18] Denmark's Mash Makes and Germany's Neustark and Carbonfuture sit in similar positions. US-based biochar suppliers dominate the right side of the index, with Wakefield Biochar, Douglas County Forest Products, Freres Engineered Wood, and Oregon Biochar

[17] I borrowed the idea of the hype index from the *cdr.fyi* creators' 2022 year in review summary (CDR.fyi 2022); my data is accurate through 26 March 2023.
[18] This observation appears likely to change soon, as Climeworks publicly announced it had successfully removed CO_2 (with independent verification) in January 2023 (Calma 2023). The point here is not to say that Climeworks is all bark and no bite, but instead to highlight the fact that Climeworks and other suppliers have made significantly more sales than deliveries. That the Climeworks announcement was news at all is illustrative of this difference.

Solutions all clocking significant delivery totals. US biomass CDR supplier Charm Industrial and Finnish biochar supplier Carbofex round out the major CDR deliverers. Overall, the total proportion of global CDR deliveries to sales is somewhere around 8-9% as of March 2023.

It is worth pausing here to meditate on the evident difference between tons sold and delivered in the carbon dioxide removal industry. At this stage, most suppliers (57 of 84) have delivered zero tons of carbon dioxide removal. Even if we bracket out the suppliers who have also sold zero tons – a sympathetic reading might suggest these suppliers will soon be emerging from their R&D phase – a majority (42 of 69) remains situated on the vertical axis of the Hype Index.[19] They have sold carbon dioxide removal promises but have yet to make any biophysical modifications to the atmosphere; they are, at this stage, much hype and little substance. It is this observation – that the CDR industry is more hype than substance[20] – that often provides evidence for accusations of mitigation deterrence and similar critical viewpoints among social scientists and climate professionals (Carton 2019; McLaren & Markusson 2020; Thanki 2023). I concur with these critical assessments, and find their perspectives convincing as far as they go; if CDR remained wholly promissory and minimally material, then these viewpoints would be sufficient to denounce its existence in this conjuncture. However, carbon dioxide removal has begun to move beyond the merely promissory. In section 2d I will outline recent CDR developments in US legislation and policy as a first illustration of carbon dioxide removal's growing materiality before moving into my exploration of the US carbon dioxide removal industry proper.

3d. CDR and the US Government

In July 2022, the US Department of Energy held its inaugural Carbon Negative Shot Summit – a virtual coming together of the top minds across industry, academia, government, labor, and environmental NGOs to collaborate toward "deployment of viable, just, and sustainable carbon dioxide removal in the United States" (DOE 2022). Dr. Jennifer Wilcox chaired the Summit and opened with a jubilant proclamation that the climate provisions in the

[19] Perhaps the greatest existing example of hype is 1PointFive. A joint DAC venture created by US-based Occidental Petroleum and Canada-based Carbon Engineering, 1PointFive is listed in *cdr.fyi* as having sold 400,000 tons (all purchased by Airbus in March 2022) but still having delivered zero tons more than a year later. I have left 1PointFive off the Hype Index to avoid skewing the data, and to better illustrate that 1PointFive *is not an outlier* when it comes to carbon dioxide removal hype.

[20] One might consider this claim too harsh – it is difficult, after all, to be a CDR startup – but I would counter that I am actually being generous by taking these suppliers' delivery totals as truth. There exists no independent verification body to judge such practices, and so 8-9% may very well be giving the industry too much credit.

recently passed Infrastructure Investment and Jobs Act (hereafter, IIJA)[21] were "the largest example of government support for carbon dioxide removal technology that the world has ever seen" (DOE 2022). Senator Sheldon Whitehouse (D-RI) called carbon dioxide removal "absolutely essential" to successful US climate policy, "an absolutely vital portfolio piece" (DOE 2022). Congressman Seth Peters (D-CA) admonished the attendees to remember the importance of "robust bipartisanship" before Ken Wagner, a Republican state official in Oklahoma, told the Summit that he sees carbon dioxide removal "both as an environmental driver and an opportunity to develop industries" (DOE 2022). Secretary of Energy Jennifer Granholm rounded out the keynote speakers with a call to avoid alienating American industry – we "cannot live", she claimed, without industries like cement, aviation, agriculture, and the like. Industry must be brought on board because "this is an all-hands on deck" task ahead. "Carbon removal is finally having its moment," the Secretary concluded (DOE 2022).

3di. CDR in US National Strategy

Carbon dioxide removal funding in the United States is quite new. Government allocation only scaled to the tens of millions in 2020 (Deich 2021), but growth is occurring exponentially. In the fiscal year 2022, funding passed the billion dollar per year mark (Suarez 2022). The seismic shift happened with the passage of the IIJA in late 2021. The text of that legislation plainly states what must occur: "carbon removal and storage technologies, including direct air capture, must be deployed at large-scale in the coming decades to remove CO_2 directly from the atmosphere" (IIJA 2021 p. 558) so as to counteract the effects of climate change. Why carbon dioxide removal to accomplish this effect? The IIJA is again rather upfront: "large-scale deployment of carbon capture, removal, utilization, transport, and storage: (A) is critical for achieving mid-century climate goals; and (B) will drive regional economic development, technological innovation, and high-wage employment" (IIJA 2021 p. 558). Given this framing of innovation and employment, it may come as little surprise that CDR is largely a bipartisan issue at this stage, with Republican House Speaker Kevin McCarthy, for example, leading the charge to open a DAC Hub in his home district (Hiar 2023).

[21] This legislation is known colloquially in US contexts as the 'Bipartisan Infrastructure Law," in recognition of the compromises made to get (some) Republicans onboard.

Shortly after inauguration, in November 2021, the Biden Administration published a new climate-strategic document and submitted it to the UNFCCC. Officially co-authored by the US's first official Climate Advisor, Gina McCarthy, and Special Presidential Envoy for Climate John Kerry, *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* (hereafter, LTS) (2021) lays out the post-Trump US climate goals: halving emissions by 2030; achieving net-zero emissions across the US by 2050; and producing "net-negative emissions" every year in the latter half of the century. Concurring with the IPCC's magisterial synthesis of climate science – "the science is real" (Biden 2021) – and heeding the imperative to limit warming below 1.5ºC, the LTS aims "to prevent unacceptable climate change impacts and risks." (US Government 2021 p. 1). Wildfires, superstorms, flooding, extreme heat and other events are already impacting people, ecosystems, and economies even at 1.0C of warming; the 2020s are thus "the decisive decade" for reducing emissions and avoiding even more acute climate impacts (US Government 2021 p. 13). Achieving net-zero emissions by 2050 need not be a rearguard tactic, however; at least according to US national strategy.

It could instead be a spur for doing much of what is currently done, but in a greener manner. The ecological crisis itself "presents vast opportunities" for a different ("better") kind of economic growth, one that will "create millions of good paying jobs" while "clean[ing] our waters and air, and ensur[ing] all Americans can live healthier, safer, stronger lives." (US Government 2021 p. 1). The transition provides the impetus for manufacturing "crucial technologies like batteries, electric vehicles, and heat pumps" while taking advantage of a "well-trained workforce" and "a unique endowment of natural resources." (US Government 2021 p. 54). Crisis and opportunity read like synonyms in this formulation. It is worth briefly pausing here to consider that the United States, a nation-state with a singularly devastating historical contribution to atmospheric CO_2 concentrations and still a major home to fossil capital in 2023, has articulated a state strategy not only addressing the ecological crisis, but also managing to see "vast opportunities" on the horizon. The complete reversal from Bush- and Trump-era denialism, and marked ambition in comparison to Obama's climate agenda, is jarring; perhaps Adrienne Buller is right to claim the end of the age of climate denial (Buller 2022). What, then, are the US's long term interests as the LTS sees them?

Achieving net-zero emissions will have four main benefits for the United States. First, retiring fossil plants (thus reducing emissions and air pollution) will have positive impacts on public health, avoiding up to 300,000 premature deaths through 2050. It will also lessen the pollution of ecosystems, which the LTS chooses to value at between $1-3 trillion through mid-century. Second, the investments necessary for the transition to a greener economy will develop US industries, enhance international competitiveness, and propel sustained economic growth; echoing Green New Deal rhetoric, the LTS implores the US to "lead" with a green economy. Third, "the US Department of Defense recognizes climate change as a vital, globally destabilizing national security threat" so climate action will help ensure the global stability within which to lead. And finally, the LTS views infrastructure improvements and transit-oriented development as not only amenable to reducing emissions, but also more thoroughly connecting the States and improving "quality of life." (US Government 2021 p. 5, 50-54).

How does the US plan on arriving at these goals? Through an elegant, five-pronged approach: decarbonize electricity, electrify end-uses, substitute hydrogen and clean fuels for fossil fuels, reduce methane and other non-CO_2 emissions, and deploy large-scale carbon dioxide removal. The US National Climate Strategy (NCS), a "companion" text mentioned over 20 times in the LTS and supposed to outline immediate policies and actions in detail, has yet to be released.[22] So, necessarily remaining at somewhat of a distance: by 2050, the LTS foresees 70% (4.5 $GtCO_2$) of annual emissions reductions coming from transitioning (decarbonizing) the energy sector (including fossil fuels with carbon capture and storage (CCS)); approximately 1 $GtCO_2e$ of reductions through "addressing" non-CO_2 gasses; and between 1 and 1.8 $GtCO_2$ from large-scale CDR (USG 2021 p. 6-7).

3dii. US Government CDR Initiatives

To materialize large-scale CDR, the US federal government's approach has been wide-reaching and ambitious; in this section I will provide a succinct tour of some of these initiatives. On an unusually warm November day in 2021, US Energy Secretary Jennifer Granholm took the stage at COP26 in Glasgow to announce the US Government's "first major effort in carbon dioxide removal": the Carbon Negative Shot (Plumer 2021; Energy Earthshots 2021). The then-latest Department of Energy (DOE) initiative, modeled after a similar

[22] The NCS was expected to be unveiled at COP26 in Glasgow but the Administration "stopped talking about it" after Biden's Build Back Better bill failed in late 2021. Gina McCarthy was charged with leading the NCS; after her September 2022 departure its fate remains unclear (Chemnick 2022).

Obama-era program to lower the cost of solar energy ("SunShot"), is intended to "spur innovation" and "position US enterprises as leaders" (Energy Earthshots 2021) in carbon dioxide removal. DOE is aiming to lower the cost of removing a metric ton of CO_2 to below $100, including both capture and storage, in less than a decade.[23] To do so entails directing government-wide research efforts toward low-cost solutions, funding pilot demonstration projects, and developing common and transparent standards with which to measure removal efficacy (Energy Earthshots 2021; Plumer 2021). The Carbon Negative Shot lays out a series of "performance elements" that define the worthy technologies meant to be spurred by the initiative: full life-cycle accounting of carbon emissions to ensure true carbon negativity; high-quality and durable storage on the magnitude of one hundred years or more; and ability to be operational at the gigaton scale. Not wanting to pick a single winner prematurely, the Shot "requires that multiple CDR approaches" be developed at scale and lists six approaches that it is especially interested in: direct air capture (DAC); soil carbon sequestration; biomass carbon removal and storage (BiCRS); mineralization; ocean CDR; and afforestation/reforestation (Energy Earthshots 2021 p. 1).[24]

While the Carbon Negative Shot was designed to provide an incentive for carbon dioxide removal technologies themselves to become cheaper and more efficient, further legislation is addressing carbon dioxide removal at other levels. The Inflation Reduction Act (IRA), a massive 750-page legislative omnibus hailed by some as "the biggest federal climate deal in history" and scorned by others as "a legislative ransom note written by the fossil fuel industry" was signed into law in August 2022 (Carbon180 2022; Marcetic 2022). Though packed with a wide array of provisions, climate-related and not, most interesting for carbon dioxide removal in the IRA is the tax code's remarkable reform of 45Q. 45Q is shorthand for the tax subsidy given by the US Government to qualifying entities that capture and/or sequester CO_2. Before the IRA, the vast majority of 45Q claims were made by oil companies for the purposes of enhanced oil recovery (or EOR), a process wherein CO_2 is injected into oil wells in order to drive more black gold to the surface. 45Q was "an oil production subsidy" masquerading as a climate change solution , a climate joke with only fossil capital laughing (Harvey & House 2022). But the IRA has changed

[23] Cost estimates per ton vary, especially across CDR methods. Biochar is cheapest (around $100/ton) while DAC struggles to get below $500/ton.
[24] Remarkably, the Carbon Negative Shot policy guidelines leave aside biochar – the single most prominent CDR method in the US. More on this in the Discussion.

the face of 45Q. While its role in subsidizing EOR has not changed, 45Q has expanded the carbon dioxide removal subsidy potential. Most significant is the raise in payouts: what used to be $35 and $50 credits per ton (for carbon utilization and carbon storage respectively) have surged to $130 and $180 per ton, completely reorienting the calculus for carbon dioxide removal (Carbon180 2022; De La Garza 2022). This surge has been accompanied by a series of secondary reforms in the IRA: the minimum removal quotas have been lowered to allow small operations to make claims; cash payouts ("direct compensation") have replaced tax equity deductions, increasing the liquidity of the credit; and the commence construction deadline has been extended from 2026 to 2033, allowing new projects ample time to take advantage of the changes. As a result, a potential US carbon dioxide removal industry explosion may be in the offing. In the words of one carbon professional, the IRA has inaugurated "the most generous subsidy for permanent carbon removal in the world" (The Carbon Curve 2022).

As an example, take "direct compensation," a modification of the means by which CDR companies come to pocket government subsidies. On the surface a mere cosmetic difference, in reality "direct compensation" is a substantial reform that alters the US's longstanding approach to the matter. Under the old tax equity framework, claimants were "for varying reasons typically unable to use tax credits themselves. Rather, they [were] compelled to 'sell' project tax breaks to third-party investors in return for upfront capital invested, diverting significant shares of intended subsidies and imposing additional costs" (Knuth 2021, p. 4). In other words, small startups working from tiny offices and with minimal cash flow needed money up front, but the subsidy would only come as a tax break on next year's return. A year is a long time in a startup's life, and such a delay entails substantial risk. Third party-investors would thus step in to cut deals, giving startups the capital up front in exchange for the tax subsidy later plus a premium. Failing to secure a deal with such a third-party investor, usually a major US financial institution, often meant that tax credits became unusable or the project failed to proceed at all. Direct compensation marks a move in CDR policymaking away from enabling institutional rent seeking, and toward a more effective subsidization of the CDR industry.

At least one major US carbon dioxide removal enterprise acknowledges the driving force of recent government CDR initiatives. Project Bison, a modular DAC plant in the planning stages for deployment in Wyoming by Los Angeles-based CarbonCapture Inc., aims to capture 5 Mt CO_2 per year by 2030 (CarbonCapture 2022). This makes Project Bison the largest announced DAC plant in the world to date, and by far the biggest with the stated goal of long-term storage.[25] CarbonCapture utilizes a modular technology process, allowing them to manufacture in one place, ship to a site, and then assemble the parts – “kind of like a Lego system” but with shipping container-like machines instead of plastic bricks (Corless, quoted in Calma 2022). They expect DAC costs to decline as technology advances (their innovation focus is in materials science and sorbent production) and for demand to grow as companies and governments seek to “fulfill their net-zero pledges with high-quality carbon credits” (Calma 2022; CarbonCapture 2022). CEO Adrian Corless, formerly of Carbon Engineering before leaving in protest against that organization’s partnership with US fossil giant Occidental Petroleum, said the IRA was “hugely impactful” on his new company’s decision to launch Project Bison. The IRA’s enhanced tax credits for 45Q provided “an acceleration. It certainly had us really rethink the scale of the project, and how quickly we would scale this project” (Corless, quoted in Calma 2022). In one interview, Corless identified the four 45Q reforms discussed above – funding, quotas, cash payouts, and timing – as “catalysts” for changing the fundamental economics of US carbon dioxide removal (The Carbon Curve 2022). The newly catalyzed CDR environment allows CarbonCapture “to think about what happens over the next ten years as being a business, rather than as a project or a subsidized project” (The Carbon Curve 2022).

A final CDR initiative in the US bears mention: the Regional Direct Air Capture Hubs program (hereafter, “DAC Hubs”). Legislated as part of IIJA, DAC Hubs provides \$3.5 billion in federal funding over five years to establish four regional carbon dioxide removal hubs in the United States. A hub is defined as “a network of direct air capture projects, potential carbon dioxide utilization off-takers, connective carbon dioxide transport infrastructure, subsurface resources, and sequestration infrastructure” clustered around a region like a city or a geographical landmark (IIJA 2021 p. 575). Regions with heavy existing concentrations of fossil infrastructure and workers are preferred “to help seed a transition from a fossil fuel workforce to a carbon removal one” (Deich 2021; IIJA 2021 p. 576). To be eligible, a hub must have the capacity to capture at least 1 Mt CO_2 annually upon completion, with the ability to store CO_2 permanently in geologic formations and/or convert the CO_2 to products or commodities. The

[25] The next largest, a 1 MtCO_2/year DAC plant in West Texas under construction by Occidental Petroleum and Carbon Engineering, will use a significant portion of the captured carbon for EOR (cf. Valle 2022). Occidental also noted and celebrated the updated 45Q: “the Inflation Reduction Act’s increased incentives will further accelerate DAC deployment as a solution to help achieve net zero” and expanded its DAC construction plans from 70 to 100 facilities by 2035 (Occidental Petroleum 2022; Ramkumar 2023).

methods stated to be *eligible* for funding under the multibillion dollar program are DAC, BiCRS, mineralization, and ocean CDR (Holness & Jacobson 2022).[26] Despite enhanced oil recovery initially being declared *ineligible*, a group of lawmakers led by Joe Manchin (D-WV) reversed that decision in December 2022 (Axelrod 2022). How much of the $3.5 billion goes toward subsidizing fossil capital or towards building carbon dioxide removal at scale remains to be seen.

The nodal office at the core of federal carbon dioxide removal is the Office of Fossil Energy and Carbon Management (FECM), housed in the Department of Energy. FECM's mission is "to minimize the environmental impacts of fossil fuels while working towards net-zero emissions" (FECM 2023). The rhetorical line walked in this statement – aiming to minimize the *impacts* of fossil fuels, not the combustion of the fuels themselves – is emblematic of the US's green capitalist approach to the carbon problem. The leader of FECM reports to the Under Secretary for Science and Innovation in the DOE, a minor bureaucratic detail that speaks to how the office understands itself: as an innovative scientific organization tinkering with carbon policy and tech. FECM's mission to minimize fossil impacts whilst avoiding upsetting the oil-soaked status quo leads it rather neatly toward negative emissions and carbon dioxide removal, and indeed this is where the Carbon Negative Shot, DAC Hubs, and much of the US Government's CDR research is located. The office's peculiar name is a legacy of its prior stimulative mission – formerly as the "Office of Fossil Energy" with a mandate "to increase the production of fossil fuels domestically" – that has since morphed to one of bureaucratic carbon management, or in Dr. Jennifer Wilcox's words, "putting guardrails in place" to contain the carbon problem (Wilcox 2022).[27] A former chief of staff articulated FECM's mission as "dedicated to decoupling the idea of carbon dioxide removal from the fossil fuel industry" (Funes 2021). In sum, this office is full of historical baggage and rife with contradiction. Holly Buck, perhaps the leading social scientist working on carbon dioxide removal, took a position at FECM in April 2022; Noah Deich, co-founder of Carbon180, joined FECM a few months later as a Deputy Assistant Secretary (Deich 2022); the budget and high-powered appointments at FECM seem, at the time of writing, to grow monthly.

In concluding this schematic tour of US CDR legislation and policy in early 2023, we might present a single sentence gloss as follows: carbon dioxide removal is becoming a

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[26] Once again, I note in passing the absence of biochar.
[27] Wilcox led FECM as Acting Assistant Secretary until May 2022; she presently serves as Principal Deputy Assistant Secretary, or second in command.

respectable, state-facilitated climate solution. While still only comprising a fraction of total US government spending, CDR in the United States is one avenue by which the Biden Administration intends to achieve its emissions goals (net-zero by 2050). Tax dollars are already being allocated and spent to catalyze the scale-up of the CDR industry, with more likely to follow. In moving away from establishing background and toward this thesis's original contributions, I wish to consider how exactly this growing industry ticks.

4. Theoretical Framework and Literature Review

The capitalist class does not have a unified position on the climate emergency.

Kevin Young, "Fossil Fuels, the Ruling Class, and Prospects for the Climate Movement" (2022) p. 142

Green [capitalism] promises a miracle: to organize a revolutionary transformation without revolution – we can just do what we already do, but 'green', and we will be richer, more equal, and good stewards of Spaceship Earth.

Geoff Mann and Joel Wainwright, Climate Leviathan (2018) p. 121

4a. Marxist Approach

I will investigate the US CDR industry with the assistance of a vibrant and multivalent theoretical approach – namely, Marxism, and especially its ecological strands. Scholars of ecological Marxism emphasize the many ways that capitalist production brings about ecological degradation, and seek to highlight these links in service to a more ecologically sustainable, just, and post-capitalist world (O'Connor 1998; Foster 2000; Malm 2016; 2018; Saito 2017; 2023; Mann & Wainwright 2018; Ajl 2021; Surprise & Sapinski 2022; Heron & Dean 2022; Fraser 2022). These studies' many theoretical and conceptual contributions – particularly those laid out in Malm's (2016) and Mann & Wainwright's (2018) studies – permeate my thinking throughout the thesis. For now, however, I will succinctly highlight three important theoretical touchstones for grounding my discussion of US carbon dioxide removal.

The first theoretical touchstone is the concept of the *ecological background conditions of possibility* for capitalism. Theorized by Nancy Fraser over the past decade (2014; 2021; 2022), capitalism's background conditions of possibility refer to the dimensions of capitalist society – social reproduction, political legitimacy, racialized expropriation, and the Earth's ecology – that are simultaneously outside the economic sphere and co-constitutive of it. Capitalism, in other words, cannot function without these four core dimensions; at the same time, however, these dimensions cannot be reduced to their role in the (re)production of capitalist society – they also have their own non-capitalist logics. Fraser's contribution extends Marx's analysis of capitalist society: whereas Marx, contra the bourgeois economists, ventured into the "hidden abode of production" to understand the creation of surplus value, Fraser looks "behind the hidden abode" to uncover how capitalist production is possible at all (2014). Understanding the four background conditions as possessing a tension between capitalist and non-capitalist logics opens up an understanding of ecological degradation firmly rooted in Marxist analysis, without supposing ecology as entirely *determined by* or entirely *separate* from capitalist society (Malm 2018). And in Fraser's latest diagnosis she is confident in identifying an inherent tendency for capitalism to undermine or "cannibalize" its background conditions of possibility: "Like the ouroboros that eats its own tail, capitalist society is primed to devour its own substance," pushing its background conditions of possibility into crisis (2022 p. 15). Ecological crisis is not *incidentally* capitalist in character; instead, our ecological crisis is a capitalist crisis at a *structural* level, undermining capitalist society's ecological conditions of possibility.

A second theoretical touchstone is the notion of *climate capital*, or the fraction of the capitalist class "whose interests align with climate action" (Surprise & Sapinski 2022 p. 3). This class fraction, its theorizers posit, is distinct from other capitalist class fractions (e.g., fossil capital) in that it seeks to internalize, manage, and profit from ecological crises without fundamentally altering capitalist growth dynamics or class domination (Sapinski 2015; 2016; Newell & Paterson 2011; Carroll 2019). In other words, rather than a naked denial of ecological crisis a la fossil capital (Orekes & Conway 2010), climate capital "listens to the science" and moves to manage the crisis on capital's terms. The question of composition – who makes up climate capital? – is an open question in many of these studies, but Surprise & Sapinski (2022) muster the characterization "sectors more aligned with technology capital and inclined to climate action," linking tech with climate capital (p. 4). They add finance as a frequent mediator of climate capital alongside tech, while noting that finance also remains imbricated amongst fossil capital (Ibid.). Renewable energy is also an obvious (if still relatively small) participant, and I contend that we ought to add the carbon dioxide removal industry to our conceptions of climate capital. However, climate capital remains undertheorized as a distinct class fraction, perhaps because it tries to encapsulate under its heading sectors (e.g. tech and finance) whose accumulation strategies are only incidentally pro-climate.[28] Climate capital is thus conceptually fuzzier than Surprise & Sapinski (2022) and others presuppose, and ought not to be used to

[28] Indeed, even some companies or sectors historically associated with *fossil capital* (e.g. Shell) could be marginally considered climate capital under this definition to the extent that they engage in CO_2-abatement activities like CCS. The goal of these entities remains value creation (not solving the ecological crisis) but pro-climate activities like CCS are not always bad for business.

distinguish between entire economic sectors as they do. Rather than discard the notion of climate capital altogether, however, I submit that we ought to step back from looking for climate capital among essentially distinct ontological fractions so we can use the "climate capital" concept to name a certain orientation to the ecological crisis – that of management, rather than denial. In other words, climate capital ought to name a class fraction with a self-identified interest in climate action, not a sector of the economy. With this reworking, climate capital ultimately remains useful for this thesis in that it provides language to identify a real trend among the capitalist class: that of some capitals offering material support for (rather than denial of) the management of the planetary ecological crisis.. For whatever complex of reasons, climate capitals are those capitals that see ecological crisis management as in their interest. To the degree that climate capital's management strategy becomes the hegemonic one, we might speak of a project of "green capitalism."

The final theoretical touchstone is that of *green capitalism*. Green capitalism names the hegemonic strategy to manage the crisis in capitalism's ecological background conditions of possibility. In her excellent study on the subject, Adrienne Buller (2022) turns a critical eye toward understanding the logic of why capital would care to manage the crisis. She convincingly highlights the fixation on "climate risk" in the financial industry when she quotes Larry Fink, CEO of mammoth investment firm BlackRock, asserting in a recent annual public letter that "climate risk is investment risk" and that attending to that risk by pushing governments toward climate action is not "woke" but a straightforward path to maintaining profits (Buller 2022 p. 90-91). Such sentiments are shared across the financial sector, the "vanguard industry of green capitalism," but are also widespread across the tech, insurance, and real estate industries (Buller 2022 p. 89; Dietz et al. 2016; Clayton et al. 2021; Bouri et al. 2022). The era of elite climate denial has concluded, Buller asserts; instead, climate risk must not only be acknowledged but actively managed to keep the wheels of capital accumulation spinning. I concur with Buller's assessments. However, we should (as Buller also emphasizes) avoid falling into the trap of conceiving of the green capitalist project as anti-fossil. There is an important distinction between being *against fossil fuels* and being *for solving the ecological crisis*; the green capitalist project advocates the latter. Surprise and Sapinski (2022) identify solar geoengineering as a green capitalist mechanism for carefully walking this line; I add carbon dioxide removal as another such mechanism. Green capitalism thus aims to manage the ecological crisis in order to stabilize capitalist society and renew the expansion of capital accumulation, not to stop burning fossil fuels or any of the other common demands of the climate movement. Mann and Wainwright's (2018) formulation of green capitalism as "green Keynesianism"[29] highlights this dimension: that (capitalist) civilization itself is at stake, that active management of the crisis is necessary, and that elites have the know-how to do so without upsetting capitalist social relations.

4b. Key Terms

In this section, I will explicate two concepts – the real subsumption of nature and the spatiotemporal fix – in order to further situate my understanding of the US carbon dioxide removal industry moving forward. These concepts will be deployed in service of answering my second research question – What might be the logic underlying the development of the US CDR industry? – in the Discussion.

4bi. The Real Subsumption of Nature

In order to think through the politics of carbon dioxide removal, I first take up the Marxist concept of the "real subsumption of nature." Subsumption, for Marx, is a category meant to capture what capitalists actually *do* with the power granted to them in a capitalist system; that is, it is intended to illuminate what happens to a process once capital grasps it (Mau 2023 p. 233-234). In Marx's original formulation, subsumption refers exclusively to the *labor process*, when production is subsumed under the logic of capital. Subsumption is *formal* when capital takes up a labor process whose technical and organizational structure is non- or pre-capitalist without fundamentally altering it; formal subsumption implies only a change in property relations and no further restructuring. Subsumption becomes *real*, however, when capital "radically remolds" the "social and technological conditions of the labour process" (Marx, cited in Mau 2023 p. 235). Under the *real subsumption of labor*, capital shatters existing labor processes just to stitch them back together in a form more beneficial for the valorization of value.

Although Marx limited his discussion of subsumption to the labor process, it has been fruitfully extended in a handful of directions, among them being the subsumption of *nature* (Burkett 1999; Boyd et al. 2001; Malm 2016; 2018). Key to this formulation is the "ontological

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[29] Despite finding Mann and Wainwright's (2018) framing of "green Keynesianism" extremely illuminating, I stick to the "green capitalism" terminology so as to avoid the historical baggage associated with the postwar Keynesian welfare state.

priority" of labor and (the rest of) nature; labor and nature share "an ineradicable *autonomy* from capital" and are governed by logics that do not originate in capital (Malm 2018 p. 197). This ineradicable autonomy is an obstacle for capital, and consequently capitalist production is subject to a structural pressure "to iron out the bumps of nature" in Søren Mau's memorable phrase (2023 p. 254); this is *the real subsumption of nature*. "Capital cannot do without the stranger of nature," Malm notes, "so it chases it and seeks to subordinate it, integrate it into a disciplinary regime and make its most erratic impulses redundant" (Malm 2018 p. 201).

Historically, capital has always had to wrestle with the autonomy of nature in the production process, and it has succeeded in winning more than a few bouts, allowing it to attain a higher degree of relative control over nature. Andreas Malm's eminent study (2016) of the transition from water power to steam engines in the British textile industry illustrates a crucial turning point, when water power – functioning as "quasi-autonomous and immune to real subsumption" – was replaced with coal-fired steam power, an energy source more amenable to real subsumption (p 313). Coal power worked well for a while, until workers located at strategic points – mining, railways, shipping – took advantage of capital's reliance on coal to exercise their power; capital responded in taking a further step in the real subsumption of nature by shifting to *oil*, a fuel that "flowed along networks … where there is more than one possible path and the flow of energy can switch to avoid blockages or overcome breakdowns" (Mitchell 2011 p. 38; cf. Huber 2013). The notion of the "real subsumption of nature" names this process, when capital "intervenes in natural processes in order to suppress the autonomy of nature and accommodate these processes to the demands of valorization" (Mau 2023 p. 258).

How can thinking through the notion of the real subsumption of nature help us to understand the US carbon dioxide removal industry? My contention proceeds in three movements. First, as outlined in the earlier discussion of Nancy Fraser's background conditions of capitalism, I contend that high levels of atmospheric CO_2 are or soon will threaten profits via a crisis in the ecological background conditions of capitalism (Kollewe 2022; Dietz et al. 2016; Swiss Re Institute 2021; WEF 2023).[30] Second, to stabilize these ecological background conditions and ensure a productive environment for "the demands of valorization," capital, I contend, can "intervene in natural processes [in this case, the atmospheric concentrations of

[30] This is a debatable point that I could continue defending below; in the interest of space, however, I submit that further substantiation would be outside the scope of the thesis.

CO_2][31] in order to suppress the autonomy of nature" (Mau 2023 p. 258). Finally, I contend that one mechanism for intervention is through developing carbon dioxide removal technologies. We can theorize such a mechanism as *a new form for the real subsumption of nature*, this time not in the production process but *in the background conditions of capitalism*. I return to further substantiate this line of argument in the Discussion.

4bii. Spatiotemporal Fix

To further elucidate the ecological contradictions of capitalism and the efforts to resolve them, I turn to David Harvey's notion of the spatiotemporal fix. Capital, Harvey (2006) argues, has an immanent drive to reposition its internal contradictions by spatially reordering itself. In other words, capital unsettles old geographical logics and remakes new ones in order to resolve tendencies towards a crisis of overaccumulation. By locating new outlets for geographical expansion and fresh rounds of accumulation, it can temporarily "fix" these crises. The double meaning of "fix" is crucial: in addition to "solving" the crisis, the displacement and deferral of capitalist contradictions literally involves the creation of fixed capital, that is, capital physically "fixed" in space. Fixed capital can take the form of infrastructure, machinery, the built environment, etc.; the important part is that it cannot be moved without considerable cost, if at all. "Fixing" capital in this way, however, creates its own contradictions in that the fixed capital has inertia – hindering capital's mobility and risking devaluation in future crises (Harvey 2001; 2006; Carton 2019).

Ekers and Prudham (2015; 2017; 2018) build on Harvey's formulation of the spatiotemporal fix by emphasizing its ecological implications. The spatial restructuring and geographical expansion of production processes is, they argue, necessarily a socioecological process, an alteration in the human metabolic interaction with the rest of nature. The upshot is that fixed capital is always economic *and* extraeconomic – producing fresh means of value creation *and* fresh socionatures – in a process that "fuse[s] capital accumulation, socioenvironmental change, and the conditions and experiences of everyday life" (Ekers and Prudham 2018:19). What they call "socioecological fixes" thus defer crises by producing both

[31] The atmosphere has, until carbon dioxide removal, been only *formally* subsumed by capital, primarily as a sink for carbon emissions and as a stable environment for accumulation. Thus, the high levels of atmospheric CO_2 is not a result of "natural" processes in the sense of nonhuman, but instead of capitalist processes (primarily the post-Industrial Revolution burning of fossil fuels) that remained in the realm of *formal subsumption*.

space and nature in forms more amenable to accumulation. I prefer to stick with Harvey's original "spatiotemporal fix" terminology, with the understanding that it includes the socioecological dimensions highlighted by Ekers and Prudham.

What is the form of the crisis the spatiotemporal fix sets out to solve? Wim Carton holds that the ecological crisis has two related but distinct expressions: biophysical and sociopolitical (Carton 2019). Even though both are ultimately mediated by social and political processes (ecological crises do not lead to economic crises *directly*), distinguishing between the two is useful because they imply different spatiotemporal fixes in response. If the ecological crisis experienced by capital is primarily a sociopolitical threat, then the fix need only be made at the sociopolitical level and not the biophysical level. In other words, if sea level rise threatened capital, it would be forced to respond biophysically or risk losing valuable assets (one cannot argue with the sea). But if it were a sociopolitical threat that threatened capital – impending asset devaluation implemented by a powerful climate movement, for example – it need not engage directly; it could arguably be sufficient "to be *perceived* to be addressing the problem" (Carton 2019 p. 755) in order to insure against the threat of political illegitimacy. Indeed, this is the logic of much of what can be called "greenwashing" today. Ekers and Prudham (2018) remind us that it is not a matter of material versus ideological fixes – any fix is simultaneously a concrete *and* a hegemonic project – but rather *how* ecological crisis is experienced by capital *as a crisis* matters in how capital goes about fixing it.

To conclude this brief discussion of the spatiotemporal fix, I want to consider how we might begin to theorize the spatiotemporal fix in relation to carbon dioxide removal. In his study on solar geoengineering, Kevin Surprise (2018) contends that spatiotemporal fixes do not necessarily need to take place in the sphere of capitalist production, but could instead buttress what we would call the background conditions of capitalism, with Fraser (2022). He shows that while private capital is increasingly funding the research and development of solar geoengineering as a potential "safety valve" to cool the planet (or at least decrease the rate of warming), it is governments who would necessarily implement this fix because there are little to no new avenues for accumulation involved. Solar geoengineering, in other words, is not an especially profitable industry in its own right, even at planetary scale. The key here is instead the potential massive gains in existing forms of value creation that would accompany a solar geoengineering fix – reduced biophysical destruction of existing assets from climatic events as the planet cools, and reduced sociopolitical pressure to leave fossil assets stranded. Carton agrees with Surprise, and argues that the spatiotemporal fix can work "defensively" by "preventing the devaluation of *existing forms of value creation*" even as it works offensively through geographical expansion and opening new forms of accumulation (Carton 2019 p. 756). Carton proceeds to focus on the sociopolitical threat that ecological crisis poses to capital and how negative emissions provide a means to be perceived to be addressing the problem; this is, undoubtedly, the more immediate crisis for capital at the present moment. I wish to extend Carton's argument by considering how the emerging carbon dioxide removal industry presents a defensive spatiotemporal fix for the (less immediate but still very real) *biophysical* threat of climate change, providing a means of addressing the growing concentration of atmospheric CO_2 in the name of preserving existing assets and accumulation strategies from climatic destruction.

5. Methodology, Method & Positionality

5a. Methodology – Critical Realism[32]

This thesis is taken up within the epistemological tradition of critical realism. It presumes the existence of a world independent of one's knowledge about it, while simultaneously problematizing all embodied beings' ability to access that world. Ontologically, reality is stratified into three layers. The deepest layer is the real; this is the domain of (natural or social) objects with structures and causal powers that exist regardless of our understanding of them. Then there is the actual, the domain of events – this is what actually happens or occurs when the causal powers are activated. Finally, there is the empirical as the domain of experience, which is how humans experience the real and the actual (Sayer 2000; Bhaskar 2008 [1975]). Critical realism differs from other epistemological approaches – like naive realism and positivism – because of its positional and self-reflexive approach to epistemology (England 2006: 289). It theorizes knowledge and scientific truth as always intimately tied up with relations of power, thus foreclosing the possibility of accessing the ontological essence of the world unmediated (Harrison 2006: 133). Knowledge is always already embodied and situated; any claim to possess an "objective" view from nowhere is an irresponsible "god trick" (Haraway 1988: 581).

In the critical realist approach, social structures are regarded as ontologically "real" social entities with causal powers that exist as more than the sum of their parts; they are emergent. These real structures are not static, however; they are shaped by agency while simultaneously obligating, facilitating, and reordering agency in dialectical movement. In other words, social structures change through time and throughout space in both necessary and contingent ways that are not able to be fully known ahead of time. Approaching the US CDR industry in this way calls forth a reflexive accounting of how *these* structures develop *this* way in an open, nondeterministic way. It permits the taking up of *relations* – structural and conjunctural – rather than just individuals as valid units of analysis. And it necessitates signposting where alternative paths were foregone, potentially helping to shed light on courses of action in the present.

5b. Method – Social Network Analysis

A Social Network Analysis (SNA) was employed to map the connections that make up the US CDR industry. SNA is a method used in the social sciences to map actors and their social

[32] Here I build on my own previous writings from the Human Ecology master's programme (course: HEKM22).

relations, and a way to uncover underlying patterns of interactions that may not be immediately apparent (Borgatti et al. 2009). My decision to deploy an SNA follows from my methodological premises in that it attempts to map the social relations of the world "out there" from the limited and situated perspective of a researcher. I will seek to establish the validity of my truth-claims through transparency, self-reflexivity and methodical rigor instead of, e.g., appeals to a naive positivism or a strong social constructionism. The aim of this method was primarily to answer research question one: what organizations, carbon credit transactions, and investment flows constitute the US CDR industry?

Using RStudio, a programming environment for statistical computing and graphing, a novel database was created of global CDR suppliers, aggregating information on tons sold, tons delivered, location, method of CDR, and links to purchasers (See **Appendix A**). This database was used to generate a weighted network, and then exported to Excel to generate a series of tables and graphs to illustrate US CDR transactions in 2023. Next, a second database was created consisting of CDR investment links and directionality across the industry including: CDR suppliers, venture capital/incubators, philanthropy, government, corporations, NGOs, research institutes/universities, industry groups, and key CDR documents. This database was used to create a series of networks to broadly illustrate the industry, as well as to identify relevant node attributes such as out-centrality and in-centrality within the context of the network.

I began the SNA by synthesizing data from all US-based CDR suppliers who had sold at least one ton of carbon dioxide removal (through March 2023) and linked their purchasers. This data (purchasers) came primarily from *cdr.fyi*, an open-source effort to bring transparency and accounting to the global CDR industry, and were supplemented by personal verification and web searches. These data were cleaned, and the transactional relationships between CDR suppliers and buyers mapped using *igraph* in RStudio. Some purchases in *cdr.fyi* were recorded but not specified (as an example, an "Aggregate Purchase" was made for 328 tons of carbon dioxide removal from Charm Industrial in June 2022). Such aggregations were included in suppliers' totals in my dataset but excluded from network representation. Taking into account the potential for data unreliability (noted in section 2), alongside the fact that many CDR purchases are not made public anyway, I make no claims to comprehensiveness with this network. Apart from the minimally manipulated data listed in *cdr.fyi*, there have been no attempts to compose any picture of the US CDR industry; my understanding is that this is the first such attempt.

5c. Methodological Limitations, Reflections and Positionality

Some limitations of critical realism bear mentioning. In a critical realist approach where there exists an objective world “out there” that remains inaccessible in an unmediated manner, one needs some measurement of a claim’s truth-value. Everyone is situated, yes, but not everyone is equally correct about their truth-claims. For many critical realist practitioners, this problem is addressed by judging a claim’s “practical adequacy,” or the extent to which a claim “generates expectations about the world and about the results of our actions which are realized” (Sayer 2000: 43). Needless to say, “practical” knowledge does not always equal “good” knowledge; a claim could be practically true or rational within a larger system that is irrational and destructive. For whom a given claim is “practically true” and toward what aims it is so must be constantly grappled with. Another limitation, perhaps elementary, is that the self-reflexivity demanded by critical realism is easier said than done. Acknowledging my individual situatedness does not automatically absolve me of its power. The work remains ongoing.

To have confidence in the findings of a method like Social Network Analysis, it is worth considering what it *does not* do. This method does not take up personal experiences or emotions. It does not allow the subjects of its inquiry to speak directly to a reader. It does not foreground the working culture at these organizations, or the motivations that drive people working at them to do what they do. It does not engage with phenomenological first-person experiences in any way, nor does it give a sense of the discursive framing of what carbon dioxide removal is within an organization. Organizations themselves are assumed to be monolithic entities with no relevant internal differentiation. There are more qualifiers that I could provide, as all possible research methods have strengths and weaknesses, but I also want to show that an SNA can provide unique insight as a method too. An SNA allows us to clarify connections that are initially hard to see. It facilitates systems thinking, instead of overly focusing on individuals. It takes up dynamic flows instead of simply remaining with static entities. An SNA is replicable, drawing as it does on publicly accessible information, and it is transparent if one knows the researcher’s protocol and datasets (see **Appendices**). Finally, an SNA is fun to perform, engages a researcher’s logical and creative faculties, and visually communicates information in ways that land well with non-specialist audiences.

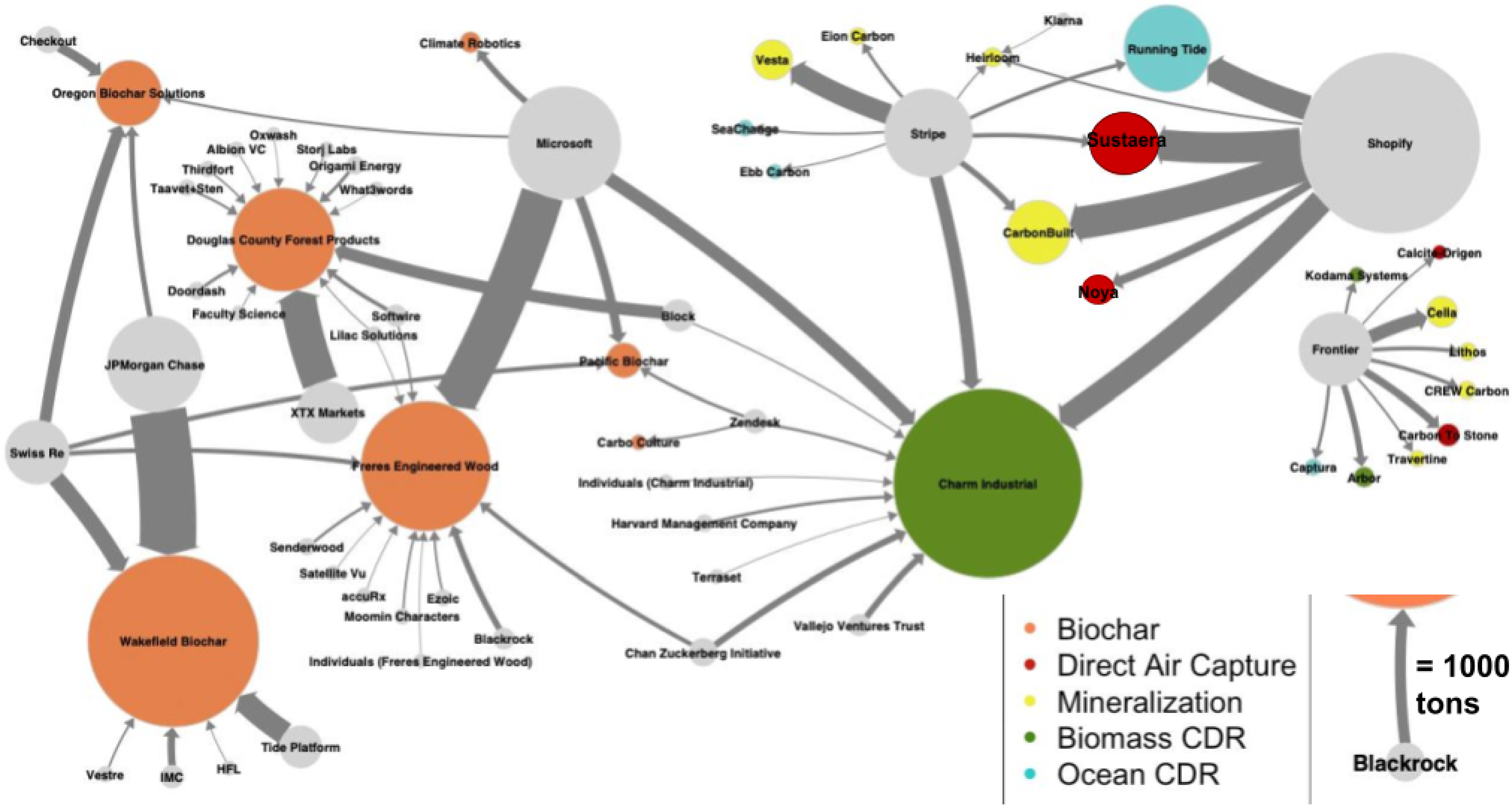
Who is this researcher behind the text? Of perhaps first importance is my position as an American researcher working as a foreign, fee-paying Master’s student at a Swedish university in Lund. That constellation of factors sets up the social environment in which this work is done, such as how much time and effort I can bring to the research (a good amount), the priority status of this endeavor in my life (quite high), and the institutional support available to me (fairly high). Secondarily, but no less important, is my many identities – as a cis man, white, middle-class, disabled, non-religious, Marxist, etc. – and all the ways that they consciously and unconsciously make up the self behind the author labeled Jacob Ferrell on the front page. The overdetermination of my overlapping identities means that I am always simultaneously speaking from each of them in some form, and you, dear reader, can note in passing the important ones that I have outlined above so as to know from where positionality claims are made.

6. Findings - Social Network Analysis

Network 1 maps US-based CDR suppliers in connection to their purchasers through March 2023. This network, what I call the "Core US CDR Network" shows only those entities that bought or sold carbon dioxide removal above a certain threshold, in this case 100 tons. In other words, all CDR suppliers shown in the network have confirmed sales of at least 100 tons, and all CDR purchasers shown have confirmed purchases of at least 100 tons. The decision to exclude transactions of less than 100 tons was motivated by a desire to communicate a clear picture of the major players, rather than a thorough summary. However, an extended network that includes *all recorded purchasers* is located in the appendix (**Appendix B**). The arrow width within the network represents purchase magnitude – the bigger the purchase (in tons), the thicker the arrow. Arrow length is incidental and was freely adjusted for overall network clarity.

Tech and finance corporations dominate US CDR purchasing as shown in **Network 1**. The seven largest buyers of carbon dioxide removal are, in order: Shopify, Microsoft, JP Morgan Chase, Stripe, Frontier, Swiss Re, and XTX Markets. Of these entities, three are major financial players (JP Morgan Chase, Swiss Re, XTX Markets), three are tech giants (Shopify, Microsoft, Stripe), and the last (Frontier) is a recently formed CDR-focused endeavor jointly launched by tech corporations Facebook-Meta, Microsoft, Shopify, and Stripe alongside US management consulting firm McKinsey & Co. In addition to their considerable transaction volumes, the tech entities also enjoy a relatively high quantity of supplier connections with Frontier (9), Stripe (9), Shopify (6), and Microsoft (5) all spreading their dollars among five or more suppliers of all method types. The financial entities, on the other hand, have fewer supplier connections, with Swiss Re at four, JP Morgan Chase at two, and XTX Markets buying all their carbon dioxide removal from a single supplier. Further, the financial entities purchase carbon exclusively from biochar suppliers; for these entities, all carbon removed comes from a handful of rural Oregon- and Georgia-based biochar companies. The tech companies, in contrast, largely avoid purchasing from biochar suppliers with Microsoft being the sole tech company to bridge the divide (four of its five suppliers utilize biochar). Indeed, the four tech entities' purchasing connections skew toward mineralization at ten connections; ocean CDR, DAC, and biomass CDR have five connections each, and biochar has only Microsoft's four.

In close connection with the purchasing imperatives of these tech and finance corporations, biomass and biochar suppliers proffer the bulk of the carbon dioxide removal



Network 1. Core US CDR Suppliers and Purchasers (>100 tons)

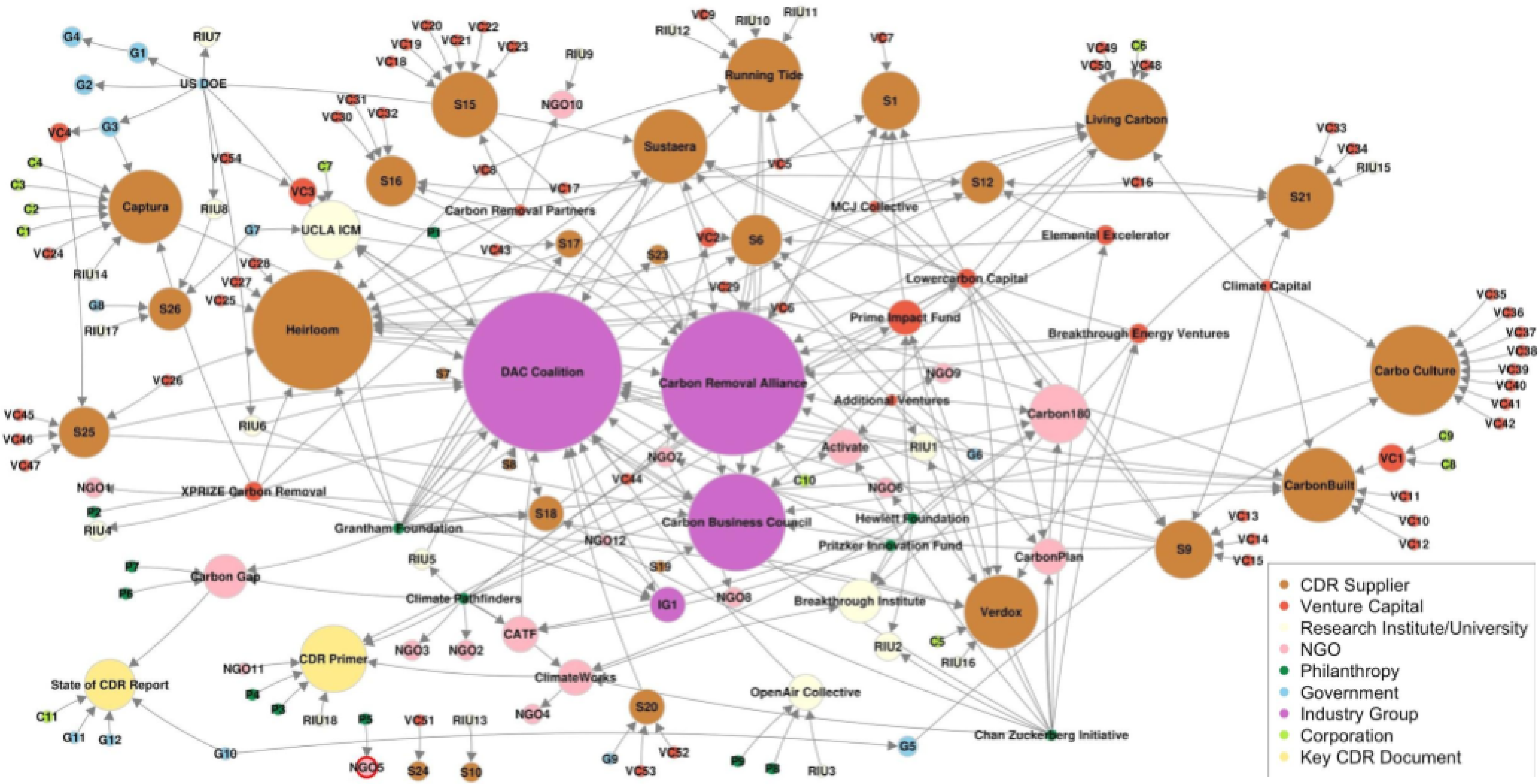
shown in **Network 1**. Charm Industrial, a Bay Area-based supplier that liquefies plant biomass before burying it deep underground, leads all suppliers in tons sold. The next three largest by volume sold – Wakefield Biochar, Freres Engineered Wood, and Douglas County Forest Products (DCFP) – employ biochar as a carbon dioxide removal method. Wakefield's expertise lies in producing soil-enhancing agricultural products for the rural southern US, with carbon dioxide removal an exciting characteristic "as a bonus" (Wakefield Biochar 2023). Freres and DCFP are sawmills and lumber yards in the Oregon countryside that only recently came into the carbon dioxide removal business. Running Tide, an ocean-CDR supplier in Portland, Maine, rounds out the top five suppliers by volume. By quantity of connections, a similar picture becomes apparent: DCFP leads (11), with Freres (10), Charm (9), and Wakefield (4) following behind; only Oregon Biochar is new to the list at four distinct buyers of at least 100 tons. In total, 28 US-based suppliers have sold at least 100 tons of carbon dioxide removal through March 2023, with the median supplier selling 1150 tons.

Network 2 maps the US-based CDR industry through March 2023, including CDR suppliers, venture capital/incubators, philanthropy, government, corporations, NGOs, research institutes/universities, industry groups, and key CDR documents. The dataset for this network was assembled through snowball Internet search, relying particularly on crunchbase.com, pitchbook.com, and the various websites of the entities themselves. All connections were double checked between the two entities, or, at a minimum, verified by a trusted third party source like a newspaper. These data are original to this project, and can be found in the appendix in spreadsheet format (see **Appendix E**). Arrows in **Network 2** point in the direction of the flow of funds. Unlike in **Network 1,** where a two-way transaction occurred between CDR buyers and sellers (one entity paid money and received CDR credits, the other removed carbon and received money), transactions in this network are unidirectional. In other words, the recipient offers no immediate return; instead, they take the funds and do with them what they will. This does not necessarily mean that the originator of the funds has no input whatsoever, merely that the transaction shown is not characterized by reciprocity. The implication is that these connections are of a more overtly political nature, and will be examined as such.

In **Network 2**, node size was coded to represent the degree of in-centrality, or quantity of arrows pointing *toward the node*. Since arrows *toward the node* show investment flows *into an entity*, we might intuitively suspect **Network 2** to make CDR suppliers and other sponges of investment like NGOs and Industry Groups appear large. This is indeed the case, as we will see below. Unlike the previous network, arrow width in this network is *not* weighted; this would have added another layer of complexity to a network that is already teeming with visual information. In any case, data on exact dollar amounts is extremely hard to come by without extensive industry access, and even then no single actor would know the magnitude of all the relevant flows. Arrow length is again incidental and was freely adjusted with network clarity in mind.

Network 2 shows that funding within the US CDR industry generally flows into industry groups, CDR suppliers, and NGOs.[33] Two industry groups in particular, the DAC Coalition and the Carbon Removal Alliance, are on the receiving end of a diverse array of CDR-industry flows. The former was founded in 2022 as a lobbying arm and collaboration hub for direct air capture, while the latter came into being in early 2023 with a similar function inclusive of all CDR methods. Both organizations count CDR suppliers, venture capital funds, and corporations as members, and despite their novelty, these groups seem poised to occupy important roles in the development of the industry. Carbon Business Council is another active industry group that formed in 2022; it counts more than 80 members across the CDR and CCS landscapes, and has a greater carbon utilization-slanted focus than the other organizations. After these industry groups, CDR suppliers possess high levels of in-centrality with Heirloom (14), Carbo Culture (10), and Living Carbon (9) inhabiting the top three spots and Verdox, Captura, Sustaera, CarbonBuilt, and Running Tide tied for fourth sitting at eight in-connections each. In **Network 2**, the large biochar suppliers by volume are nowhere to be found (having little to no outside investors); indeed, the three suppliers with the most investor in-connections have barely sold any carbon dioxide removal and are tiny in **Network 1**. In fact, Living Carbon, shown in **Network 2** with nine distinct investors, has yet to sell a single ton of carbon dioxide removal. The main carbon dioxide removal NGOs are, in order of in-centrality: Carbon180 (6), Carbon Gap (4), CarbonPlan (3), ClimateWorks (3), Clean Air Task Force (CATF) (3), and Activate (3). Carbon180 plays an especially central industry role as “a new breed of climate NGO” that orients itself around carbon dioxide removal, with white papers that are widely read and staff that have gone on to

[33] Network 2 shows names for some nodes and codes for others; for a version of Network 2 that shows **names for all nodes**, see **Appendix C**. For a code key, see **Appendix E**.



Network 2. US CDR Investor Network – In-centrality

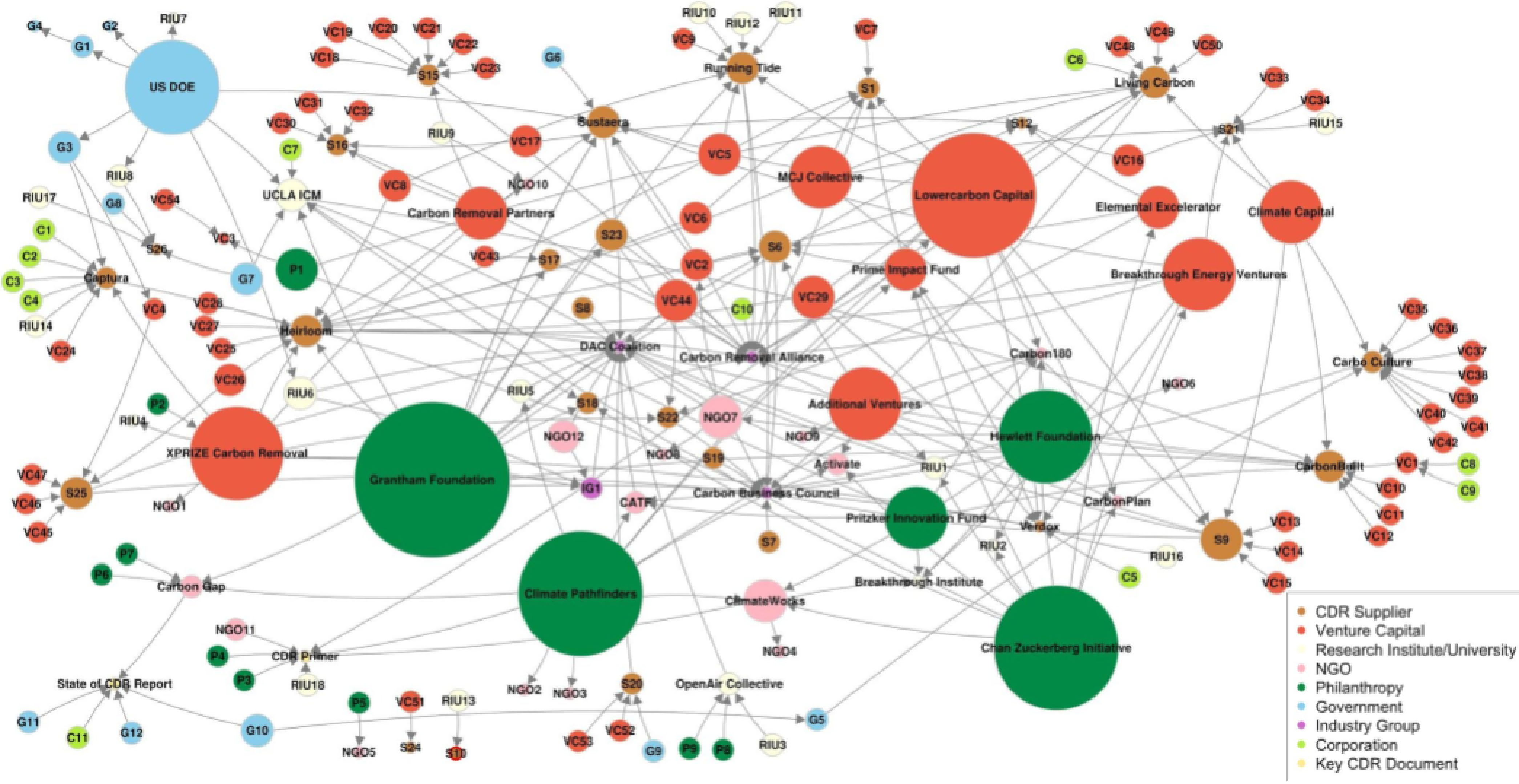
take prominent roles at Carbon Removal Alliance and DOE's Office of Fossil Energy & Carbon Management.

CDR-focused research institutes/universities and key CDR documents are also recipients of a relatively high degree of industry funding as shown in **Network 2**. UCLA's Institute for Carbon Management (UCLA ICM) possesses the greatest in-centrality among the former, receiving funding from state bodies like the National Science Foundation and Department of Energy alongside venture capital investment and philanthropic donations. Located in the engineering school, researchers at UCLA ICM produced the CDR suppliers CarbonBuilt and SeaChange, and are a significant center of ocean CDR research production. The Breakthrough Institute is another notable research institute node in the network. OpenAir Collective is not strictly an institute, but a volunteer-led hub for carbon dioxide removal research and education. Two influential CDR industry reports are included in the network: CDR Primer (2021) and the State of CDR Report (2023). The first was funded by an array of actors – venture capital, philanthropy, NGOs – whilst the latter was primarily a (European) government-sponsored project with help from Bank of America. These reports were included based on the high frequency with which one encounters them when seeking out online CDR resources, paired with their broad topicality. More reports, books, or journal articles might have been included, but I leave that network analysis to others for now.

In **Network 3**, node size was coded to represent the degree of out-centrality, or quantity of arrows *originating at the node and moving outwards.* Since arrows moving outward from a node show investment flows into other entities, the large nodes represent a greater quantity of different investment destinations. It bears repeating here that node size does *not* communicate investment magnitude, in dollars or another metric; a smaller node may well invest more money in carbon dioxide removal than a bigger node. Rather, node size in **Network 3** communicates the quantity, or degree, of out-connections so as to give a sense of which entities are highly connected in the US CDR industry. As such, arrow width is again unweighted and arrow length incidental.

Network 3 exhibits the sources of funding in the CDR industry, illustrating that it generally originates with venture capital, philanthropy and government sources.[34] Lowercarbon

[34] Network 3 shows names for some nodes and codes for others; for a version of Network 3 that shows **names for all nodes**, see **Appendix D**. For a code key, see **Appendix E**.



Network 3. US CDR Investor Network – Out-centrality

Capital immediately jumps out as the largest venture capital firm in the constellation with investments in eleven different CDR suppliers, NGOs, and key CDR documents. Founded by Chris Sacca, prominent Silicon Valley investor and staple of US Democratic Party politics alongside his partner Crystal, Lowercarbon invests in companies that make money “slashing CO_2 emissions, sucking carbon out of the sky, and buying us time to unf**k the planet” (Lowercarbon Capital 2023). Second among venture capital is XPRIZE Carbon Removal, a $100 million CDR technology competition funded by Tesla founder Elon Musk’s philanthropic Foundation. XPRIZE Carbon Removal has given financial support to eight entities across the network and is poised to give more as the largest incentive prize in history. Breakthrough Energy Ventures and Additional Ventures are tied for third with six out-connections a piece. The former is a powerhouse investor group led by Microsoft billionaire Bill Gates in collaboration with more than 35 extremely wealthy investors including Jeff Bezos, Jack Ma, Dustin Moskovitz, and Michael Bloomberg, among others. The latter was founded by Mike Shroepfer, former Chief Technology Officer at Facebook-Meta and Erin Hoffman, a Silicon Valley-based investor, in 2017 to “solve some of humanity’s most complex challenges” (Additional Ventures 2023). Climate Capital (5), MCJ Collective (5), Carbon Removal Partners (4), Prime Impact Fund (4), and Elemental Excelerator (4) round out the top nine venture capital investors in US carbon dioxide removal.

Philanthropic and government out-connections are as important to the CDR industry as venture capital, as **Network 3** makes manifest. Looming large in the network is the Grantham Foundation, the philanthropic vehicle created by Jeremy and Hannilore Grantham in 1997 dedicated to environmental causes. Jeremy Grantham is the billionaire founder and chief investment strategist at GMO, an investment capital firm based in Boston. The Foundation funds no less than thirteen different entities across the US CDR constellation. Facebook-Meta co-founder and CEO Mark Zuckerberg and his partner Priscilla Chan are funding the CDR industry through their philanthropic Chan Zuckerberg Initiative – CZI has eleven out-connections, funding mostly carbon dioxide removal NGOs, research institutes, and venture capital funds. Climate Pathfinders, a program run by the St. Louis-based Rio Vista Foundation, is equally key to the network with eleven out-connections of its own. Rounding out the major philanthropies are the Hewlett Foundation and the Pritzker Innovation Fund with eight and five out-connections respectively. The US Department of Energy (US DOE) is the major governmental out-connector in the network with eight connections to universities, research institutes, and sub-Department governmental bodies like FECM and ARPA-E.[35] In total, across **Network 3** we can consider eleven venture capital funds and philanthropies to be especially connected to the CDR industry (>5 out-connections); those eleven entities are listed in greater detail in **Table 1** below.

[35] The 45Q tax credit is also a growing government-based source of funding in the US CDR industry; however, given the recent nature of the credit expansion (August 2022) and the delays in government reporting, its precise contribution to the US CDR constellation must lie outside the scope of this thesis.

Table 1. Leading investors in US CDR

Organization	Description/Background	# of out-connections	CDR industry out-connections
Grantham Foundation	Founded by Jeremy and Hannilore Grantham in 1997; Jeremy was co-founder and Chairman of investment capital firm GMO	13	CarbonBuilt; Carbon Gap; Climate Robotics; Direct Air Capture Coalition; Ebb Carbon; Heirloom; Running Tide; SeaChange; Sustaera; Travertine; UCLA Institute for Carbon Management; Verdox; Vesta
Lowercarbon Capital	Venture capital firm founded by Chris Sacca, prominent Silicon Valley investor and staple of US Democratic Party politics, with his partner Crystal Sacca	11	Carbon180; CarbonPlan; Carbon Removal Alliance; CDR Primer; Charm Industrial; Heirloom; Living Carbon; Noya; Running Tide; Sustaera; Verdox
Chan Zuckerberg Initiative	Founded in 2015 by Facebook-Meta co-founder and CEO Mark Zuckerberg with his partner Priscilla Chan; not strictly a philanthropic foundation, CZI does a combination of grantmaking and impact investing	11	Activate; Bipartisan Policy Center; Breakthrough Energy Ventures; Carbon180; CarbonPlan; ClimateWorks; Elemental Excelerator; Great Plains Institute; Prime Impact Fund; SeaChange; UCLA Institute for Carbon Management
Climate Pathfinders	Program run by the private St. Louis-based Rio Vista Foundation from 2019-2022; the program's Director also contributed to the launch of Carbon Gap and now works on renewable energy at DOE	11	Activate; American University Institute for Carbon Removal Law & Policy; Carbon180; Carbon Gap; CDR Primer; Clean Air Task Force; Clear Path; ClimateWorks; Livermore Lab; Lowercarbon Capital; Prime Impact Fund

XPRIZE Carbon Removal	A $100 million carbon dioxide removal technology prize competition across four years, 2021-2025; funded by Elon Musk and the Musk Foundation	8	Calcite-Origen; Captura; Climate Foundation; Global Carbon Removal Partnership; Heirloom; Iowa State University Bioeconomy Institute; Sustaera; Verdox
Hewlett Foundation	Private charitable foundation established in 1966 by William and Flora Hewlett (of Hewlett-Packard Company fame); one of the largest philanthropic institutions in the US	8	Breakthrough Institute; Carbon180; Clean Air Task Force; ClimateWorks; Great Plains Institute; Prime Impact Fund; Rocky Mountain Institute; World Resources Institute
Breakthrough Energy Ventures	Powerhouse investor group led by Microsoft billionaire Bill Gates in collaboration with more than 35 extremely wealthy investors including Jeff Bezos, Jack Ma, Dustin Moskovitz, Michael Bloomberg, among others	6	Breakthrough Institute; Carbon Removal Alliance; Heirloom; Kodama Systems; Sustaera; Verdox
Additional Ventures	Founded by Mike Shroepfer, former CTO at Facebook-Meta and Erin Hoffman, a Silicon Valley-based investor	6	Activate; Aspen Institute; Bipartisan Policy Center; Carbon180; CarbonPlan; Vesta
Pritzker Innovation Fund	Founded by Rachel Pritzker, a member of one of the US's wealthiest families, in 2004; Rachel Pritzker is also Chair of the Board at the Breakthrough Institute	5	Breakthrough Institute; Carbon180; CarbonBuilt; Clean Air Task Force; UCLA Institute for Carbon Management
Climate Capital	Founded in 2019 by Silicon Valley investor Sundeep Ahuja as an early stage fund for climate startups	5	Carbo Culture; CarbonBuilt; Kodama Systems; Living Carbon; Noya
MCJ Collective	Founded in 2019 by Jason Jacobs, host of My Climate Journey podcast; the show’s listeners became an investment fund	5	Charm Industrial; Heirloom; Kodama Systems; Living Carbon; Noya

To understand the alignment of the eleven leading CDR investors with various capitalist economic sectors, I trace board-level interlocks within the corporate community. These interlocks substantiate the governance-level connections made when corporate directors sit on the boards of multiple organizations (Scott 1985; Carroll, Huijzer & Sapinski 2023). In its capacity to make decisions over an organization's strategic direction and administration of usable assets, a board of directors has the ability to determine how surplus value is allocated. Data about board members' interlocks to various economic sectors thus help to illustrate which sectors CDR investors are embedded within. As shown in **Table 2**, among the 49 directors of the top eleven CDR investors, I count a total of 66 board interlocks.[36] The average of 1.3 board interlocks per director is slightly high (cf. Surprise & Sapinski's (2022) analysis of solar geoengineering),[37] and may indicate a greater degree of embeddedness for CDR investors in their respective economic sectors.

Table 2. Board-level interlocks between top CDR investors and different economic sectors

Economic Sector	**N**	**%**
Technology, Equipment, & Communications	26	39.4%
Finance, Investment & Real Estate	17	25.8%
Commercial, Advisory, and Misc. Services	12	18.2%
Carbon-Linked Industrial	8	12.1%
Other Industrial/Manufacturing	1	1.5%
Carbon Extraction	2	3.0%
Total	**66**	**100%**

The breakdown of the connections within the corporate community (**Table 2**) show sectoral associations of CDR investors: the technology and communications sector comprises 39.4% of the links, the financial sector 25.8%, and the commercial and services sector 18.2%. Taken together, the tech and finance sectors comprise almost two-thirds of the board interlocks of CDR investors. What is counterintuitive about this table, however, is the relative lack of board interlocks to the industrial and carbon extraction sectors. Indeed, a mere 12.1% of interlocks

[36] I examined the board of the Musk Foundation in lieu of XPRIZE, since the decision to allocate funding came from the former.

[37] In Surprise & Sapinski's (2022) study, from which I draw inspiration for **Table 2**, the authors found 62 board interlocks among 91 directors of the top funders of solar geoengineering research (<1 board interlock per director).

connected fossil-heavy industrial firms (automotives, aviation, shipping, steel, chemicals) to CDR investors, and a pair of connections to fossil companies themselves (a Grantham trustee also sits on a Shell advisory board, and Breakthrough Energy Ventures counts Mukesh Ambani, head of Indian petroleum giant Reliance Industries, as a board member). Four of the eight carbon-linked industrial interlocks come from Elon Musk's and his brother Kimbal's board seats at Tesla and SpaceX. The relative absence of fossil-linked capital from public funding and investment in the US CDR industry is remarkable. In sum, the tech and finance sectors are the ones primarily funding the US CDR industry at this stage, not fossil capital or its industrial allies.[38]

[38] *Primarily* is the key word here; there are indeed fossil-linked investors in the CDR ecosystem (Occidental Petroleum is building large-scale DAC plants in Texas, for example – see FN25). Shell, Toyota, Equinor, Saudi Aramco, Southern California Gas Company, and other fossil investors can indeed be found in **Networks 2** and **3**. Rather than a black-or-white binary, I am making a *relative* point regarding funding prominence supported by the data.

7. Discussion

7a. Funding

The US CDR industry is constituted by a social and financial network of carbon credit transactions, investment decisions, and philanthropic grants. Technology firms, primarily but not exclusively located in Silicon Valley, play an outsized role in the carbon dioxide removal ecosystem through the purchasing of removals by Microsoft, Shopify, Stripe, Frontier, and others, and through investors like Lowercarbon Capital, Chan-Zuckerberg Initiative, and the Elon Musk-sponsored XPRIZE who made their fortunes in tech. Large financial firms constitute nodes of almost equal importance to the US CDR industry, with entities like JP Morgan Chase, Swiss Re, and XTX Markets purchasing large totals of removals outright, and often playing facilitator roles for new VC funding rounds. These findings are not intuitive; much recent critical literature on carbon capture and carbon dioxide removal highlights the links between fossil fuel companies and negative emissions technologies (Carton 2020; Perry 2023; Krauss 2019). The difference in findings can be traced to a key intentional difference in objects of analysis.

The primary dataset used for this thesis compiled at *cdr.fyi* systematically sets aside carbon capture and storage (CCS) projects, almost all of which are directly linked to fossil capital or large industrial units. The data used here focuses on carbon dioxide *removal* and not carbon *capture*. Any technology that captures carbon dioxide from an existing source, like flue gas from cement production, was separated out by the *cdr.fyi* dataset's creators as *not removal*, and was subsequently left aside. This is an absolutely crucial point to understand: even though this dataset does not manifest the point, fossil capital is heavily involved in the carbon capture business and we ignore those links at our own peril. But my intention here is not to examine all the ways carbon capture technology is being utilized in the United States. If it were, a serious consideration of CCS and its fossil links would be crucial. Rather, my intention is to draw attention to an important difference in the way the technologies are being used – not just as CCS, but also as CDR – and to explore the links that make up the latter's budding logics of possibility.

7b. Biochar

Biochar occupies a special place as a carbon dioxide removal method in the United States. To date, it is the method with the most tons delivered, three of the five biggest suppliers by tons sold ply their trade via biochar, and the major purchaser financial firms buy their carbon dioxide removal almost exclusively from biochar suppliers (see **Network 1**). What explains the CDR industry's focus on the humble process of pyrolysis? Part of the answer stems from the relative cheapness of the method; according to *cdr.fyi*'s data, only biomass is cheaper per ton with both slightly more expensive than $100. It only makes good business sense to get the most bang for your buck. But a deeper reason for the biochar emphasis seems to come from the business model itself: biochar suppliers are not simply biochar suppliers, but are actually companies focused on other commodities (lumber, agricultural products) that have begun side hustles in the carbon dioxide removal industry. Taking advantage of the subsidies that accompany sales of carbon credits, the large biochar suppliers spin waste products into fresh commodities via CDR. Take one example: Freres Engineered Wood, the third largest supplier by volume of CDR in the US, is a family-run lumber processing firm in Oregon. Next to their wood engineering facility they have constructed a cogeneration plant to produce heat and electricity from leftover "woody material with no other beneficial use" (Freres Engineered Wood 2023). Whatever residuals that remain after the useless material is burned (the waste of the waste) is what gets turned into biochar. A business model based on the commodification of existing waste vectors is apparently more attractive at this early stage of the industry than still-unproven-at-scale DAC facilities or risky ocean-CDR experiments. The era of biochar's unique prominence as a CDR method may be nearing its end, however. Biochar's limited storage duration disqualifies it as a carbon dioxide removal method in the eyes of some standard-makers (there are no biochar suppliers in the Carbon Removal Alliance, an industry group with a dedication to durability) and it runs into important land- and biological-based limitations. The US Government, too, has resisted the inclusion of biochar in its CDR initiatives. Ultimately, at this nascent stage of the US CDR industry, it should be no surprise that the immaturity of carbon dioxide removal durability standards facilitates a purchasing focus on biochar. However, biochar's limited durability may point toward a diminishing of its dominance as a CDR method in the not too distant future.

7c. Toward what end is the US CDR industry?

Without pretending to offer a systematic or complete answer to this section's question, I intend here to circle back to the theoretical concepts from Section 4 in order to sketch some provisional answers to my second research question – What might be the logic underlying the development of the US CDR industry? – that may be able to inform future research.[39] I intend here to engage in rigorous and sober speculation regarding the present and future of carbon dioxide removal.

First, I contend that carbon dioxide dioxide removal can be understood as a mechanism for the real subsumption of nature in the form of atmospheric stability. Thinking of CDR this way helps us to avoid thinking capital has had a viridescent change of heart regarding its ecological sustainability simply because prominent capitalist entities and actors support carbon dioxide removal. In reality, (parts of) capital act on climate via CDR because the real subsumption of nature increases their power (*potestas*) over nature and labor, not because liberal reason has won the climate denial wars. By moving the atmosphere from the realm of formal subsumption and into that of real subsumption, capital has pretensions to exercise greater control over atmospheric cycles, fluctuations, and stability – that is, over capitalism's ecological background conditions of possibility. The ultimate goal remains, as usual, capital accumulation and the valorization of value. Carbon dioxide removal is thus one mechanism among many in the green capitalist strategy to manage the ecological crisis toward capital's ends. Denial is no longer sufficient; active intervention to save capitalist civilization is again the mantra of the times. "Civilization," John Maynard Keynes wrote in 1938, is "a thin and precarious crust, erected by the personality and will of a very few, and only maintained by rules and conventions skillfully put across and guilefully preserved" (Keynes 1938, cited in Mann & Wainwright 2018, p. 121). When Lowercarbon, or Microsoft, or Elon Musk invest in the US carbon dioxide removal industry, we ought to understand their actions not as benevolent but as capitalist self-interest to step in and "save civilization" from ecological crisis. "This is what it all boils down to: We think that markets might actually hold the key to unf***ing the planet," says Lowercarbon Capital's founder Chris Sacca. "Insurance companies, industrial giants, real estate developers, farmers, and even militaries are starting to see the direct trillions of dollars of self-interest they have in sucking some carbon out of the atmosphere" (Sacca 2021).

Second, I contend that as a mechanism for the real subsumption of nature, the US carbon dioxide removal industry can operate as a defensive spatiotemporal fix against the devaluation of fossil assets. Before diving into this claim, consider a brief digression into the potential for renewable energy (not carbon dioxide removal) to function as a defensive spatiotemporal fix.

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[39] My intention is also to continue developing these answers in my own future research.

McCarthy (2015) proposed renewable energy as a spatiotemporal fix and argued that it could act as an outlet for excessive capital while simultaneously staving off ecological crisis (see also Angel 2022; Kreuter & Lederer 2022; Baker 2021). Furnaro (2021) convincingly countered, however, that renewable energy is only a spatiotemporal fix if fossil energy use decreases proportionally when renewable energy comes online, else it simply becomes supplementary energy. In other words, renewables could only be a biophysical fix if they replace, not supplement, fossil energy. Fossil sources still accounted for around 80% of global energy production in 2022 (IEA 2022); renewables are thus not yet an effective spatiotemporal fix because they do not address the crisis in capitalism's ecological background conditions of possibility. Carbon dioxide removal, on the other hand, need not see a world with zero fossil energy sources in order to function as a spatiotemporal fix. Instead, large-scale intervention into the atmosphere via CDR can theoretically achieve "net-zero" emissions even as new fossil energy reserves are located, dug up, and burned. The buildout of a significant CDR industry – something that is still perhaps decades away – would deprioritize the incentive to leave fossil fuels in the earth, and in this sense would function "defensively" against those forces, biophysical and sociopolitical, that would devalue or strand those fossil assets. It remains to be seen if the CDR industry can become its own accumulation strategy, but it appears that the main focus will always be the defense of existing assets and accumulation strategies through the management of atmospheric CO_2.

8. Further Research Reflections

Before moving into the conclusion, there are a series of observations that I would like to flag for future research. The first is that data unavailability was a constant hurdle in compiling my datasets and networks. There currently exists no central verification body or nodal institution to publish comprehensive CDR data. This reflects the early stage of the industry, the diversity of methods, and global nature of the problem; almost all actors in the CDR ecosystem have expressed some desire for better standardization and verification (MRV is the relevant industry acronym for “monitoring, verification, and reporting”). I expect this dearth of data to change in the coming years, and with more data ought to come further insights. Secondly, there is significant overlap between investors in CDR and investors in solar geoengineering or solar radiation management (SRM) (Surprise & Sapinski 2022). Further research might explore these linkages and explore which other “climate tech” proposals are being supported (like green hydrogen). Calls for CDR and SRM within the same breath are already being made by influential voices like The *Economist* (2022). The third observation is that this was a uniquely American case study in many ways, and that further research in other countries or regions will likely bring forward alternative insights and conclusions. Developments for other countries or the global level should not be implied by this thesis, and I encourage studies to take whatever is useful from this thesis to apply to other contexts. The final observation concerns the status of CDR among its left-leaning proponents. Despite my work’s emphasis on the ways CDR is useful for green capitalism, there are serious discussions to be had about the appropriation of CDR technology for a post-capitalist world. While these discussions must unfortunately lie outside the scope of my discussions, I flag Max Ajl’s (2021), David Wallace-Wells’ (2021), Andreas Malm and Wim Carton’s (2021), and Holly Buck’s (2019) work for nuanced and sober discussions of the potential of CDR for emancipatory politics. I remain sympathetic yet agnostic on carbon dioxide removal’s emancipatory potential.

9. Conclusion

This thesis has conducted a political ecological study into how we can understand the politics of the US carbon dioxide removal industry. Drawing on ecological Marxist concepts such as capitalism's ecological background conditions of possibility, climate capital, and green capitalism, a theoretical framework was created to approach the US CDR industry. In order to answer research question one, this thesis sought to understand how CDR supplier-purchaser transactions and industry investment flows reflected the politics of the US CDR industry's participants.

The applied method chosen to answer this research question was a Social Network Analysis (SNA), used to generate qualitative and quantitative social network data. The data and coding procedures followed were included in the **Appendices** to increase the replicability and validity of the results. This method explored the suppliers and purchasers of carbon dioxide removal with an emphasis on the magnitude and vector of their interconnections, and also explored the investment flows throughout the broader carbon dioxide removal ecosystem in the United States (including CDR suppliers, venture capital firms, philanthropies, NGOs, government entities, universities and research institutes, corporations, industry groups, and key CDR documents).

I found that tech and financial firms are the key capitalist economic sectors driving the US CDR industry through their purchases of high amounts of removals from suppliers and through investment spread throughout the industry. This result is counterintuitive because similar studies on CCS have repeatedly found strong links to the fossil fuel industry; thus, strong links between the US CDR industry and fossil capital might have been reasonably presupposed. To answer my second research question and make sense of this counterintuitive finding, I proposed to utilize the Marxist concepts of the real subsumption of nature and the (defensive) spatiotemporal fix so as to understand *why* capitalist sectors like tech and finance would be interested in carbon dioxide removal. By really subsuming atmospheric nature via CDR, the tech and finance sectors are able to address the crisis in capitalism's ecological background conditions of possibility without needing to directly challenge the hegemony of fossil capital; instead, they can strive for negative emissions and "net-zero" while postponing the devaluation of fossil assets, a defensive spatiotemporal fix that preserves existing lucrative accumulation strategies. The tech and finance sectors are *for solving the ecological crisis* (**not** *against fossil fuels*, a crucial distinction) and can thus be said to be pursuing a green capitalist project to manage the crisis towards capital's ends.

This thesis is meant to give an important contribution to the field of Human Ecology, firstly by focusing on an empirical case study, something that is uncommon within the critical CDR literature, but also by expanding the application of an ecological Marxist approach to a subject that is still new and somewhat controversial. It also highlights the importance of theoretically-informed case studies that remain open to surprises and counterintuitive findings. The data for this study are also a contribution: while roughly one third of the data come from *cdr.fyi*, the rest were personally collected for the occasion of this thesis and are made available with the intention of facilitating others' further research. Finally, it is hoped that by painting a picture of the US CDR industry and articulating a theoretical language for understanding how and why it ticks, a contribution has been made in taking a step towards an emancipatory and sustainable climate future.

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11. Appendices

A. Global CDR Supplier Data

Organization Name	Organization Type	Location - City	Location - Country	CDR Method	Tons Sold	Tons Delivered
44.01	CDR Supplier	-	UK	Mineralization	5823	0
1PointFive	CDR Supplier	-	Canada	Direct Air Capture	400000	0
Aperam BioEnergia	CDR Supplier	-	Brazil	Biochar	800	800
Arbor	CDR Supplier	Los Angeles, CA	USA	Biomass CDR	1000	0
AspiraDAC	CDR Supplier	-	Australia	Direct Air Capture	500	0
Auen Pflege Dienst APD Flaach	CDR Supplier	-	Switzerland	Biochar	272	0
Bio Restorative Ideas	CDR Supplier	San Juan, Puerto Rico	USA	Biochar	1150	0
Biokol.se	CDR Supplier	-	Sweden	Biochar	11	0
Bussme	CDR Supplier	-	Sweden	Biochar	909	909
Calcite-Origen	CDR Supplier	Durham, NC	USA	Direct Air Capture	278	0
Captura	CDR Supplier	Los Angeles, CA	USA	Ocean CDR	508	0
Capture6	CDR Supplier	San Francisco Bay Area, CA	USA	Direct Air Capture	0	0
Carbin Minerals	CDR Supplier	-	Canada	Mineralization	580	0
Carbo Culture	CDR Supplier	Los Angeles, CA	USA	Biochar	388	0
CarboFex	CDR Supplier	-	Finland	Biochar	7660	3931
Carbon Cantonne	CDR Supplier	-	Canada	Direct Air Capture	0	0
Carbon Collect	CDR Supplier	-	Ireland	Direct Air Capture	0	0

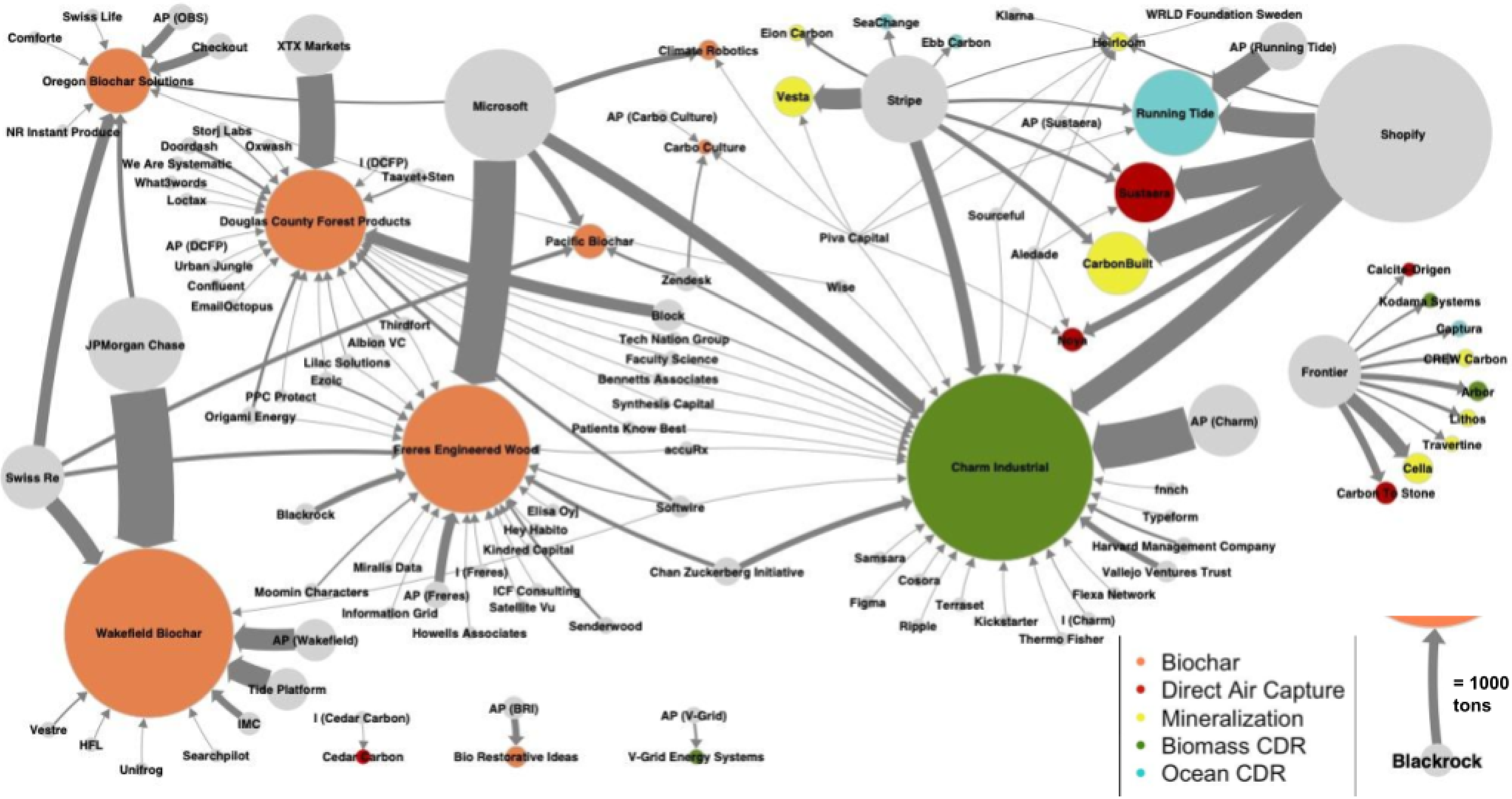
Carbon Cycle	CDR Supplier	-	Germany	Biochar	3346	1782
Carbon Engineering	CDR Supplier	-	Canada	Direct Air Capture	11434	0
Carbon Infinity	CDR Supplier	-	UK	Direct Air Capture	0	0
Carbon To Stone	CDR Supplier	Ithica, NY	USA	Direct Air Capture	1269	0
CarbonBuilt	CDR Supplier	Los Angeles, CA	USA	Mineralization	6168	0
CarbonCapture Inc.	CDR Supplier	Los Angeles, CA	USA	Direct Air Capture	0	0
CarbonCure	CDR Supplier	-	Canada	Mineralization	7375	0
Carbonfuture	CDR Supplier	-	Germany	Biochar	17350	0
Carbyon	CDR Supplier	-	The Netherlands	Direct Air Capture	0	0
Cedar Carbon	CDR Supplier	Brooklyn, NY	USA	Direct Air Capture	1	0
Cella	CDR Supplier	New York, NY	USA	Mineralization	2198	0
Charm Industrial	CDR Supplier	San Francisco Bay Area, CA	USA	Biomass CDR	20554	5954
Climate Robotics	CDR Supplier	Houston, TX	USA	Biochar	1004	0
Climeworks	CDR Supplier	-	Switzerland	Direct Air Capture	69137	0
CREW Carbon	CDR Supplier	New Haven, CT	USA	Mineralization	615	0
Douglas County Forest Products	CDR Supplier	Roseburg, OR	USA	Biochar	11730	11269
Drax	CDR Supplier	-	UK	Biomass CDR	0	0
e-quester	CDR Supplier	-	Canada	Direct Air Capture	0	0
Ebb Carbon	CDR Supplier	San Francisco Bay Area, CA	USA	Ocean CDR	256	0
Echo2	CDR Supplier	-	Australia	Biochar	6499	1410
Ecoera	CDR Supplier	-	Sweden	Biochar	1078	892

EcoLocked	CDR Supplier	-	Germany	Biochar	0	0
Eion Carbon	CDR Supplier	Princeton, NJ	USA	Mineralization	500	0
Emergent Waste Solution	CDR Supplier	-	Canada	Biochar	50	50
Freres Engineered Wood	CDR Supplier	Lyons, OR	USA	Biochar	14373	6396
Gekka Biochar	CDR Supplier	-	Romania	Biochar	17	17
GreenSand	CDR Supplier	-	Denmark	Mineralization	3154	2228
Heirloom	CDR Supplier	San Francisco Bay Area, CA	USA	Mineralization	804	0
Hjelmsäters Egendom	CDR Supplier	-	Sweden	Biochar	704	650
Husk	CDR Supplier	-	Spain	Biochar	3526	0
Inplanet	CDR Supplier	-	Germany	Mineralization	1041	0
InterEarth	CDR Supplier	-	Australia	Biomass CDR	8130	0
Jeffries Group	CDR Supplier	-	Australia	Biochar	29	29
Karbon Capture	CDR Supplier	-	UK	Biochar	104	104
Kodama Systems	CDR Supplier	San Francisco Bay Area, CA	USA	Biomass CDR	416	0
Lithos	CDR Supplier	Seattle, WA	USA	Mineralization	640	0
Living Carbon	CDR Supplier	San Francisco Bay Area, CA	USA	Biomass CDR	0	0
Mash makes	CDR Supplier	-	Denmark	Biochar	50846	0
Mission Zero	CDR Supplier	-	UK	Direct Air Capture	716	0
Netzero	CDR Supplier	-	France	Biochar	184	184
Neustark	CDR Supplier	-	Switzerland	Mineralization	38479	0
Nordgau	CDR Supplier	-	Germany	Biochar	756	677
NovoCarbon	CDR Supplier	-	Germany	Biochar	1744	1684
Noya	CDR Supplier	San Francisco Bay Area, CA	USA	Direct Air Capture	1473	0
Oplandske Bio Rudshøgda	CDR Supplier	-	Norway	Biochar	521	516
Oregon Biochar Solutions	CDR Supplier	White City, OR	USA	Biochar	6484	4077

Pacific Biochar	CDR Supplier	San Francisco Bay Area, CA	USA	Biochar	2771	1500
Planetary	CDR Supplier	-	Canada	Ocean CDR	730	0
Premier Forest	CDR Supplier	-	UK	Biochar	207	207
Pyrocal	CDR Supplier	-	Australia	Biochar	6	6
RepAir	CDR Supplier	-	Israel	Direct Air Capture	199	0
Running Tide	CDR Supplier	Portland, ME	USA	Ocean CDR	9018	0
SeaChange	CDR Supplier	Los Angeles, CA	USA	Ocean CDR	365	0
Silicate	CDR Supplier	-	Ireland	Mineralization	900	0
Skynano	CDR Supplier	Knoxville, TN	USA	Direct Air Capture	0	0
Soletair Power	CDR Supplier	-	Finland	Direct Air Capture	0	0
Sonnenerde	CDR Supplier	-	Austria	Biochar	189	0
Sustaera	CDR Supplier	Cary, NC	USA	Direct Air Capture	5959	0
Terra Fertilis	CDR Supplier	-	France	Biochar	281	281
TerraFixing	CDR Supplier	-	Canada	Direct Air Capture	0	0
Travertine	CDR Supplier	Boulder, CO	USA	Mineralization	365	0
UNDO	CDR Supplier	-	UK	Mineralization	3318	48
V-Grid Energy Systems	CDR Supplier	Los Angeles, CA	USA	Biomass CDR	411	171
Verdox	CDR Supplier	Woburn, MA	USA	Direct Air Capture	0	0
Vesta	CDR Supplier	San Francisco Bay Area, CA	USA	Mineralization	3337	0
Wakefield Biochar	CDR Supplier	Valdosta, GA	USA	Biochar	25674	16794
zs2 Technologies	CDR Supplier	-	Canada	Direct Air Capture	0	0

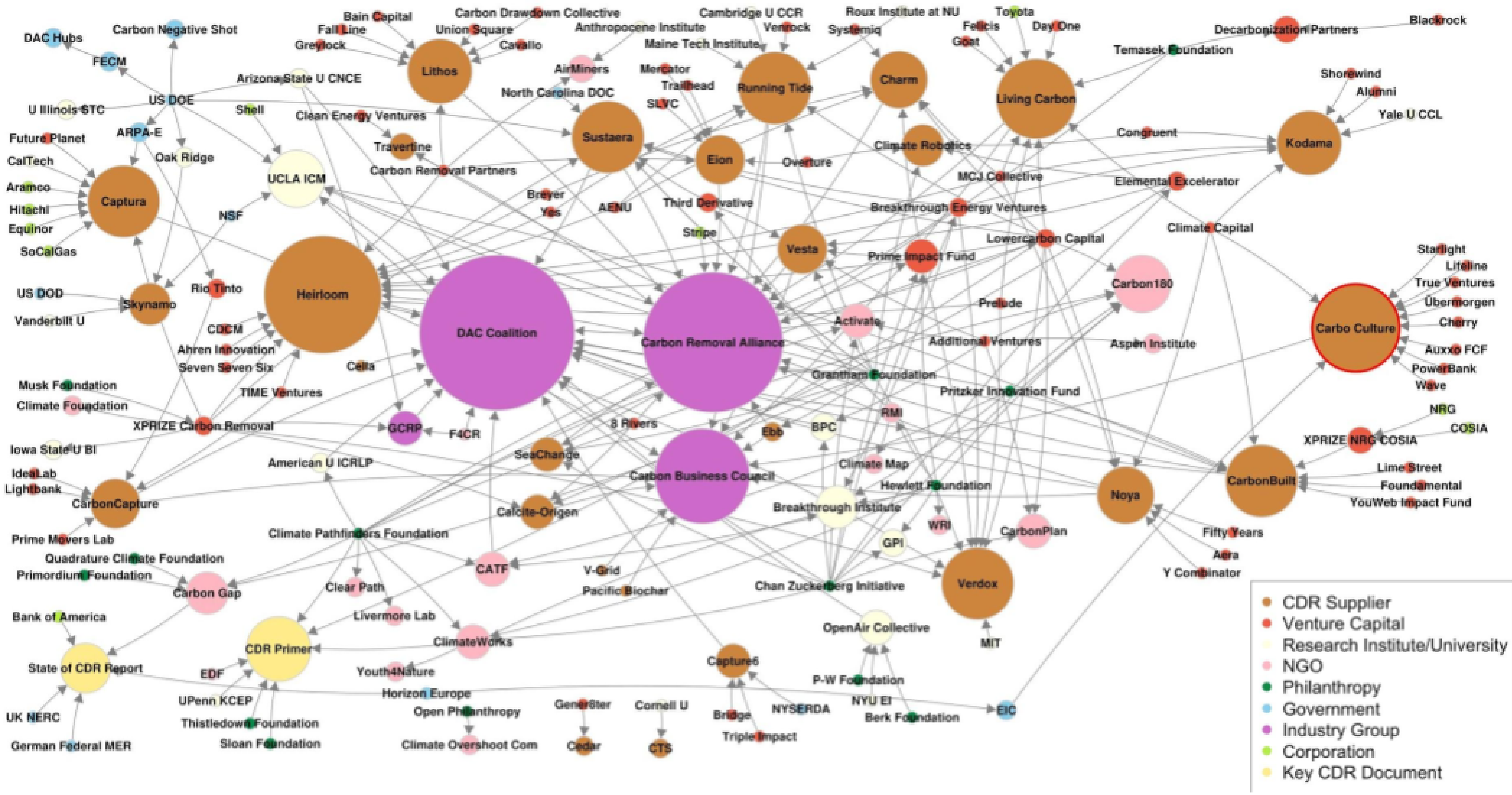
**Data accurate through 26 March 2023 via* cdr.fyi

B. All US CDR Supplier and Purchaser Network (at least one ton)

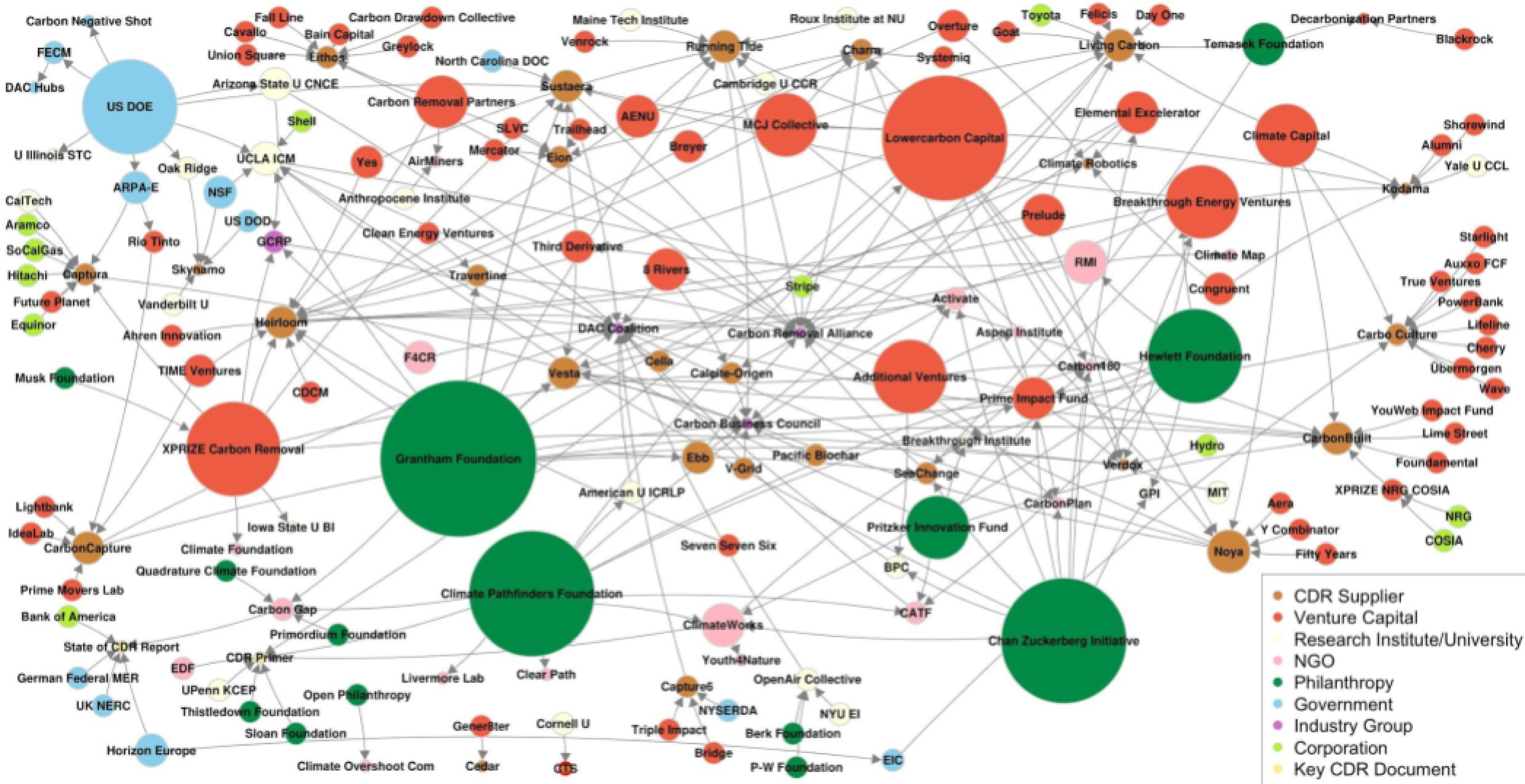


**AP = Aggregate Purchases; I = Individuals*
***Data accurate through 26 March 2023 via* cdr.fyi

C. US CDR Investor Network – In-centrality (names)



D. US CDR Investor Network – Out-centrality (names)



E. RStudio Edgelists

*a. Suppliers and Purchasers Edgelist (**Network 1** & Appendix B)*

#	Purchaser	Supplier	Weight
1	Frontier	Arbor	1000
2	AP (BRI)	Bio Restorative Ideas	1150
3	Frontier	Calcite-Origen	278
4	Frontier	Captura	508
5	Piva Capital	Carbo Culture	5
6	Zendesk	Carbo Culture	375
7	AP (Carbo Culture)	Carbo Culture	8
8	Frontier	Carbon To Stone	1269
9	Stripe	CarbonBuilt	968
10	Shopify	CarbonBuilt	5200
11	I (Cedar Carbon)	Cedar Carbon	1
12	Frontier	Cella	2198
13	Shopify	Charm Industrial	4000
14	Microsoft	Charm Industrial	2200
15	Stripe	Charm Industrial	2083
16	AP (Charm)	Charm Industrial	7180
17	Block	Charm Industrial	255
18	Chan Zuckerberg Initiative	Charm Industrial	1076
19	Zendesk	Charm Industrial	432
20	Vallejo Ventures Trust	Charm Industrial	1041
21	Softwire	Charm Industrial	35
22	Harvard Management Company	Charm Industrial	500
23	Aledade	Charm Industrial	83
24	I (Charm)	Charm Industrial	186
25	Faculty Science	Charm Industrial	9
26	accuRx	Charm Industrial	10
27	Wise	Charm Industrial	45
28	Patients Know Best	Charm Industrial	3
29	Sourceful	Charm Industrial	83
30	Tech Nation Group	Charm Industrial	1
31	Thermo Fisher	Charm Industrial	70
32	Samsara	Charm Industrial	41
33	Synthesis Capital	Charm Industrial	14
34	Piva Capital	Charm Industrial	16
35	Flexa Network	Charm Industrial	27
36	Ripple	Charm Industrial	25
37	Bennetts Associates	Charm Industrial	4
38	Figma	Charm Industrial	20
39	Typeform	Charm Industrial	13
40	Kickstarter	Charm Industrial	10
41	fnnch	Charm Industrial	8
42	Cosora	Charm Industrial	1
43	Terraset	Charm Industrial	153
44	Microsoft	Climate Robotics	1000
45	Piva Capital	Climate Robotics	4
46	Frontier	CREW Carbon	615
47	Storj Labs	Douglas County Forest Products	250
48	Confluent	Douglas County Forest Products	34
49	Faculty Science	Douglas County Forest Products	170
50	Loctax	Douglas County Forest Products	38
51	Patients Know Best	Douglas County Forest Products	94
52	Synthesis Capital	Douglas County Forest Products	26

53	Thirdfort	Douglas County Forest Products	290
54	Softwire	Douglas County Forest Products	637
55	Taavet+Sten	Douglas County Forest Products	382
56	Block	Douglas County Forest Products	2000
57	Bennetts Associates	Douglas County Forest Products	18
58	PPC Protect	Douglas County Forest Products	10
59	Albion VC	Douglas County Forest Products	178
60	Urban Jungle	Douglas County Forest Products	24
61	Ezoic	Douglas County Forest Products	58
62	Origami Energy	Douglas County Forest Products	536
63	Tech Nation Group	Douglas County Forest Products	80
64	Oxwash	Douglas County Forest Products	105
65	EmailOctopus	Douglas County Forest Products	48
66	We Are Systematic	Douglas County Forest Products	53
67	What3words	Douglas County Forest Products	118
68	XTX Markets	Douglas County Forest Products	5874
69	AP (DCFP)	Douglas County Forest Products	2
70	I (DCFP)	Douglas County Forest Products	5
71	Lilac Solutions	Douglas County Forest Products	200
72	Doordash	Douglas County Forest Products	500

73	Stripe	Ebb Carbon	256
74	Stripe	Eion Carbon	500
75	Satellite Vu	Freres Engineered Wood	124
76	Albion VC	Freres Engineered Wood	70
77	Microsoft	Freres Engineered Wood	6926
78	Origami Energy	Freres Engineered Wood	61
79	Chan Zuckerberg Initiative	Freres Engineered Wood	729
80	I (Freres)	Freres Engineered Wood	105
81	PPC Protect	Freres Engineered Wood	10
82	Kindred Capital	Freres Engineered Wood	27
83	AP (Freres)	Freres Engineered Wood	1615
84	Moomin Characters	Freres Engineered Wood	339
85	accuRx	Freres Engineered Wood	169
86	Senderwood	Freres Engineered Wood	452
87	Elisa Oyj	Freres Engineered Wood	36
88	Hey Habito	Freres Engineered Wood	81
89	Swiss Re	Freres Engineered Wood	771

90	Thirdfort	Freres Engineered Wood	63
91	Blackrock	Freres Engineered Wood	1000
92	Softwire	Freres Engineered Wood	287
93	ICF Consulting	Freres Engineered Wood	50
94	Miralis Data	Freres Engineered Wood	20
95	Information Grid	Freres Engineered Wood	9
96	Ezoic	Freres Engineered Wood	348
97	Howells Associates	Freres Engineered Wood	20
98	Lilac Solutions	Freres Engineered Wood	150
99	Aledade	Heirloom	30
100	Klarna	Heirloom	122
101	Piva Capital	Heirloom	1
102	Shopify	Heirloom	400
103	Sourceful	Heirloom	5
104	Stripe	Heirloom	244
105	WRLD Foundation Sweden	Heirloom	2
106	Frontier	Kodama Systems	416
107	Frontier	Lithos	640
108	Aledade	Noya	27
109	Shopify	Noya	1445
110	Piva Capital	Noya	1
111	Checkout	Oregon Biochar Solutions	1585

112	Comforte	Oregon Biochar Solutions	3
113	JPMorgan Chase	Oregon Biochar Solutions	867
114	Microsoft	Oregon Biochar Solutions	411
115	NR Instant Produce	Oregon Biochar Solutions	2
116	Swiss Life	Oregon Biochar Solutions	53
117	Swiss Re	Oregon Biochar Solutions	1913
118	Wise	Oregon Biochar Solutions	89
119	AP (OBS)	Oregon Biochar Solutions	1561
120	Microsoft	Pacific Biochar	1500
121	Swiss Re	Pacific Biochar	771
122	Zendesk	Pacific Biochar	500
123	Piva Capital	Running Tide	9
124	Shopify	Running Tide	4100
125	Stripe	Running Tide	600
126	AP (Running Tide)	Running Tide	4309
127	Stripe	SeaChange	365
128	Aledade	Sustaera	80
129	Shopify	Sustaera	5000
130	Stripe	Sustaera	714
131	AP (Sustaera)	Sustaera	165
132	Frontier	Travertine	365
133	AP (V-Grid)	V-Grid Energy Systems	411
134	Stripe	Vesta	3333
135	Piva Capital	Vesta	4
136	JPMorgan Chase	Wakefield Biochar	9100
137	Softwire	Wakefield Biochar	47

138	Vestre	Wakefield Biochar	336
139	Swiss Re	Wakefield Biochar	2700
140	Tide Platform	Wakefield Biochar	3711
141	AP (Wakefield)	Wakefield Biochar	3538
142	Searchpilot	Wakefield Biochar	31
143	IMC	Wakefield Biochar	1200
144	Unifrog	Wakefield Biochar	15
145	HFL	Wakefield Biochar	180

Data accurate through 26 March 2023 via* cdr.fyi *b. Investor Network Edgelist (Network 2** & **Network 3**, and Appendices C + D)*

	Investor	Investee
1	8 Rivers Capital	Calcite-Origen
2	8 Rivers Capital	Carbon Removal Alliance
3	8 Rivers Capital	Direct Air Capture Coalition
4	Activate	Direct Air Capture Coalition
5	Additional Ventures	Vesta
6	Additional Ventures	Activate
7	Additional Ventures	Bipartisan Policy Center
8	Additional Ventures	Carbon180
9	Additional Ventures	CarbonPlan
10	Additional Ventures	Aspen Institute
11	AENU	Charm Industrial
12	AENU	Running Tide
13	AENU	Heirloom
14	Aera VC	Noya
15	Ahren Innovation Capital	Heirloom
16	Alumni Ventures	Kodama Systems
17	American University Institute for Carbon Removal Law & Policy	Direct Air Capture Coalition
18	Anthropocene Institute	AirMiners
19	Aramco Ventures	Captura
20	Arizona State University Center for Negative Carbon Emissions	Direct Air Capture Coalition
21	Arizona State University Center for Negative Carbon Emissions	Global Carbon Removal Partnership
22	ARPA-E	Captura
23	ARPA-E	Rio Tinto
24	Auxxo Female Catalyst Fund	Carbo Culture
25	Bain Capital Ventures	Lithos
26	Bank of America	State of CDR Report
27	Berk Foundation	OpenAir Collective
28	Blackrock	Decarbonization Partners
29	Bipartisan Policy Center	Direct Air Capture Coalition
30	Breakthrough Energy Ventures	Sustaera
31	Breakthrough Energy Ventures	Heirloom
32	Breakthrough Energy Ventures	Kodama Systems
33	Breakthrough Energy Ventures	Verdox
34	Breakthrough Energy Ventures	Breakthrough Institute
35	Breakthrough Energy Ventures	Carbon Removal Alliance
36	Breyer Capital	Charm Industrial
37	Breyer Capital	Heirloom
38	Bridge Investment	Capture6
39	Calcite-Origen	Carbon Business Council
40	California Institute of Technology	Captura
41	Cambridge University Centre for Climate Repair	Running Tide
42	Captura	Carbon Business Council

43	Capture6	Direct Air Capture Coalition
44	Carbo Culture	Carbon Business Council
45	Carbon Drawdown Collective	Lithos
46	Carbon Gap	State of CDR Report
47	Carbon Removal Partners	Lithos
48	Carbon Removal Partners	Heirloom
49	Carbon Removal Partners	Eion Carbon
50	Carbon Removal Partners	AirMiners
51	CarbonBuilt	Carbon Removal Alliance
52	CarbonBuilt	Direct Air Capture Coalition
53	CarbonCapture Inc.	Direct Air Capture Coalition
54	CarbonCapture Inc.	Carbon Business Council
55	Clean Air Task Force	Direct Air Capture Coalition
56	Cavallo Ventures	Lithos
57	Carbon Direct Capital Management	Heirloom
58	Cella	Direct Air Capture Coalition
59	Chan Zuckerberg Initiative	SeaChange
60	Chan Zuckerberg Initiative	Activate
61	Chan Zuckerberg Initiative	Bipartisan Policy Center
62	Chan Zuckerberg Initiative	Breakthrough Energy Ventures
63	Chan Zuckerberg Initiative	Carbon180

64	Chan Zuckerberg Initiative	CarbonPlan
65	Chan Zuckerberg Initiative	ClimateWorks Foundation - Carbon Dioxide Removal
66	Chan Zuckerberg Initiative	Great Plains Institute
67	Chan Zuckerberg Initiative	Prime Impact Fund
68	Chan Zuckerberg Initiative	UCLA Institute for Carbon Management
69	Chan Zuckerberg Initiative	Elemental Excelerator
70	Charm Industrial	Carbon Removal Alliance
71	Cherry Ventures	Carbo Culture
72	Clean Energy Ventures	Travertine
73	Climate Capital	CarbonBuilt
74	Climate Capital	Noya
75	Climate Capital	Kodama Systems
76	Climate Capital	Carbo Culture
77	Climate Capital	Living Carbon
78	Climate Pathfinders Foundation	Activate
79	Climate Pathfinders Foundation	Carbon180
80	Climate Pathfinders Foundation	ClimateWorks Foundation - Carbon Dioxide Removal
81	Climate Pathfinders Foundation	American University Institute for Carbon Removal Law & Policy
82	Climate Pathfinders Foundation	Lowercarbon Capital
83	Climate Pathfinders Foundation	Prime Impact Fund
84	Climate Pathfinders Foundation	CDR Primer

85	Climate Pathfinders Foundation	Clean Air Task Force
86	Climate Pathfinders Foundation	Livermore Lab Foundation
87	Climate Pathfinders Foundation	Clear Path
88	Climate Pathfinders Foundation	Carbon Gap
89	ClimateWorks Foundation - Carbon Dioxide Removal	CDR Primer
90	ClimateWorks Foundation - Carbon Dioxide Removal	Youth4Nature
91	ClimateWorks Foundation - Carbon Dioxide Removal	Breakthrough Institute
92	Congruent Ventures	Climate Robotics
93	Congruent Ventures	Kodama Systems
94	Cornell University	Carbon To Stone
95	COSIA	XPRIZE NRG COSIA
96	Day One Ventures	Living Carbon
97	Ebb Carbon	Carbon Removal Alliance
98	Ebb Carbon	Carbon Business Council
99	Environmental Defense Fund	CDR Primer
100	European Innovation Council	Carbo Culture
101	Eion Carbon	Carbon Removal Alliance
102	Elemental Excelerator	Vesta
103	Elemental Excelerator	Climate Robotics
104	Elemental Excelerator	Calcite-Origen
105	Equinor Ventures	Captura
106	Foundation for Climate Restoration	Direct Air Capture Coalition
107	Foundation for Climate Restoration	Global Carbon Removal Partnership
108	Fall Line Capital	Lithos
109	Office of Fossil Energy & Carbon Management	DAC Regional Hubs Program
110	Felicis Ventures	Living Carbon
111	Fifty Years VC	Noya
112	Foundamental	CarbonBuilt
113	Future Planet Capital	Captura
114	Global Carbon Removal Partnership	Direct Air Capture Coalition
115	Gener8ter	Cedar Carbon
116	German Federal Ministry of Education & Research	State of CDR Report
117	Goat Capital	Living Carbon
118	Grantham Foundation	Running Tide
119	Grantham Foundation	CarbonBuilt
120	Grantham Foundation	Sustaera
121	Grantham Foundation	Sustaera
122	Grantham Foundation	Vesta
123	Grantham Foundation	Climate Robotics
124	Grantham Foundation	Heirloom
125	Grantham Foundation	SeaChange
126	Grantham Foundation	Travertine
127	Grantham Foundation	Ebb Carbon
128	Grantham Foundation	Verdox
129	Grantham Foundation	UCLA Institute for Carbon Management
130	Grantham Foundation	Carbon Gap
131	Grantham Foundation	Direct Air Capture Coalition
132	Greylock Partners	Lithos
133	Heirloom	Carbon Removal Alliance
134	Heirloom	Direct Air Capture Coalition

135	William & Flora Hewlett Foundation	Carbon180
136	William & Flora Hewlett Foundation	Great Plains Institute
137	William & Flora Hewlett Foundation	Clean Air Task Force
138	William & Flora Hewlett Foundation	Breakthrough Institute
139	William & Flora Hewlett Foundation	ClimateWorks Foundation - Carbon Dioxide Removal
140	William & Flora Hewlett Foundation	Prime Impact Fund
141	William & Flora Hewlett Foundation	World Resources Institute - Carbon Removal
142	William & Flora Hewlett Foundation	Rocky Mountain Institute
143	Hitachi Ventures	Captura
144	Horizon Europe	European Innovation Council
145	Horizon Europe	State of CDR Report
146	Hydro	Verdox
147	IdeaLab Studio	CarbonCapture Inc.
148	Lifeline Ventures	Carbo Culture
149	Lightbank	CarbonCapture Inc.
150	Lime Street Ventures	CarbonBuilt
151	Lithos	Carbon Removal Alliance
152	Living Carbon	Carbon Removal Alliance
153	Living Carbon	Carbon Business Council
154	Lowercarbon Capital	Charm Industrial
155	Lowercarbon Capital	Running Tide
156	Lowercarbon Capital	Sustaera
157	Lowercarbon Capital	Noya
158	Lowercarbon Capital	Heirloom
159	Lowercarbon Capital	Verdox

160	Lowercarbon Capital	Living Carbon
161	Lowercarbon Capital	Carbon180
162	Lowercarbon Capital	CarbonPlan
163	Lowercarbon Capital	CDR Primer
164	Lowercarbon Capital	Carbon Removal Alliance
165	Maine Technology Institute	Running Tide
166	MCJ Collective	Charm Industrial
167	MCJ Collective	Noya
168	MCJ Collective	Heirloom
169	MCJ Collective	Kodama Systems
170	MCJ Collective	Living Carbon
171	Mercator Partners	Eion Carbon
172	Massachusetts Institute of Technology	Verdox
173	Musk Foundation	XPRIZE Carbon Removal
174	North Carolina Department of Commerce	Sustaera
175	Noya	Carbon Removal Alliance
176	Noya	Direct Air Capture Coalition
177	Noya	Carbon Business Council
178	NRG	XPRIZE NRG COSIA
179	NSF	Skynano
180	NSF	UCLA Institute for Carbon Management
181	NYSERDA	Capture6
182	New York University Entrepreneurial Institute	OpenAir Collective
183	Oak Ridge National Laboratory	Skynano
184	Open Philanthropy	Climate Overshoot Commission

185	OpenAir Collective	Direct Air Capture Coalition
186	Overture VC	Climate Robotics
187	Overture VC	Eion Carbon
188	Preston-Werner Foundation	OpenAir Collective
189	Pacific Biochar	Carbon Business Council
190	PowerBank Ventures	Carbo Culture
191	Prelude Ventures	Heirloom
192	Prelude Ventures	Verdox
193	Prelude Ventures	Living Carbon
194	Prime Impact Fund	Charm Industrial
195	Prime Impact Fund	Vesta
196	Prime Impact Fund	Verdox
197	Prime Movers Lab	CarbonCapture Inc.
198	Primordium Foundation	Carbon Gap
199	Pritzker Innovation Fund	CarbonBuilt
200	Pritzker Innovation Fund	Carbon180
201	Pritzker Innovation Fund	UCLA Institute for Carbon Management
202	Pritzker Innovation Fund	Clean Air Task Force
203	Pritzker Innovation Fund	Breakthrough Institute
204	Quadrature Climate Foundation	Carbon Gap
205	Rio Tinto	CarbonCapture Inc.
206	Rocky Mountain Institute	Third Derivative
207	Rocky Mountain Institute	The Climate Map
208	Rocky Mountain Institute	Direct Air Capture Coalition

209	Roux Institute at Northeastern University	Running Tide
210	Running Tide	Carbon Removal Alliance
211	Running Tide	Carbon Business Council
212	SeaChange	Carbon Removal Alliance
213	Seven Seven Six VC	Heirloom
214	Shell	UCLA Institute for Carbon Management
215	Shorewind Capital	Kodama Systems
216	Alfred P. Sloan Foundation	CDR Primer
217	SLVC	Eion Carbon
218	SoCalGas	Captura
219	Starlight Ventures	Carbo Culture
220	Stripe	Carbon Removal Alliance
221	Sustaera	Carbon Removal Alliance
222	Sustaera	Direct Air Capture Coalition
223	Systemiq Capital	Charm Industrial
224	Temasek Foundation	SeaChange
225	Temasek Foundation	Living Carbon
226	Temasek Foundation	Decarbonization Partners
227	Third Derivative	Sustaera
228	Third Derivative	Vesta
229	Thistledown Foundation	CDR Primer
230	TIME Ventures VC	Heirloom
231	TIME Ventures VC	CarbonCapture Inc.
232	Toyota Ventures	Living Carbon
233	Trailhead Capital	Eion Carbon

234	Travertine	Carbon Removal Alliance
235	Triple Impact Capital	Capture6
236	True Ventures	Carbo Culture
237	Übermorgen Ventures	Carbo Culture
238	UCLA Institute for Carbon Management	CarbonBuilt
239	UCLA Institute for Carbon Management	Direct Air Capture Coalition
240	UK Natural Environment Research Council	State of CDR Report
241	Union Square Ventures	Lithos
242	University of Pennsylvania Kleinman Center for Energy Policy	CDR Primer
243	US Department of Defense	Skynano
244	US Department of Energy	Sustaera
245	US Department of Energy	UCLA Institute for Carbon Management
246	US Department of Energy	Office of Fossil Energy & Carbon Management
247	US Department of Energy	Carbon Negative Shot
248	US Department of Energy	ARPA-E
249	US Department of Energy	Arizona State University Center for Negative Carbon Emissions
250	US Department of Energy	University of Illinois Sustainable Technology Center
251	US Department of Energy	Oak Ridge National Laboratory

252	V-Grid Energy Systems	Carbon Business Council
253	Vanderbilt University	Skynano
254	Venrock	Running Tide
255	Vesta	Carbon Removal Alliance
256	Vesta	Carbon Business Council
257	Wave Ventures	Carbo Culture
258	XPRIZE Carbon Removal	Sustaera
259	XPRIZE Carbon Removal	Captura
260	XPRIZE Carbon Removal	Heirloom
261	XPRIZE Carbon Removal	Calcite-Origen
262	XPRIZE Carbon Removal	Verdox
263	XPRIZE Carbon Removal	Iowa State University Bioeconomy Institute
264	XPRIZE Carbon Removal	Climate Foundation
265	XPRIZE Carbon Removal	Global Carbon Removal Partnership
266	XPRIZE NRG COSIA	CarbonBuilt
267	Y Combinator	Noya
268	Yale Carbon Containment Lab	Kodama Systems
269	Yes VC	Running Tide
270	Yes VC	Heirloom
271	YouWeb Impact Fund	CarbonBuilt

c. *Code Key for **Network 2** & **Network 3***

Code	Organization Name
S1	Charm Industrial
S2	Wakefield Biochar
S3	Freres Engineered Wood
S4	Douglas County Forest Products
S5	Oregon Biochar Solutions
S6	Vesta
S7	Pacific Biochar
S8	Cella
S9	Noya
S10	Carbon To Stone
S11	Bio Restorative Ideas
S12	Climate Robotics
S13	Arbor
S14	CREW Carbon
S15	Lithos
S17	Travertine
S18	SeaChange
S19	V-Grid Energy Systems
S20	Capture6
S21	Kodama Systems
S22	Calcite-Origen
S23	Ebb Carbon
S24	Cedar Carbon
S25	CarbonCapture Inc.
S26	Skynano
Captura	Captura
Carbo Culture	Carbo Culture
CarbonBuilt	CarbonBuilt
Heirloom	Heirloom
Living Carbon	Living Carbon
Running Tide	Running Tide
Sustaera	Sustaera
Verdox	Verdox
C1	SoCalGas
C2	Equinor Ventures
C3	Aramco Ventures
C4	Hitachi Ventures
C5	Hydro
C6	Toyota Ventures
C7	Shell
C8	NRG
C9	COSIA
C10	Stripe
C11	Bank of America
G1	Office of Fossil Energy & Carbon Management
G2	Carbon Negative Shot
G3	ARPA-E
G4	DAC Regional Hubs Program
G5	European Innovation Council
G6	North Carolina Department of Commerce
G7	NSF
G8	US Department of Defense
G9	NYSERDA
G10	Horizon Europe
G11	UK Natural Environment Research Council
G12	German Federal Ministry of Education & Research
US DOE	US Department of Energy
IG1	Global Carbon Removal Partnership

Carbon Removal Alliance	Carbon Removal Alliance
DAC Coalition	Direct Air Capture Coalition
Carbon Business Council	Carbon Business Council
CDR Primer	CDR Primer
State of CDR Report	State of CDR Report
NGO1	Climate Foundation
NGO2	Livermore Lab Foundation
NGO3	Clear Path
NGO4	Youth4Nature
NGO5	Climate Overshoot Commission
NGO6	World Resources Institute - Carbon Removal
NGO7	Rocky Mountain Institute
NGO8	The Climate Map
NGO9	Aspen Institute
NGO10	AirMiners
NGO11	Environmental Defense Fund
NGO12	Foundation for Climate Restoration
Activate	Activate
Carbon180	Carbon180
CarbonPlan	CarbonPlan
Carbon Gap	Carbon Gap
CATF	Clean Air Task Force
ClimateWorks	ClimateWorks Foundation - Carbon Dioxide Removal
P1	Temasek Foundation
P2	Musk Foundation
P3	Alfred P. Sloan Foundation
P4	Thistledown Foundation
P5	Open Philanthropy

P6	Quadrature Climate Foundation
P7	Primordium Foundation
P8	Preston-Werner Foundation
P9	Berk Foundation
Chan Zuckerberg Initiative	Chan Zuckerberg Initiative
Climate Pathfinders	Climate Pathfinders
Grantham Foundation	Grantham Foundation
Hewlett Foundation	William & Flora Hewlett Foundation
Pritzker Innovation Fund	Pritzker Innovation Fund
RIU1	Bipartisan Policy Center
RIU2	Great Plains Institute
RIU3	New York University Entrepreneurial Institute
RIU4	Iowa State University Bioeconomy Institute
RIU5	American University Institute for Carbon Removal Law & Policy
RIU6	Arizona State University Center for Negative Carbon Emissions
RIU7	University of Illinois Sustainable Technology Center
RIU8	Oak Ridge National Laboratory
RIU9	Anthropocene Institute
RIU10	Cambridge University Centre for Climate Repair
RIU11	Roux Institute at Northeastern University
RIU12	Maine Technology Institute
RIU13	Cornell University
RIU14	California Institute of

	Technology
RIU15	Yale Carbon Containment Lab
RIU16	Massachusetts Institute of Technology
RIU17	Vanderbilt University
RIU18	University of Pennsylvania Kleinman Center for Energy Policy
Breakthrough Institute	Breakthrough Institute
OpenAir Collective	OpenAir Collective
UCLA ICM	UCLA Institute for Carbon Management
VC1	XPRIZE NRG COSIA
VC2	Third Derivative
VC3	Decarbonization Partners
VC4	Rio Tinto
VC5	AENU
VC6	Breyer Capital
VC7	Systemiq Capital
VC8	Yes VC
VC9	Venrock
VC10	YouWeb Impact Fund
VC11	Lime Street Ventures
VC12	Foundamental
VC13	Fifty Years VC
VC14	Y Combinator
VC15	Aera VC
VC16	Congruent Ventures
VC17	Overture VC
VC18	Bain Capital Ventures
VC19	Greylock Partners
VC20	Cavallo Ventures
VC21	Union Square Ventures
VC22	Fall Line Capital

VC23	Carbon Drawdown Collective
VC24	Future Planet Capital
VC25	Seven Seven Six VC
VC26	TIME Ventures VC
VC27	Carbon Direct Capital Management
VC28	Ahren Innovation Capital
VC29	Prelude Ventures
VC30	Mercator Partners
VC31	SLVC
VC32	Trailhead Capital
VC33	Shorewind Capital
VC34	Alumni Ventures
VC35	Cherry Ventures
VC36	True Ventures
VC37	Übermorgen Ventures
VC38	Lifeline Ventures
VC39	Starlight Ventures
VC40	PowerBank Ventures
VC41	Auxxo Female Catalyst Fund
VC42	Wave Ventures
VC43	Clean Energy Ventures
VC44	8 Rivers Capital
VC45	Prime Movers Lab
VC46	IdeaLab Studio
VC47	Lightbank
VC48	Felicis Ventures
VC49	Day One Ventures
VC50	Goat Capital
VC51	Gener8ter
VC52	Triple Impact Capital
VC53	Bridge Investment
VC54	Blackrock

Additional Ventures	Additional Ventures
Breakthrough Energy Ventures	Breakthrough Energy Ventures
Carbon Removal Partners	Carbon Removal Partners
Climate Capital	Climate Capital
Elemental Excelerator	Elemental Excelerator

Lowercarbon Capital	Lowercarbon Capital
MCJ Collective	MCJ Collective
Prime Impact Fund	Prime Impact Fund
XPRIZE Carbon Removal	XPRIZE Carbon Removal

F. RStudio Codes

a. *R Programming Code for* ***Network 1***

```
library(igraph)
cdr_edgelist_purchasers <- read.csv("cdr_edgelist_purchasers.csv")
cdr_attributes_purchasers <-
read.csv("cdr_attributes_purchasers.csv")
cdrNetwork_purchasers <- graph_from_data_frame(d =
cdr_edgelist_purchasers, directed = TRUE, vertices =
cdr_attributes_purchasers)
V(cdrNetwork_purchasers)$color <-
  ifelse(V(cdrNetwork_purchasers)$Type_CDR ==
           "Biochar", "sienna1", "lightgray")
V(cdrNetwork_purchasers)$color <-
  ifelse(V(cdrNetwork_purchasers)$Type_CDR ==
           "DAC", "red3", V(cdrNetwork_purchasers)$color)
V(cdrNetwork_purchasers)$color <-
  ifelse(V(cdrNetwork_purchasers)$Type_CDR ==
           "Mineralization/Enhanced Weathering", "yellow2",
V(cdrNetwork_purchasers)$color)
V(cdrNetwork_purchasers)$color <-
  ifelse(V(cdrNetwork_purchasers)$Type_CDR ==
           "Biomass", "chartreuse4", V(cdrNetwork_purchasers)$color)
V(cdrNetwork_purchasers)$color <-
  ifelse(V(cdrNetwork_purchasers)$Type_CDR ==
           "Ocean Carbon Capture", "cyan3",
V(cdrNetwork_purchasers)$color)
cdrNetwork_purchasersCore <- delete_edges(cdrNetwork_purchasers,
     E(cdrNetwork_purchasers)[weight<100])
Isolated = which(degree(cdrNetwork_purchasers)==0)
cdrNetwork_purchasersIso =delete.vertices(cdrNetwork_purchasers,
Isolated)
V(cdrNetwork_purchasersIso)$size <-
V(cdrNetwork_purchasersIso)$Tons_Sold/300+5
```

```
tkplot(cdrNetwork_purchasersIso,
     layout = layout_nicely(cdrNetwork_purchasersIso),
     vertex.label.color = "black",
     vertex.label.family = "Arial",
     vertex.label.font = 2,
     vertex.label.cex = .9,
     vertex.frame.color = "lightgrey",
     edge.curved = 0.1,
     edge.width = E(cdrNetwork_purchasersIso)$weight/200,
     edge.color = "grey",
     edge.arrow.size = .8)
legend("topright", legend=c("Biochar", "Direct Air Capture",
"Mineralization", "Biomass CDR", "Ocean CDR"), col=c("sienna1",
"red3", "yellow2", "chartreuse4", "cyan3"), pch=20)
```

b. *R Programming Code for* ***Network 2***

```
library(igraph)
cdr_edgelist_investors <- read.csv("cdr_edgelist_investors.csv")
cdr_attributes_investors <- read.csv("cdr_attributes_investors.csv")
cdrNetwork_investors <- graph_from_data_frame(d =
cdr_edgelist_investors, directed = TRUE, vertices =
cdr_attributes_investors)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "CDR Supplier", "peru", "olivedrab2")
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Venture Capital/Incubator", "tomato2",
V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Research Institute/University", "lightyellow1",
V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "NGO", "lightpink", V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Philanthropy", "springgreen4",
V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Government", "skyblue", V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
```

```
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Industry Group", "orchid3",
V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Key CDR Document", "lightgoldenrod1",
V(cdrNetwork_investors)$color)
Isolated = which(degree(cdrNetwork_investors)==0)
cdrNetwork_investorsIso = delete.vertices(cdrNetwork_investors,
Isolated)
incentrality <- degree(cdrNetwork_investorsIso, mode = c("in"))
proportional_incentrality <- (incentrality - min(incentrality)) /
diff(range(incentrality))
tkplot(cdrNetwork_investorsIso,
       layout = layout_nicely(cdrNetwork_investorsIso),
       vertex.label.color = "black",
       vertex.label.cex = .9,
       vertex.label.family = "Arial",
       vertex.label.font = 2,
       vertex.frame.color = "lightgrey",
       vertex.size = proportional_incentrality*60+5,
       edge.curved = 0.1,
       edge.width = 0.7,
       edge.color = "grey",
       edge.arrow.size = .8)
legend("topleft", legend = c("CDR Supplier",
                             "Venture Capital",
                             "Research Institute/University",
                             "NGO",
                             "Philanthropy",
                             "Government",
                             "Industry Group",
                             "Corporation",
                             "Key CDR Document"),
                  col = c("peru", "tomato2", "lightyellow1",
"lightpink", "springgreen4", "skyblue", "orchid3", "olivedrab2",
"lightgoldenrod1"), pch = 19)
```

c. R Programming Code for ***Network 3***

```
library(igraph)
cdr_edgelist_investors <- read.csv("cdr_edgelist_investors.csv")
cdr_attributes_investors <- read.csv("cdr_attributes_investors.csv")
```

```
cdrNetwork_investors <- graph_from_data_frame(d =
cdr_edgelist_investors, directed = TRUE, vertices =
cdr_attributes_investors)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "CDR Supplier", "peru", "olivedrab2")
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Venture Capital/Incubator", "tomato2",
V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Research Institute/University", "lightyellow1",
V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "NGO", "lightpink", V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Philanthropy", "springgreen4",
V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Government", "skyblue", V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Industry Group", "orchid3",
V(cdrNetwork_investors)$color)
V(cdrNetwork_investors)$color <-
  ifelse(V(cdrNetwork_investors)$Type_Org ==
           "Key CDR Document", "lightgoldenrod1",
V(cdrNetwork_investors)$color)
Isolated = which(degree(cdrNetwork_investors)==0)
cdrNetwork_investorsIso =delete.vertices(cdrNetwork_investors,
Isolated)
outcentrality <- degree(cdrNetwork_investorsIso, mode = c("out"))
proportional_outcentrality <- (outcentrality - min(outcentrality)) /
diff(range(outcentrality))
plot(cdrNetwork_investorsIso,
       layout = layout_nicely(cdrNetwork_investorsIso),
       vertex.label.color = "black",
       vertex.label.cex = .9,
       vertex.label.family = "Arial",
       vertex.label.font = 2,
       vertex.frame.color = "lightgrey",
```

```
       vertex.size = proportional_outcentrality*60+5,
       edge.curved = 0.1,
       edge.width = 0.7,
       edge.color = "grey",
       edge.arrow.size = .8)
legend("topleft", legend = c("CDR Supplier",
                             "Venture Capital",
                             "Research Institute/University",
                             "NGO",
                             "Philanthropy",
                             "Government",
                             "Industry Group",
                             "Corporation",
                             "Key CDR Document"),
                  col = c("peru", "tomato2", "lightyellow1",
"lightpink", "springgreen4", "skyblue", "orchid3", "olivedrab2",
"lightgoldenrod1"), pch = 19)
```