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Carbon Geoengineering and the Metabolic Rift: Solution or Social Reproduction?

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Abstract
Using the concepts of metabolism and metabolic rift as a framework, this paper examines carbon geoengineering technologies as a solution to climate change and explores if it is possible to mend an ecological metabolic rift without fundamental changes in the social metabolic order. Carbon geoengineering technologies have become a key component of scenarios to limit the extent of global warming and are being discussed as a means to sequester carbon and, therefore, mend the carbon cycle. However, most applications of carbon geoengineering thus far do not result in net negative emissions. Strategies to make operations profitable result in neutral or positive, rather than negative, emissions. While these strategies have the potential to reduce greenhouse gas concentrations, the current social order constrains their use and effectiveness. Instead of being applied as part of the solution to climate change, carbon geoengineering is being strategically promoted by the fossil fuel industry in ways that serve to reproduce and maintain the current social order.

Keywords
metabolism, metabolic rift, environment, carbon, geoengineering, capture, sociology

Introduction

In October 2018, the Intergovernmental Panel on Climate Change (IPCC) released a special report stating that agreements to keep global warming within 2°C of preindustrial temperatures should be

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reconsidered and that even an average temperature increase of 1.5°C would mean substantial changes in ecological and social systems. The report calls for "rapid, far-reaching and unprecedented changes in all aspects of society" to keep warming below 1.5°C (IPCC, 2018). Highlighted in the report is the necessary use of negative emissions technologies (NETs), or strategies that result in the net movement of carbon from the atmosphere to within the Earth's surface—the opposite of fossil fuel extraction and combustion. Increasingly these technologies are being referred to as "carbon geoengineering," a broad term to describe strategies for the purposeful movement of carbon in this manner. As stated in news coverage of the IPCC report, "carbon removal is now an absolute necessity for avoiding worst-case scenarios" and through using carbon geoengineering "we can tweak the carbon cycle" (Irfan, 2018). Following the release of the report, carbon geoengineering companies have received increasing levels of financial investment (Magill, 2018).

Carbon geoengineering technologies are now considered essential in limiting warming due to increasing levels of greenhouse gas (GHG) emissions. Given the critical role of NETs as described in IPCC reports, climate policy scenarios, and in the media, a closer analysis of carbon geoengineering is warranted. Recent reports offer an abundance of information on technical and economic feasibility (Bui et al., 2018; National Academy of Science, 2018). Here, we offer an alternative analysis grounded in Marxist theory. Specifically, we revisit the concepts of metabolism and metabolic rift to frame carbon geoengineering. Given the goals of using carbon geoengineering to "tweak the carbon cycle" (Irfan, 2018), we examine if it can contribute to mending the metabolic rift causing climate change. We examine how carbon geoengineering might alter carbon metabolism as well as how this effort is shaped and limited by the social metabolic order (defined below). While metabolism and metabolic rift have been critical for understanding drivers of environmental problems, we apply these concepts to evaluate carbon geoengineering as a proposed solution.

Metabolism and Metabolic Rift

The concepts of metabolism and metabolic rifts can be seen as "the core element of [Marx's] ecological critique" (Foster, 2002: 74). While Marx discussed both a social and ecological conception of metabolism, their empirical interconnectedness, which Clark and Foster (2010) have termed "the dialectic of social and ecological metabolism," is most relevant to understand environmental problems. Below, we briefly review the concept of metabolism, highlighting the interconnectedness between notions of social and ecological metabolism, introduce the concept of metabolic rift, and illustrate how these concepts support an understanding of climate change.

In a capitalist society the drive for profit produces a particular social metabolism. Marx (1973: 158) argued that exchange value's dominance under capitalism creates a system "of general social metabolism, of universal relations, of all-round needs and universal capacities . . . formed for the first time" where isolated individuals are socialized by an alienated commodity dependence. In another reference to "social metabolism," Marx (1970: 51–52) noted that "[t]he exchange of commodities is the process in which the social metabolism . . . gives rise to definite social relationships of production, into which individuals enter in the course of this metabolism."

This social metabolism is linked to ecological metabolism. The primary use of "metabolism" by Marx (1977: 283) was to explain the relationship between humans and nature through labor: the labor process is "the universal condition for the metabolic interaction [*Stoffwechsel*] between man and nature, the everlasting nature-imposed condition of human existence" (1977: 290). In other words, the relationship between society and nature is a necessary one, because nature supplies material needs.

These notions of metabolism illustrate how ecological problems are directly linked to "capital's order of social metabolic reproduction" (Mészáros, 1995: 39). Mészáros argues that capital's social metabolic order does not, and cannot, recognize absolute boundaries (i.e. natural limits) due to its "uncontrollability." The basis of its uncontrollability is capital's blind and endless "totalizing" quest for accumulation and self-expansion that subjects all aspects of society and nature (e.g. education, health care, agriculture, art, manufacturing, and commerce) to its pursuit (1995: 41). Under such a social metabolic order, the reproductive demands of both society and ecosystems are compromised in pursuit of profit. The most significant part of Mészáros' development of "social metabolism" is stressing the fundamental role of exchange value in shaping society and its relation with nature. The dominance of exchange value and the never-ending drive for profits has profound consequences for the degradation of society and nature—pushing society beyond ecological limits. The dominance of exchange value over use value pushes capital's social metabolic order "to transcend whatever social or natural limits it confronts" (Clark and Foster, 2010: 131)—no matter how socially and ecologically destructive the consequences. As stated by Mészáros (1995: 173),

> [n]either the degradation of nature nor the pain of social devastation carries any meaning at all for its [capital's] system of social metabolic control when set against the absolute imperative of [capital's] self-reproduction on an ever-extended scale.

Thus, social metabolism dominates the whole metabolism of the socio-ecological world.

Scholars have used the concept of metabolism to examine how society alters biophysical cycles creating "metabolic rifts" that result in environmental problems (Ergas and Clement, 2016). In his seminal publications, Foster (1999, 2000) examines the concept as applied by Marx to soil fertility. Privatization and land enclosure forced large portions of rural populations to move into cities. Intensive agricultural methods, the lack of human waste for fertilizer, and the long-distance trade of food and fiber to these cities "disturbs the metabolic interaction between man and the earth, i.e. it prevents the return to the soil of its constituent elements consumed by man in the form of food and clothing." The human waste that was once used for fertilizer accumulated in the cities. These processes "provoke an irreparable rift in the interdependent process of social metabolism, a metabolism prescribed by the natural laws of life itself" (Marx, 1981: 949).

Since Foster's work (1999, 2000), other scholars have examined how the concept of metabolism can illuminate relationships and identify dangerous rifts in socio-ecological systems. Clausen and Clark (2005) apply metabolic rift theory to explore environmental degradation in marine ecosystems. Capitalist fisheries have caused a metabolic rift through the depletion of global fish stocks. This in turn undermines the fisheries industry, which is seeking "quick fixes" through investing in aquaculture. Clark and York (2005) apply the concept of metabolism to changes in the global carbon cycle. They identify capitalist production as a driver of GHG emissions—furthering increased production, energy extraction, and combustion of fossil fuels. They explain that climate change emerged as a result of a metabolic rift in the carbon cycle: capitalism has created a rift through releasing more carbon emissions than can be absorbed. In their book *The Ecological Rift*, Foster et al. (2011) comprehensively apply metabolic analysis to reveal the devastating effects that capitalism has had on planetary systems.

We extend the work of Clark and York (2005) and Foster et al. (2011) to further examine the intersection of ecological and social metabolism in the carbon cycle. Carbon that once remained for thousands or millions of years underground has been extracted at an increasing rate, burned, and emitted into the atmosphere. As Clark and York (2005: 406) explain, this rift is the result of human activities aimed to maximize profits:

> Previous modes of production primarily lived and operated within the "solar-income constraint," which involves using the immediate energy captured and provided by the sun. By mining the earth to remove

> stored energy (past plants and animals) to fuel machines of production, capitalist production has broken the solar-income budget constraint, and this has thrown [society] out of ecological equilibrium with the rest of the biosphere.

In other words, acting within the social metabolic order of capitalism humans have harnessed energy, in the form of fossil fuels, to further efforts to accumulate capital. As explained further by Clark and York (2005: 408), “[t]here is no drive to maintain the social metabolism in relation to the natural metabolism” and “[g]iven the logic of capital and its basic operations, the rift in the carbon cycle and global climate change are intrinsically tied to capitalism.”

As increasing global temperatures threaten the future survival of humans, ecosystems, and all other species (IPCC, 2018; IPBES, 2019), an increasing number of solutions are being put forth to address the rift in the carbon cycle. Climate change mitigation efforts have primarily focused on the “greening” of markets, policies, and technologies to reduce GHG emissions with limited to no success (Gunderson et al., 2018a). As the situation appears increasingly dire, others have proposed ways to “geoengineer” the climate, addressing the issue as an engineering problem that can be solved through tweaking specific levers. Advocates of geoengineering claim that it will be difficult or impossible to limit global temperature increases to 1.5 or 2°C above preindustrial levels without technological interventions that either reduce solar radiation or pull GHGs out of the atmosphere (Connolly, 2017). These strategies are being taken seriously, with the IPCC holding an “Expert Meeting on Geoengineering” in 2011 and the IPCC reports increasingly discussing geoengineering for climate change mitigation (IPCC, 2012, 2014, 2018). In response to the IPCC special report (2018), carbon geoengineering has received unprecedented attention as a necessary way to mend the growing rift in the carbon cycle.

While metabolic framing has been widely used to understand environmental problems, we apply metabolic framing to examine a proposed solution. In the sections that follow, we examine the potential for specific carbon geoengineering strategies to address the rift in the carbon cycle and if it is possible to technologically mend this rift within a profit-driven capitalist social order (metabolism). Our primary question: *is it possible to mend the rift in carbon metabolism without fundamental changes in the social metabolic order?*

Carbon Geoengineering

We use the term carbon geoengineering as a broad term to include strategies that aim to capture and sequester carbon, either from sources of combustion or from the atmosphere, and store it in the Earth’s surface. While the IPCC and other scientists are primarily focused on NETs, which by definition result in a net removal and storage of carbon, many strategies claiming to capture or store carbon do not actually result in negative emissions, yet they are promoted as carbon geoengineering solutions. We include these strategies specifically to illustrate how they represent *false solutions* promoted for specific purposes. While there are also "natural climate mitigation” strategies (more on these later) we focus on the “high-tech” strategies that are receiving the most media attention and funding.

The clearest potential environmental benefit of carbon geoengineering is carbon emission abatement. As stated by Moreno-Cruz et al. (2018: 4),

> as long as emissions are not set to zero, there is no clear distinction on the effects of mitigation or carbon geoengineering in the climate-carbon system . . . [yet] unlike mitigation alone, it can lead to net-negative changes in the atmospheric CO_2 stock in any given year, much faster than natural processes.

Many strategies are associated with carbon geoengineering, but they vary greatly in their approach, aims, and results. In the following text we briefly review the primary “high-tech” strategies associated with carbon geoengineering and highlight their possible effectiveness in the current social metabolic order. Like others (e.g. Robock, 2008; Matthews, 2012), we include carbon capture and storage as a geoengineering strategy, though some argue that it is more accurately defined as a mitigation strategy (e.g. Vaughan and Lenton, 2011). As we will illustrate, some of these promoted solutions are not NETs. It is important to illustrate why they represent false solutions.

Post-Combustion Carbon Capture and Storage

Post-combustion carbon capture and storage (CCS) is a widely discussed and promoted strategy, yet it is not an NET. It refers to capturing CO_2 at sources of fossil fuel combustion, such as coal or gas-fired power plants (de Coninck and Benson, 2014; Leung et al., 2014; Pires et al., 2011; Wennersten et al., 2015). Put simply, post-combustion CCS "involves the CO_2 capture at the point of generation, compressing it to a supercritical fluid, and then sequestering it" for long-term storage in "sinks" underground or under the ocean (Leung et al., 2014: 1446). In this way, post-combustion CCS can result in carbon neutrality for fossil fuel-based power plants. While some argue CCS is not truly a "geoengineering" strategy and others call it "clean fossil" (e.g. Markusson, 2017), because it is often bundled with other carbon geoengineering approaches that aim to store carbon through the use of technology, we include it here in our analysis.

Despite the potential for carbon-neutral energy production, very few post-combustion CCS examples exist. Scientists and engineers have been developing post-combustion CCS technology since the 1950s (Keith et al., 2018); however, it was not until the late 1990s and early 2000s that industrial-scale post-combustion CCS projects began to emerge (de Coninck and Benson, 2014). To date only a handful of demonstration projects exist and after decades of research have yet to show that these projects are economically viable: they cost approximately $1 billion and without carbon pricing or technology mandates both private and government investment has remained minimal (Reiner, 2016).

A reporter in *Forbes* (Stone, 2018) recently described the one "working scale" post-combustion CCS power plant in the USA:

> NRG Energy's Petra Nova coal power plant in Texas captures 1.4 million tons of CO_2 per year. For perspective, that's about four millionths (4 × 10-6) of the 37 gigatons of global yearly anthropogenic emissions. Captured CO_2 from this coal plant is sent via 80 miles of bespoke pipeline to an oil field where it is injected into oil wells, helping to push out more oil and, in clear irony, perpetuating the fossil fuel cycle.

This CCS facility captures 33% of carbon emissions from only one combustion unit, uses natural gas in the conversion process, and pumps the captured carbon to an oil field boosting oil extraction from 300 to 15,000 barrels each day. In addition, it is not certain what amount of the injected carbon remains underground. This system was designed to further fossil fuel extraction in order to increase profitability. Therefore, it is not even a carbon-neutral CCS facility when the combustion of the fossil fuels extracted is considered. While post-combustion CCS could be designed to create carbon-neutral power plants through direct storage (without increasing fossil fuel extraction), due to a lack of profitability, development of this strategy has largely stagnated (National Academies of Sciences, Engineering, and Medicine, 2018) due to the constraints in the dominant social order to prioritize profit.

Enhanced Oil Recovery

Even more paradoxical is the promotion of CO_2 enhanced oil recovery (CO_2-EOR) as a technological solution to climate change, also not an NET. CO_2-EOR continues to be promoted as part of the solutions portfolio to address climate change (Biello, 2009; IEA, 2015), yet is another false solution promoted for specific purposes. As described earlier as part of the Petra Nova operation, CO_2-EOR involves injecting CO_2 into depleted or near depleted oil and gas reserves in order to extract otherwise unrecoverable reserves (Leung et al., 2014). It has been used for decades in the oil and gas industry. The majority of the CO_2 injected underground stays underground, although it depends on geological and operations details (Azzolina et al., 2015) and some CO_2 could leak back into the atmosphere (Bruhn et al., 2016). Marriot (2013) claims that approximately 95% of the CO_2 remains permanently sequestered underground. Most CO_2 sources in CO_2-EOR come from large natural reservoirs underground, not from industrial sources or direct air removal, but the potential exists to design CO_2-EOR for maximizing "net" carbon storage.

The "net" carbon storage referred to by proponents of CO_2-EOR is defined within the boundaries of the stand-alone EOR project and fails to consider the CO_2 emitted from the combustion of the oil recovered. Looking at data from multiple CO_2-EOR projects, Jaramillo et al. (2009) find that between 3.7 and 4.7 metric tons of CO_2 are emitted for every metric ton of CO_2 injected. Energy Justice Network (2018) also gathered data from CO_2-EOR projects and calculated total CO_2 emissions: for a project in Saskatchewan 2.8 times more CO_2 is released from extracted oil than is sequestered, and for another CO_2-EOR project in Texas 47% of the amount of CO_2 pumped underground is re-released through the burning of the extra oil produced.

Although CO_2-EOR results in additional fossil fuel extraction and therefore a net increase in GHG emissions, CO_2-EOR continues to be promoted as an effective and profitable CCS solution. A 2009 *Scientific American* article, titled "Enhanced Oil Recovery: How to Make Money from Carbon Capture and Storage Today," focuses on the financial benefits of EOR as a carbon storage method (Biello, 2009). More recently the profitability of CO_2-EOR was highlighted by the International Energy Agency (2015) in their report titled *Combining EOR with* CO_2 *Storage for Profit*: "Novel ways of conducting CO_2-EOR could help achieve a win-win solution for business and for climate change mitigation goals, offering commercial opportunities for oil producers while also ensuring permanent storage of large quantities of CO_2 underground."

The International Energy Agency proposes EOR+, which adds the goal of carbon storage to EOR, and highlights approaches that can be "economically interesting" for industry, and encourages "co-exploiting the storage of CO_2 with oil extraction to generate more profits." These arguments fail to consider the total increase in GHG emissions from the fossil fuels extracted through EOR, indicating an assumption that CO_2-EOR is a useful strategy because these fossil fuels would be extracted and burned anyway. This "win-win" strategy is increasingly supported by the US government: the Department of Energy announced new funding for EOR projects in October 2018, only days after the IPCC released their special report (DOE, 2018).

Bioenergy With Carbon Capture and Storage

Bioenergy with CCS (BECCS) is the strategy most widely incorporated into current integrated assessment models (IAMs) used to guide climate policy and international agreements (Anderson and Peters, 2016). Of all the scenarios showing a high likelihood of staying within a 2°C target, 87% include widespread BECCS (Fuss et al., 2014). The National Academy (2018) explains that the inclusion of BECCS rather than other strategies in IAMs is a result of BECCS' potential affordability and that modules for other removal technologies remain undeveloped. As explained by Fridahl (2017: 89), BECCS involves carbon being sequestered in plants that are then burned for power generation while capturing and storing the carbon emissions from combustion:

> The logic is simple: as plants grow they encapsulate atmospheric CO_2 in biomass that is harvested and used to produce, for example, electricity, heat, biofuels, and pulp/paper. Instead of allowing the CO_2 to

recirculate into the atmosphere, it is captured, transported, and deposited in long-term geological storage sites.

In this way, BECCS has the potential to result in negative carbon emissions (Pour et al., 2017).

However, BECCS remains primarily theoretical with the only empirical evidence from separate bioenergy and CCS facilities and a single ethanol-based BECCS demonstration plant (Anderson and Peters, 2016; Global CCS institute, 2016; Turner et al., 2018). Adding CCS to BE power plants also involves significant and possibly prohibitive added costs (National Academies of Sciences, Engineering, and Medicine, 2018). In addition, analyses of BECCS illustrate that finding suitable land, storage basins, and biomass availability limits potential negative emissions, as well as issues related to the transportation of biomass and CO_2 and social and political barriers (Baik et al., 2018; Fridahl and Lehtveer, 2018; Turner et al., 2018). Plants or crops grown for energy also compete with food crops for available agricultural lands (National Academies of Sciences, Engineering, and Medicine, 2018). Given these constraints and unknowns, Anderson and Peters (2016: 182, 183) argue that the prominence of BECCS in emissions scenarios and policy formulation is “disturbing” and represents a “high-stakes gamble.” To date, there has been little to no implementation of BECCS, and it remains an “effective” strategy only in theory. It is far from achieving the results suggested by its use in IAMs and has yet to show it can be the ultimate “rift mending” solution.

Direct Air Capture

Direct air capture (DAC) and storage has been called the only high-tech carbon geoengineering strategy that could be truly carbon negative (Siegel, 2018). It involves taking carbon directly from the air and sequestering it underground. Locations for DAC can be chosen based on the best storage possibilities, since the carbon can be captured from air anywhere (Wang et al., 2015). It has substantial negative emissions potential; however, it requires a significant amount of energy: one estimate states that DAC requires 0.3 megawatt-hours per metric ton of captured CO_2, roughly equivalent to 35% of the total output of a typical power plant (Senftle et al., 2017). Total negative emissions, therefore, depend on the source of energy used. As explained by the National Academy of Sciences (2018), DAC “requires a tremendous amount of energy and if the energy demands are met through fossil fuel energy sources then it greatly reduces potential CO_2 sequestration.” In addition, it is the most expensive carbon geoengineering approach because capturing diffuse CO_2 from the atmosphere requires considerably more energy than capturing more concentrated CO_2 from a site of combustion. Scientists and engineers have developed DAC technology to transform CO_2 into either a solid or a liquid; however, processes to create a solid are more expensive and pose more logistical challenges for operations (Keith et al., 2018). Creutzig et al. (2019) argue that DAC outperforms BECCS, as it requires less energy and land, and argue that DAC powered by renewable energy has great potential. Despite this potential, a shift to renewable energy–powered DAC would still use a significant amount of water (Fasihi, et al., 2019; Smith et al., 2016; Socolow, 2011) and mineral resources (for wind and solar) that are becoming increasingly scarce (Moreau et al., 2019). Without further innovations, the resource requirement of DAC would likely limit widespread application globally—yet this is not the primary constraint currently limiting DAC expansion.

The technology to rapidly expand DAC exists, yet this expansion currently remains constrained by the economics. As explained in a National Academy of Sciences report (2018), “[d]irect air capture flux and capacity potential has no fundamental physical limit, making its primary limitation financial.” Stone (2018) similarly states that DAC may have the most potential for negative emissions, but it remains largely undeveloped due to higher costs and no profitable product for sale. Therefore, the carbon geoengineering companies that have designed and created DAC facilities (including Carbon Engineering, Climeworks, Global Thermostat, Infinitree, and Skytree) have focused on converting CO_2 into a usable product for sale, or DAC and utilization (Siegel, 2018; National Academies of Sciences, Engineering, and Medicine, 2018).

Direct air capture and utilization (DACU) turns the captured carbon into a usable product. The degree of carbon sequestration depends on what kind of product is produced. As explained by the National Academy of Sciences (2018), when discussing if DACU can be considered a NET,

> Capture and reuse in short-lived products, like chemical fuels, is not included in this report as a NET, because the carbon in the products would be returned quickly to the atmosphere. However, capture in long-lived products, like many structural materials, is included, because the product itself is then the storage reservoir.

Similarly, Bui et al. (2018) explain the range of effectiveness of DACU projects. Products are only carbon-negative if atmospheric CO_2 is used to make a solid product that is more stable than CO_2 and will provide long-term storage. Otherwise products that produce chemicals or fuels offer only temporary storage that is carbon neutral (Bui et al., 2018).

However, due to the higher costs associated with conversion into a solid (Keith et al., 2018), most DACU projects involve turning CO_2 into a short-lived product. The most developed use is turning CO_2 into fuel products, reusing carbon to substitute for extracted fossil fuels (Bruhn et al., 2016). Start-up firm Carbon Engineering has been working on a "low-cost" method to turn CO_2 into usable fuels or "carbon-neutral hydrocarbons" (Keith et al. 2018; Meyer, 2018). However, as explained by Cuellar-Franca and Azapagic (2015: 83), "using CO_2 for fuel production only delays its emissions rather than removing it over long timescales needed for mitigating climate change."

DACU project development is shaped by economic considerations. Senftle and Carter (2017) state that CCU is "shaped by economic limitations" and to "achieve the Holy Grail, novel chemistries must allow profits derived from processing CO_2 feedstocks to outweigh the cost of capture, transportation, and conversion." As explained in an article by Siegel (2018), the low-end cost estimates for DAC start at $600 per ton of CO_2, while carbon geoengineering companies are proposing using the carbon in products for sale that will bring down the costs significantly. Carbon Engineering's production and sales of transportation fuel is estimated to bring DACU costs down to as low as $94 per ton of CO_2. More recently, Global Thermostat announced plans to turn CO_2 into carbonation for soda and aim to bring costs down to $50 per ton of CO_2 captured. These companies have designed ways to "recycle" CO_2 but these methods represent temporary carbon storage and do not result in negative emissions.

Although most of the facilities in operation can only claim to be carbon neutral, rather than an NET, financial support for DACU projects has significantly increased. The latest US federal budget contained the Furthering Carbon Capture, Utilization, Technology, Underground Storage, and Reduced Emissions Act (FUTURE Act), which would provide tax credits for each ton of CO_2 captured and utilized. In addition, following the IPCC special report (2018), carbon geoengineering companies received a surge of investment. Global Thermostat received five investment offers in a single day that added up to $200 million (Magill, 2018). These firms hope that with increasing government incentives and a potential future carbon market or tax, their initiatives will become increasingly profitable (Siegel, 2018). Until social conditions change, DAC and DACU have limited possibilities for mending our carbon rift.

Captured by Capital

In their current state of development, carbon geoengineering technologies will not result in the negative emissions necessary to mend the rift in the carbon cycle. Three of the strategies (framed as solutions) are not actually NETs: DACU, post-combustion CCS, and EOR. The two strategies with negative emissions potential, BECCS and DAC, have not been developed or implemented widely. BECCS remains an effective NET in theory, but has yet to be put to real use. DAC technologies are further developed, but the extensive costs involved have resulted in DACU to create a short-lived product, which makes the technology carbon neutral rather than an NET. Returning to the metabolism framework and our question—"is it possible to mend the rift in carbon metabolism without fundamental changes in the social metabolic order"—we find that while some carbon geoengineering technologies exist with the potential to contribute to mending the rift in the carbon cycle, capitalism continues to drive our social metabolism, limiting what is possible. DAC especially illustrates this relationship.

Increasing evidence suggests that DAC implemented widely and powered by solar or wind energy for long-term storage *could* result in meaningful carbon sequestration. Because it is so energy intensive, any DAC projects powered by fossil fuels will not be a NET. However, Wohland et al. (2018) find that DAC powered by variable renewables is a promising approach that can result in negative emissions of up to 500 metric ton (Mt) CO_2/year in Europe, using excess renewable energy only. Breyer et al. (2019) examine a regional model for DAC fully powered by wind and solar and conclude that possibilities for implementation and the benefits of these systems have been widely overlooked. While renewable energy–powered DAC has potential, limitations still exist and there are good reasons to be skeptical of widespread implementation at a level that would be significantly effective. While it may be a useful tool it is not a panacea. For example, if renewable-powered DAC becomes a real technical possibility, it would be important for policy and implementation to simultaneously phase-out fossil fuel extraction and use. At this time, new units of renewable energy do not substantially displace units of fossil fuel-based energy (York, 2012). Fossil fuel development has steadily increased despite the comparably slight expansion of renewables (York and Bell, 2019) and, without simultaneously reducing fossil fuel development, renewable energy development may contribute to *increases* in energy use by increasing supply, thereby spurring demand (York, 2016; Zehner, 2012). Without simultaneously phasing out fossil fuels, renewable-powered DAC projects could inadvertently contribute to the expansion of fossil fuel consumption and carbon emissions.

For the time being, efforts to make DAC profitable have resulted in carbon-neutral DACU operations. In this way, DAC has been captured by capital. In a world governed by economic rationality, DAC without a product to make it profitable is *irrational*. As stated by Bui et al. (2018), the need for carbon geoengineering is critical yet in the current political and economic system it is not a rational investment. Incentivizing negative emissions projects through the right carrots and sticks could make conditions more favorable (Bellamy, 2018). However, in a different social order moving beyond the profit imperative and market-based approaches, more direct and effective policies could be implemented. For example, following a model of public ownership over energy systems (see Gunderson et al., 2018b), DAC could be designed in conjunction with solar and wind projects to support a NET network. Two ownership and governance models are relevant moving forward: (1) a national DAC program (i.e. ownership and control of DAC development and implementation by the state) or (2) cooperative ownership and governance of DAC. The first step would likely be (1), though there is much to be learned from the trials and errors of renewable energy cooperatives and the movements surrounding "community energy" and "energy democracy" (e.g. Kunze and Becker, 2015). While DAC is less amendable to decentralized control compared to solar and wind, experimenting with local- and state-level collective ownership and governance models is desirable and possible.

While DAC could play a positive role, it is not a panacea and cannot be a substitute for emissions reduction. It is far from a "silver bullet" or stand-alone strategy. Even with renewable energy sources, DAC technologies remain energy and resource intensive: one study found DAC would require up to one quarter of global energy supplies (Realmonte et al., 2019). As the full potential of NETs is unknown and often overestimated in models, McLaren et al. (2019) argue that negative emissions targets should be set and managed completely separately from emissions reductions. In addition, the exaggerated account of NETs reduces actions for mitigation (or deters mitigation), increasing potential climate risks (Markusson et al., 2018). Similar to other geoengineering strategies, these NETs serve to "buy time" (a temporal fix), yet fail to challenge hegemonic drivers of climate change (Surprise, 2018).

The focus on technological means to sequester carbon, and the related profits for carbon geoengineering companies, overlooks other and likely more beneficial ways to remove carbon that are often referred to as "natural climate solutions" (Buck, 2018). These solutions include afforestation, reforestation, and restoring ecosystems (National Academies of Sciences, Engineering, and Medicine, 2018). These strategies should be supported for reasons beyond climate change, including critically needed biodiversity conservation (IPBES, 2019), have the potential to be highly effective (Monbiot, 2019), and we believe are highly preferable to any other carbon storage scheme examined in this paper. However, they have received a small amount of attention and financial investment compared to "high-tech" negative emission strategies. This illustrates how specific social factors (e.g. the profit maximization that dominates our social metabolic order) shape which sequestration strategies are promoted as solutions and which are overlooked (Buck, 2016).

Based on what is currently known about negative emissions potential, carbon geoengineering strategies in general should only be one approach among a portfolio of actions necessary to reduce GHG emissions and limit global warming. Due to energy demands, carbon geoengineering will likely not create the negative carbon flows required to return atmospheric CO_2 levels back to the "safe" levels (Wennersten et al., 2015). In other words, there is currently no ultimate techno-fix to mend the rift in the carbon cycle. In addition, there are concerns about the potential environmental and political impacts of carbon geoengineering (e.g. de Coninck and Benson, 2014; Carrington, 2018; National Academies of Sciences, Engineering, and Medicine, 2018). While carbon geoengineering could play a role in reducing warming trends, the "rapid, far-reaching and unpresented changes in all aspects of society" called for in the IPCC special report necessitate significant social-structural changes that make phasing out fossil fuels, increasing renewable energy, expanding low-carbon modes of public transportation, and overall lower levels of production and consumption the new norm (Gunderson et al., 2018a).

As promoted today, in many ways carbon geoengineering strategies serve to *perpetuate* the current driver of our social metabolism, namely the accumulation of capital. Indeed, powerful social interests back geoengineering strategies for this reason, among others (Foster, 2018; Gunderson et al., 2019b). In other words, they represent a strategy for *social reproduction* (Wright, 2010) and offer an unsound reason to delay cutting GHG emissions. The clearest potential economic benefit of carbon geoengineering, especially CCS, for the fossil fuel industry is that it "provides a vision" of a "carbon-constrained future" that still allows for fossil fuel use (Stephens, 2009: 36). CCS in particular reduces the economic threat of mitigation (see also Gibbins et al., 2006). CCS was embraced by the Bush administration "as an *alternative* to government regulation, emissions pricing and mandatory emission reductions" (Langhelle and Meadowcroft, 2009: 237, emphasis added). The fossil fuel industry has shifted from funding climate denialist research to increased interest in CCS as a solution that permits continued fossil fuel use (Stephens, 2009). Anderson and Peters (2016) calls carbon geoengineering technologies "mitigation on methadone" and explains how they allow us to continue along a path of high carbon emissions. This is highly risky: a recent report from the European Academies Science Advisory Council warns that policy depending on NETs instead of cutting emissions could fail and result in severe warming (Carrington, 2018).

The oil and gas industry has been particularly supportive of CCS. For example, Chevron played a role in developing the IPCC's Special Report on CCS (2005), the EU CCS Directive, and Australian, Canadian, and US policies related to CCS and also participated/invested in the Gorgon (Australia) and Quest (Canada) CCS projects (Chevron, "Greenhouse gas management"). Major oil and gas companies have also worked closely with government agencies to try to advance CCS technology (CO_2 Capture Project). As explained by Kruger (2017), CCS allows energy companies and governments with fossil fuel resources to continue to reap profits and accumulate wealth. Kruger (2017: 63) states that

> The presumed dominance of fossil fuels is actually one of the main reasons put forward in favor of CCS. Social structures are consolidated as unchangeable constants. Mitigation options are assessed against the background of the prevailing power relations and the current production and consumption patterns. With these preconditions CCS is valued as an important instrument to reduce the emissions caused by burning fossil fuels.

In these ways, carbon geoengineering has been captured by capital and it is being used as a strategy for social reproduction: it protects continued fossil fuel extraction and further increases profits for those who benefit from the current social order.

Conclusion: Toward a New Social Metabolism

Drawing from the concepts of metabolism and metabolic rift, we have examined carbon geoengineering strategies as a response to climate change. We specifically focus on the relationship between ecological and social metabolism. As our earlier discussion illustrates, this analysis shows limited possibilities for carbon geoengineering to contribute toward mending the carbon rift especially in our current social metabolic order. In other words, schemes aimed at mending an ecological rift remain constrained by the capitalist metabolic order that shapes what is rational and possible. While social and ecological metabolic processes are intertwined, resulting in phenomena such as climate change, our analysis indicates that recognizing both social and ecological metabolism separately serves to understand how one shapes the other. In this case, our current social metabolism governed by capitalism not only created an ecological rift, but also now constrains opportunities to mend the rift. In addition, carbon geoengineering technologies are being strategically used to protect and reproduce the current social order. In alternative social relations, DAC could play a greater and more positive role, despite its many limitations. However, optimizing "rift-mending" technologies like DAC would require new social relations prioritizing climate stability over capital accumulation—the current organizing principle of our social metabolism. Our analysis shows that metabolism and metabolic rift continue to be useful concepts to understand not only the drivers of environmental problems but also the limitations of proposed solutions. Again, we see how capital's social metabolic order dominates the whole metabolism of the socio-ecological world (Mészáros, 1995).

Can carbon geoengineering be an effective and *just* approach? Societies make choices about the different ends of a technology within the range of options made possible by the technology (e.g. Veblen, 1939; Cottrell, 1972; Feenberg, 1999), and innovation and use remain shaped by the values and interests of a given society (Bijker et al., 1987; MacKenzie and Wajcman, 1985), especially of those in power (Marcuse, 1964). In terms of social justice and specifically indigenous rights, Whyte (2018: 304) states that "[f]orces of domination render even the most well-intentioned solutions ineffective" and illustrates how climate change itself is result of "colonialism, capitalism and industrialization that continue to inflict violence and harm on Indigenous peoples" (287) and that geoengineering as a potential solution is constructed in a way that overlooks issues of ethics and justice, is likely to reinforce previous relations of domination, and increases risks to already vulnerable populations. Carbon geoengineering is on course to recreate the power asymmetries in the existing social order related to race, class, and gender. In contrast, if we transform our social order away from capitalism, the potential to address social justice including indigenous sovereignty and gender inequality increases. When the profitable decision is the only rational decision, it almost always precludes addressing social justice issues; alternatively, abandoning the profit imperative opens the door for more just transitions. There are possibly socially beneficial and just uses for carbon geoengineering, but these options remain constrained by ongoing power asymmetries and capital's social metabolic order. DAC represents another example of the contradiction between the potential of technologies to reduce environmental pressure and the institutionalized social relations that hamper this technical potential (Foster, 2002; Gunderson et al., 2018a). Instead of helping to transform society into a more sustainable and just social-ecological condition, it serves as a mechanism of social reproduction and maintains power relations and the domination of fossil fuel energy.

Technology can be specifically used for protecting nature and society, yet this requires liberation from the profit motive and use based on new substantive goals (Marcuse, 1964). In an alternate social metabolic order, carbon geoengineering has the potential to contribute to reducing CO_2 concentrations. For example, once freed from the profit imperative, DAC could be used in a way that maximizes carbon sequestration. However, in our current social order, the profit motive prevents such actions. Goldstein (2018) found similar trends examining environmental technology start-up companies: finding ways to be profitable constrains potential environmental benefits. While we still believe making the social-structural changes to rapidly reduce GHG emissions is the best and, in any case, necessary response to climate change (Stuart et al., forthcoming), we acknowledge that, in a different social context, NETs like DAC *could* be a part of a portfolio of strategies to address climate change. The full potential of DAC, however, cannot be realized in a capitalist system.

We are well aware of the false promises of eco-modernist techno-fixes to climate change, even when they are wrapped up in radical guise (e.g. see critique in Foster, 2017). An ecological society must abandon capital's social metabolic order, which is inherently unsustainable (Foster et al., 2010). However, this transition does not preclude the more effective and just use of technologies developed in, yet constrained by, capitalist social relations. While some climate technologies developed in current social conditions do not have the potential to be used for more rational ends, even if embedded in different social conditions (e.g. stratospheric aerosol injection) (e.g. Gunderson, 2019b), others do have the potential to be put to better use given new social relations (e.g. renewable energy) (Gunderson et al., 2018b). Whether a technology could be used for more rational ends in different social conditions requires an analysis of the given technology, an approach to technology assessment that is neither Promethean nor technophobic (Gunderson et al., 2019a). As awareness of these social relations and constraints increases, so do calls for social-structural transformation, for shifting priorities to put social and ecological well-being before profit, and for reducing total material and energy throughput to stay within ecological limits (Foster, 2010; Kallis, 2018; Kallis et al., 2012). These changes would truly involve "far-reaching and unprecedented changes in all aspects of society" (IPCC, 2018). In a society that no longer operates under the logic of profit maximization, the full potential of technological solutions to climate change may be realized.

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