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Carbon metabolism: Global capitalism, climate change, and the biospheric rift

BRETT CLARK and RICHARD YORK
University of Oregon

Abstract. There is widespread agreement in the natural sciences that observed increases in average global temperatures over the past century are due in large part to the anthropogenic (human generated) emission of greenhouse gases, primarily stemming from fossil fuel combustion and land use changes (e.g., deforestation). Many social processes have been identified for their contribution to climate change. However, few theoretical approaches have been used to study systematically the relations of the social with the biosphere. Our goal is to illustrate how the theory of metabolic rift provides a powerful approach for understanding human influence on the carbon cycle and global climate change. We extend the discussions of metabolism (the relationship of exchange between nature and humans) and metabolic rift to the biosphere in general and to the carbon cycle in particular. We situate our discussion of the metabolic rift in the historical context of an expanding, global capitalist system that largely influences the organization of human interactions with the environment. The general properties of a metabolic rift between nature and society include the disruption or interruption of natural processes and cycles, the accumulation of waste, and environmental degradation. Due to capitalism's inherent expansionary tendencies, technological development serves to escalate commodity production, which necessitates the burning of fossil fuels to power the machinery of production. As this process unfolded historically, it served to flood carbon sinks and generate an accumulation of carbon dioxide in the atmosphere. Technological "improvements" have actually increased the amount of resources used, since expansion in production typically outstrips gains in efficiency – a situation known as the Jevons paradox. The theory of the metabolic rift reveals how capital contributes to the systematic degradation of the biosphere.

Our aim here is to develop a broad theoretical foundation for understanding human influence on the global carbon cycle and the influence of climatic change (potentially stemming from ruptures in the carbon cycle) on societies. We build this theoretical foundation by drawing on sociological research, particularly in the field of environmental sociology, and insights from the historical materialist tradition, particularly Marx's concept of metabolic rift as developed by John Bellamy Foster. We utilized the strengths of metabolic rift theory for studying the nature-society dialectic and extend its application to understand global climate change, examining the connections between anthropogenic (human generated) influences on the carbon cycle and the accumulation of carbon in the biosphere, the inability of technological fixes to solve climate change given the "Jevons paradox," and the flooding and destruction of carbon sinks due to the ceaseless drive to accumulate capital.

The increasing concentration of carbon dioxide (CO_2) and other greenhouse gases, such as methane, in the atmosphere has likely contributed to the observed 0.6 °C increase in global temperatures over the past one hundred years. The Intergovernmental Panel on Climate Change (IPCC) now expects an increase in global temperature of 1.5–6.0 °C over this century.[1] Foster notes that an increase of 4 °C "would create an earth that was warmer than at any time in the last 40 million years," potentially threatening the survival of human civilization.[2] In the year 1999, over 23 billion metric tons of carbon dioxide were released into the atmosphere from industrial processes, half of it by the United States and Europe.[3] The IPCC estimates that global carbon emissions have to be reduced by 60 percent to prevent substantial climate change.[4] Yet, waste emissions continue to be created at a rate faster than natural systems can absorb them, contributing to the creation of a global ecological crisis.

As Rosa and Dietz note, "The capacity to support life on earth – and, therefore, all societies – depends on the moderating influences of gases that envelop the planet, warm its surface, and protect it from harmful radiation."[5] Human existence is perpetuated and social history is created through a material exchange with the larger natural world.[6] Alteration of this process of material exchange can potentially undermine the endurance of societies. The conditions found in nature and society influence and shape each other. This aspect of life is a constant. However, the specific ways this exchange is done are determined by a variety of historically organized social systems.[7] For several hundred years, capitalism has been the global hegemonic economic system, influencing human interactions with nature.

While the capacity of humans to transform nature in ways detrimental to societies has long been known, it is only recently that the social interactions with nature, as well as ecological limits, have become major subjects for sociologists.[8] The ecological sustainability of human societies is in question, as the scale of many environmental problems continues to escalate.[9] Of the multitude of environmental challenges societies face, global climate change has become one of the most pressing during the past decade. Physical scientists have conducted substantial research on the atmosphere and the global climate, widely agreeing that observed increases in average global temperatures are due to the emission of greenhouses gases generated by human societies. Increasingly, social scientists are making important contributions to the literature on climate change by examining a variety of social variables and social conditions that contribute to global warming: demographic trends, political treaties and policies, operations of economic systems, technological development, fuel efficiency, global inequalities in emissions, deforestation, social structures, appropriation of global commons, and ecological debt.[10]

An important strength of the environmental sociology literature on climate change is that it takes seriously the position that nature influences society and society influences nature. In this, it presents a valuable direction for environmental sociology in general. Furthermore, it breaks away from the reduction of nature to the status of simply being a raw material (natural resource), which, unfortunately, is quite common in the mainstream sociological literature.[11] Environmental-sociological research on climate change includes an understanding of the dynamic relationship between nature and society (where changes in each realm influence changes in the other) and the identification of the social processes that contribute to climate change. There are many important examples of sociological contributions to our understanding of human influence on the global climate. Rosa presents how human societies have an intimate interdependency with their ecological contexts and how alterations of natural processes can present grave consequences for the future sustainability of society.[12] Rudel analyzes the social forces that drive deforestation and the role deforestation plays in the accumulation of CO_2 in the atmosphere.[13] York, Rosa, and Dietz analyze how demographic and economic factors influence national rates of CO_2 emissions, revealing the drivers of global climate change.[14] Simply stated, nature is taken seriously in this literature.

Theorists from the world-systems perspective have made several important contributions to the literature on global climate change. By studying the position of countries in a global stratification system, they are able to reveal how economic inequalities and CO_2 emissions are related. Nations within the core are the primary polluters, given their scale of production and consumption and influence on the global economy.

But, scholars such as Roberts, Grimes, Manale, and Kentor have argued that nations in the periphery remain major CO_2 polluters and are unable to pursue more energy efficient paths of development (which is assumed to reduce CO_2 emissions in time), given that their economic development is bound and hindered by debt, export dependency, non-state of the art technology, and a narrow range of production.[15] Their focus is on how the structural conditions in the global society must be changed to allow for the development of more efficient technologies and greater efficiencies in energy consumption. Crenshaw and Jenkins highlight how the existence of particular social structures mediates and directs social interactions with nature. Thus, the historical inheritance of a specific economic system creates unique social patterns and constraints on how human societies interact with nature.[16]

A materialist foundation has become the bedrock of many prominent perspectives and theories in the environmental social sciences: industrial ecology/metabolism, ecological modernization, the treadmill of production, the "second contradiction" of capitalism, and the metabolic rift.[17] Industrial metabolism studies the throughput of raw materials and energy sources in productive systems, arguing that societies must actively regulate this process and develop efficient machinery to diminish the rate of material consumption. Ecological modernization assumes that through the ongoing modernization/rationalization of productive systems and public and private institutions, society will progress to a "green" state – i.e., environmental regulation and environmentally benign industries will produce a sustainable future, as market economies continue to develop. The treadmill of production theory runs counter to ecological modernization. Schnaiberg, the original developer of the treadmill of production theory, argues that modern societies, particularly market dominated ones, are driven by a relentless commitment to growth, despite its social and ecological costs. In pursuit of profit, producers constantly attempt to expand production. With the support of government, industrial production is allowed to expand, increasing the demands placed on nature and creating ever-greater amounts of waste. O'Connor, the principal proponent of the second contradiction of capitalism, agrees that modern production systems are growth dependent. At the same time, O'Connor notes that the expansion of capitalism depletes natural resources, which will then increase the production costs of capital. In time, he contends, this will create a crisis for capitalism.

All of the previously mentioned theories in environmental sociology focus on the intersection of the economy and nature. Each of them has advanced environmental sociology by taking nature seriously and making nature a variable of social science. The subject of study has encouraged a materialist orientation. Yet, at the same time, nature is often in the background. A central concern of these theories is how society interacts with nature in ways that are unsustainable, yet little time is spent analyzing natural processes and cycles: How they operate on their own; how social interactions, as organized under historical social systems, affect their operation; and how they are transformed or disrupted by social processes. In other words, one side of the dialectic of the nature-society relationship is short-changed.

Later in the article, we present our critique of ecological modernization and related approaches, such as industrial ecology. At this point, we note that both the treadmill of production and the second contradiction of capitalism have become established schools of thought in environmental sociology. Both have advanced the field, especially along political economy lines, and we have drawn from them in various ways. At the same time, we are trying to move beyond them in some respects. The treadmill of production theory is illuminating in regards to issues of scale and growth, but it says little about the system of capitalism, as it pursues endless accumulation of capital and divides nature and humanity for the sake of profit. The qualitative interactions, both within society and within nature, are often lost in analyses focusing on scale.[18] The second contradiction of capitalism illuminates how capital constantly seeks to increase its exploitation of nature and labor. Furthermore, it raises the issue of how waste can affect economic operations. However, for the most part, this theory is focused on the economic side of the dialectic, as far as how capitalism degrades nature in its operations and how this will eventually cause economic crises.[19] Natural processes that do not directly influence the conditions of production are outside this perspective.

Much of the sociological work on climate change details the current conditions that influence the accumulation of CO_2 in the atmosphere, such as particular political institutions (e.g., international treaties) and technologies. These studies are needed, but a more systematic, theoretical approach to climate change is required for developing a more thorough understanding of the society-nature dialectic. Previous studies have not grappled with how global climate change relates to the historical era of capitalism, which serves as the background condition shaping social development and interactions. Additionally, most studies have not dealt with how social interactions have transformed natural conditions and processes. The typical study simply notes that human society has contributed to the accumulation of CO_2, which could cause global climate change. Through understanding the logic of capital and its development, we consider here how such a social system confronts natural systems and affects their ability to sustain human life. Furthermore, we present how the accumulation of CO_2 in the atmosphere is tied to the accumulation of capital among the economic elite, how ongoing environmental destruction contributes to climate change, and how the structural conditions under the current economic system limit the ecological benefits of technological development.

Our goal here is to contribute to the development of theory in environmental sociology via the theory of metabolic rift. Foster has described how Marx approached environmental problems primarily through an analysis rooted in the metabolism of natural systems, which included the consideration of the relations among organisms or systems and their surroundings, as well as the material that is exchanged in these relationships.[20] Metabolism (the relationship of exchange within and between nature and humans), which is one of the foundational concepts in ecology, provides an avenue for grappling with both qualitative and quantitative dimensions of relationships. The theory of metabolic rift serves as an approach for conceptualizing relationships, but it also provides the basis for processing the empirical reality of the nature-society relationship, as any theory should do.[21] Furthermore, the metabolic approach provides the theoretical means to deal with both sides of the dialectic between society and nature, considering the processes that take place in each realm, as well as examining how these positions interact and transform each other.[22] Buttel, one of the founders of environmental sociology, states that the metabolic rift is one of the most important theories in environmental sociology.[23] Furthermore, metabolism has become a chief concept in environmental sociology and industrial ecology, especially in Europe.[24]

We draw upon the strength of metabolic rift theory for studying the nature-society dialectic and extend its application to understand global climate change, including human influence on the carbon cycle and its consequences. Broadly, our discussion consists of linking three major ideas: 1) the utility of the metabolic rift theory for comprehending recent anthropogenic changes in the global carbon cycle, given capitalist development; 2) the "Jevons paradox," where improvements in efficiency actually increase the use of natural resources under capitalist relations, therefore, diminishing the potential for developing ecological sustainability based on technological fixes; and 3) the dialectic between the flooding and destruction of carbon sinks and the endless pursuit of capital accumulation.

To accomplish our tasks, we start with a discussion of metabolism and the metabolic rift, as conceived by Justus von Liebig, Karl Marx, and most recently John Bellamy Foster. Although this theory has been used primarily to describe soil crises, we extend this model to the biosphere at large to help to understand better humans' interactions with nature and the emergence of anthropogenic climate change. We follow with a brief discussion of the history of the biosphere, specifically focusing on the atmosphere and the carbon cycle. We then discuss the technological development of capitalism and the logic of capital. In this, we contextualize recent climate change within the historical era of capitalism to understand changes in carbon metabolism, the accumulation of capital, and the carbon rift. The problem of the "Jevons paradox" is raised in regard to technological fixes to resource usage, and a critique of ecological modernization flows from this analysis. Our study culminates in a discussion of how natural carbon sinks are being both destroyed and flooded at the same time. Given the logic of capital and its drive for the accumulation of capital, refinements in the operations of capitalism will not mend the metabolic rift. Thus, the transcendence of the growth driven, capitalist system is necessary if ecological sustainability is to be obtained. Global climate change, although not the only environmental problem, is one of the most important environmental issues facing humanity. Short of systematic transformation, global climate change may produce alterations in the atmosphere, which could threaten the survival of many species, including humans. The theory of the metabolic rift illuminates the full dimensions of this environmental problem and its relationship to our society, as it is currently structured.

Metabolism and the metabolic rift

The theory of the metabolic rift draws upon the historical development of the term within the natural sciences, as well as how Marx used it to study environmental problems. In the 1850s and 1860s, agricultural chemists and agronomists in Britain, France, Germany, and the United States alerted people to the loss of soil nutrients – such as nitrogen, phosphorus, and potassium – through the transfer of food and fiber from the country to the cities. In contrast to traditional agricultural production where essential nutrients were returned to the soil, capitalist agriculture transported nutrients essential for replenishing the soil, in the form of food and other crops, hundreds, even thousands, of miles to urban areas, where they ended up as waste. In 1859, Justus von Liebig, the great German chemist, argued that the intensive methods of British agriculture were a system of robbery, as opposed to rational agriculture.[25] The soil was depleted continually of its necessary nutrients, decreasing the productive potential of the land. The degradation of the soil led to a greater concentration of agricultural land among a small number of proprietors who adopted even more intensive methods of production, including the application of artificial fertilizers, which placed demands on other natural resources. Thus, attempts to "solve" the rift (loss of soil nutrients) created additional rifts and failed to solve the primary problem, given the continuation of production based on the accumulation of capital.

German physiologists in the 1830s and 1840s adopted the term "metabolism" (which was introduced around 1815) to describe the "material exchanges within the body, related to respiration."[26] Liebig applied the term on a wider basis, using it to refer to metabolic processes in relation to "tissue degradation" and as a key concept for understanding the processes at both "the cellular level and in the analysis of entire organisms."[27] Marx employed the concept of metabolism to refer to "the complex, dynamic interchange between human beings and nature."[28] For Marx, there is a necessary "metabolic interaction" between humans and the earth.[29] Marx contended that "man *lives* on nature" and that in this dependent relationship "nature is his *body*, with which he must remain in continuous interchange if he is not to die."[30] Thus, a sustainable social metabolism is "prescribed by the natural laws of life itself."[31] Labor is the process in which humans interact with nature through the exchange of organic matter.[32] In this metabolic relationship, humans both confront the nature-imposed conditions of the processes found in the material world and affect these processes through labor (and the associated structure of production). Marx, in studying the work of soil chemists, recognized that Liebig's critique of modern agriculture complemented and paralleled his own critique of political economy.[33]

The natural conditions found in the world, such as soil fertility and species of plants in a country, are, in part, "bound up with the social relations of the time."[34] Capitalism created an "irreparable rift" (rupture) in the metabolic interaction between humans and the earth, one that is only intensified by large-scale agriculture, long-distance trade, massive urban growth, and large and growing synthetic inputs (chemical fertilizers) into the soil. The pursuit of profit sacrificed reinvestment in the land, causing the degradation of nature through depleting the soil of necessary nutrients and despoiling cities with the accumulation of waste as pollution.[35] The metabolic rift was deepened and extended with time, as capitalism systematically violated the basic conditions of sustainability on an increasingly large scale (both internally and externally), through soil intensification and global transportation of nutrients, food, and fiber.[36] Marx noted that humans' metabolic interaction with nature serves as the "regulative law of social production."[37] Capitalism is unable to maintain the conditions necessary for the recycling of nutrients. In this capitalism creates a rift in our social metabolism with nature. In fact, the development of capitalism continues to intensify the rift in agriculture and creates rifts in other realms of the society-nature relationship, such as the introduction of artificial fertilizers. Incidentally, food production has increased through expanding agricultural production to less fertile land – depleting the nutrients in these areas – and through the incorporation of large quantities of oil in the agricultural process, used in the synthesis of chemical fertilizers and pesticides, contributing to the carbon rift. Modern agriculture has become the art of turning oil into food. Constant inputs are needed simply to sustain this operation, given the depletion of the soil.[38] Marx argued that the "systematic restoration" of this metabolic relation, through a system of associated producers, was required to govern and regulate the material interchange between humans and nature.[39]

The metabolic rift theory has become a powerful conceptual tool for analyzing human interactions with nature and ecological degradation, especially regarding agricultural production.[40] Foster illustrates how Marx's conception of the metabolic rift under capitalism illuminates social-natural relations and the degradation of nature in a number of ways: (1) "The decline in the natural fertility of the soil due to the disruption of the soil nutrient cycle," through transferring nutrients over long-distances to new locations; (2) new scientific and technological developments, under capitalist relations, increase the exploitation of nature, intensifying the degradation of the soil, expanding the rift; and (3) the nutrients transferred to the city accumulate as waste and become a pollution problem.[41]

Here, we extend the theory of metabolic rift to the carbon cycle and global climate change. In this extension, we utilize the general properties provided by Marx's model of a metabolic rift, as well as the processes of the carbon cycle, where "climate is intimately embedded within human ecosystems."[42] A "metabolic rift" refers to an ecological rupture in the metabolism of a system. The natural processes and cycles (such as the soil nutrient cycle) are interrupted. The division between town and country is a particular geographical manifestation of the metabolic rift, in regards to the soil nutrient cycle. But the essence of a metabolic rift is the rupture or interruption of a natural system. Our analysis of the carbon cycle and climate change follows this notion, extending the metabolic rift to a new realm of analysis. The metabolic rift also entails the division of nature, which is tied to the division of labor, as the world is subdivided to enhance the accumulation of capital.[43] Materials and energy are transformed into new forms. In this process, environmental degradation takes place, leading to the accumulation of pollution.[44] Lastly, attempts to remedy metabolic rifts, without systematic change to the current political-economic system, compound the problems associated with rifts between the social metabolism and natural metabolism.

Metabolic rifts, like any social issue, need to be historically contextualized. For this article, the principal time period considered is the era of global capitalism, which to a large extent is the primary force organizing the social metabolism. Through the application of metabolic and rift analysis, we provide a better understanding of the dynamic relationships involved in global climate change. But to understand global climate change, the accumulation of CO_2 in the atmosphere, and the anthropogenic drivers of current patterns in CO_2 emissions, we provide a discussion of the biosphere and the carbon cycle.

The formation of the biosphere and the structure of the carbon cycle

The composition of gases in the atmosphere was not always as it is today or even as it has been in previous centuries. In 1926, Vladimir Vernadsky argued that the emergence of life from nature radically transformed the conditions that made emergence possible and illuminated how the biosphere was created.[45] Life – in interaction with the existing environment – created the atmosphere, as we know it. Life exists only in the lower regions of the sky and upper regions of the soil and ocean. An interrelationship between living and nonliving materials within the biosphere produces a cycling of chemical elements. Thus, the history of life and the biosphere is a story of coevolution.[46]

The composition of gases in the atmosphere is the product of biological processes on Earth. Three billion years ago the Earth's atmosphere had a dramatically lower concentration of oxygen than it does today. Unsurprisingly, anaerobic bacteria (i.e., bacteria that survive in the absence of oxygen) dominated the Earth. The long evolutionary history of bacteria led to numerous transformations that greatly affected the composition of gases in the atmosphere. Early bacteria survived by fermentation, breaking down the sugars and chemicals existing in the surrounding environment.[47] Some bacteria developed the ability to fix nitrogen. The early form of photosynthesis developed by bacteria used hydrogen sulfide from volcanoes as a source of hydrogen and combined it with energy from sunlight and carbon dioxide from the air to create organic compounds. At this time, oxygen was not produced in this process, given that water was not used in photosynthesis.

Fermenting bacteria metabolizing sugars produced methane and carbon dioxide as waste products, helping to create the conditions to hold heat within the biosphere. Further evolutionary changes in bacteria led to the development of a special type of blue-green bacteria (a distant ancestor to the modern era's blue-green algae) that developed the ability to use sunlight of higher energy to split the stronger bonds of hydrogen and oxygen found in water. The hydrogen was used for building sugars, while the oxygen was released. Over time, free oxygen began to accumulate in the environment. In this state, it reacted with organic matter and produced free radicals, which led to the destruction of essential biochemical compounds and carbohydrates in nature. Oxygen pollution killed numerous species. The bacterial world experienced a punctuated change in evolutionary history, as blue-green bacteria developed the ability to engage *both* in photosynthesis, producing oxygen, *and* in respiration, utilizing oxygen from the atmosphere. After over a billion years of evolution, life created a mixture of atmospheric gases that provided the conditions for the evolution of oxygen-breathing organisms.

Life on earth depends upon energy from the sun for its existence. The sun's energy is captured by plants, which store and convert it into chemical energy for its own growth. At the same time, animals eat plants to derive the necessary energy for their lives. Through plants and animals, energy is captured, stored, converted, and deposited throughout the environment, maintaining a viable world for life and its evolutionary processes. Fossil fuels hidden deep within the earth are the remains of past life, especially the first wave of gigantic ferns and giant trees.[48]

This past life captured energy, helping make life possible on the land; at the same time, these plants stored energy in their cells, before they were buried deep within the earth. Historic geological processes effectively concentrated energy by removing large quantities of carbon (in the form of hydrocarbons) from the biosphere and burying it deep underground. Otherwise, the energy in the biosphere is primarily stored in plants until they die and release this energy through decay or combustion.

Since the time that oxygen-breathing organisms evolved, the principal gases that envelop the earth have been roughly stable at approximately the current level – nitrogen comprises 78 percent of the atmosphere and oxygen approximately 21 percent. Trace gases, including greenhouse gases such as CO_2, make up the remaining fraction, which regulate the "temperature to life-supporting levels."[49] Jean-Baptiste Fourier, in the 1800s, was the first to propose that the air in the atmosphere trapped heat to warm the planet.[50] With further research, CO_2 and other greenhouse gases, which make up only a small proportion of gases in the atmosphere, were recognized as the gases that warmed the earth (the "greenhouse effect") to create a habitable climate.[51] The concentration of these greenhouse gases in the atmosphere has changed substantially over geological, and even historic, time.

The carbon cycle involves the whole biosphere, as carbon moves through the air, rocks, soil, water, and all living things in a cyclical process. All life is dependent on this process, and carbon serves as "the principal element of which all living beings . . . are made."[52] In part, carbon is absorbed and contained in nonliving forms, such as oceans, glaciers, and rocks, which serve as sinks, helping limit the accumulation of CO_2 in the atmosphere. Carbon from the atmosphere enters the life cycle through carbon fixation (a process that Liebig helped confirm), where plants' photosynthetic process converts – in conjunction with water, chlorophyll, and the sun's energy – CO_2 into carbohydrates and oxygen.[53] From this point, some carbon reenters the atmosphere through the respiration of plants. But much of the carbon is passed on to other species, and onward through the food chain, where carbon enters the soil and water as waste, as dead matter, or as CO_2 through the respiration of animals. Thus, CO_2 is released into the atmosphere only to be recirculated to the earth through a variety of pathways in natural processes.

Over the past 400,000 years, the carbon cycle and climate system have operated in a relatively constrained manner, sustaining the temperature of the earth and maintaining the balance of gases in the atmosphere.[54] Understanding the basic operations of the carbon cycle is necessary for understanding climate change. The historic accumulation of CO_2 in the atmosphere involves the rupture of the carbon cycle. Human societies, in their metabolic exchange of materials with the environment, serve as the driving force creating a rift in the carbon cycle. The long-term consequences of this rift are potentially severe.

The expansion of capitalist production and the accumulation of carbon dioxide in the biosphere

The advent of *Homo sapiens* brought forth unprecedented social interactions with nature, which included the purposeful use of fire. The anthropogenic burning of plants and trees released stored solar energy into the atmosphere. The ability to control fire decreased human vulnerability to nature. Of course, it was not until the rise of capitalism, and especially the development of industrial capital, that anthropogenic CO_2 emissions greatly expanded in scale, through the burning of coal and petroleum, exploiting the historic stock of energy that was stored deep in the earth and releasing it back into the atmosphere. As a result, the concentration of CO_2 in the atmosphere has increased dramatically, overwhelming the ability of natural sinks – which have also been disrupted by anthropogenic forces – to absorb the additional carbon and leading to climate change.

To understand the rift in carbon metabolism, one needs to understand the forces that drive CO_2 emissions. It is now widely recognized that humans alter the global climate "by interference with the natural flows of energy through changes in atmospheric composition .... Global changes in atmospheric composition occur from anthropogenic emissions of greenhouse gases, such as carbon dioxide that results from the burning of fossil fuels and methane and nitrous oxide from multiple human activities."[55] Much worse, "we have driven the Earth system from the tightly bounded domain of glacial-interglacial dynamics," one that defined the Earth system for over 400,000 years.[56] While not recognizing the potential dangers associated with increasing global temperatures, Arrhenius in 1896 noted that industrial operations were contributing to an increase of the CO_2 in the natural world.[57] We know now that the quantity of CO_2 in the atmosphere "has increased 31 percent since preindustrial times" and that "half of the increase has been since 1965."[58] Yet relatively little research has considered the anthropogenic drivers of CO_2 emissions or the systematic forces that organize social production and the release of CO_2 in the process.[59]

Often industrialism is identified as the principal factor behind global warming, but this position fails to recognize that industrialism is embedded within a particular global economic system. Understanding the forces and operations of capitalism is necessary for gaining perspective on how industrial social relations function as well as how the human-nature interchange under this system contributes to global climate change. This is not to say that other economic systems do not perpetrate and contribute to environmental degradation. Soviet-type societies caused immense environmental deterioration, but this does not negate the importance and urgency of analyzing the social relations, operations, and development of capitalism since it is the political-economic system that is dominant in the world today.

Environmental crises have existed throughout human history.[60] In fact, Moore argues that the birth of capitalism was pushed forward, in part, by environmental contradictions and crises in feudalism, namely a metabolic rift particular to the structure of feudal agricultural production.[61] His analysis advances by detailing how capitalist agricultural production continued to create a metabolic rift, but it found temporary relief through establishing a global economy, which increasingly incorporated the world into a metabolic rift of global proportions as agricultural goods (food and fiber) were transferred from colonies to European nations. Seeking endless accumulation of capital, agricultural practices were intensified, as land was consolidated into fewer hands. Foster, through an historical analysis of Liebig and Marx, documents the reemergence of a soil crisis in Europe in the 1800s.[62] Foster and Clark present how this soil crisis led to the global trade of guano to fertilize fields in Europe and eventually to the development of artificial fertilizers, which ever since have been used in larger quantities, despite the associated environmental problems that they create.[63]

The same logic that dictated the expansion and intensification of agricultural production fueled the drive behind the productive systems in cities.[64] In fact, the conditions within cities were in part a consequence of the transformation in the countryside, as people were swept from the land through the concentration of land among fewer landholders. The metabolic rift in the soil nutrient cycle continued to expand with the division between town and country, and new metabolic rifts were being created with the development of capitalism.[65] After being separated from the land, people were forced to seek work in the cities, struggling for survival, under the anarchy of the market.[66] At this point, capitalism's development of technology and its separation from the hands of workers is important. At first, human bodies operated tools, exerting energy for the production of commodities. But the drive to maintain the continuity of production fostered scientific and technological development.[67] Marx discusses how the motive force of production was transformed from humans to machines. Labor experienced a greater division of labor, as the mechanization of tools freed capitalism from the limitations of individual workers' labor power through the use of natural forces and parts of nature were transformed into fuel for the new machines. Tools became embedded within machines that labor operated. Production took place on a greater scale, demanding more energy to sustain operations. Marx commented:

> An increase in the size of the machine and the number of its working tools calls for a more massive mechanism to drive it; and this mechanism, in order to overcome its own inertia, requires a mightier moving power than that of man, quite apart from the fact that man is a very imperfect instrument for producing uniform and continuous motion.[68]

The movement from human motive power to water and wind to coal-driven steam-engines transformed capitalist production, increasing the scale of production by pushing up labor productivity to historically unprecedented levels, and by deepening the exploitation of nature and labor.[69]

Marx outlined how "the growth of machinery and of the division of labor" allowed more commodities to be produced "in a shorter time" and how "the store of raw materials must grow" at the same time.[70] All of this directly requires increases in the quantity of matter-energy throughput, for the expansion of production in the pursuit of the accumulation of capital on a greater scale. Marx explained,

> The material forms of existence of the constant capital, however, the means of production, do not consist only of such means of labour, but also of material for labour at the most varied stages of elaboration, as well as ancillary materials. As the scale of production grows, and the productive power of labour grows through cooperation, division of labour, machinery, etc., so does the mass of raw material, ancillaries, etc. that go into the daily reproduction process . . . .there must always be a greater store of raw material, etc. at the place of production than is used up daily or weekly.[71]

Thus, Marx highlights how the drive to accumulate capital fueled the development of industrial productive forces, which at the same time, created a growing need for raw materials mined from the earth to power the machines. As capitalism continues to grow, more capital is used to purchase "raw materials and the fuels required to drive the machines."[72] Thus, an expansion in productivity and technological development under capitalism increases the quantity of energy throughput that is required to expand the accumulation of capital. The operations of capitalist production became dependent on a constant supply of raw materials that could sustain its operations on an ever-greater scale. Thus, capital, as Foster explains, was pushed "to structure the energy economy around fossil fuels (a reality that is now deeply entrenched)."[73]

Just as the expansion of capitalist agricultural production globalized the metabolic rift of the soil nutrient cycle, capitalist expansion pushed forward technological development that allowed industrial production to take place at ever-greater levels. 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."[74] Daly warns that, as a result of these developments, natural cycles are overloaded and the "life-support services of nature are impaired" because of "too large a throughput from the human sector."[75] The ability to take coal and petroleum from the earth accelerated the expansion of capital, releasing large quantities of CO_2 into the atmosphere. This pattern, just as the rift in the soil nutrient cycle, continues, given the logic of capital.

Ongoing capitalist development continues to dump CO_2 into the atmosphere, placing greater demands upon the carbon cycle to metabolize this material. This uneven process only worsens, given the character of capital. To survive, capital must expand. It is engaged in a process of ceaseless expansion and constant motion. Schumpeter asserted that "capitalism is a process, stationary capitalism would be a *contradictio in adjecto*."[76] Marx emphasized that capitalism is a dynamic economic system functioning by and for the accumulation of wealth:

> However, as representative of the general form of wealth – money – capital is the endless and limitless drive to go beyond its limiting barrier. Every boundary [*Grenze*] is and has to be a barrier [*Schranke*] for it. Else it would cease to be capital — money as self-reproductive. If ever it perceived a certain boundary not as a barrier, but became comfortable within it as a boundary, it would itself have declined from exchange value to use value, from the general form

> of wealth to a specific, substantial mode of the same. Capital as such creates a specific value because it cannot create an infinite one all at once; but it is the constant movement to create more of the same. The quantitative boundary of the surplus value appears to it as a mere natural barrier, as a necessity which it constantly tries to violate and beyond which it constantly seeks to go.[77]

The operation of the capitalist system is a constant struggle to transcend existing barriers, both social and natural (such as operating within the regulative laws of natural cycles), while at the same time it creates new barriers (such as natural limits and rifts in metabolic cycles), as the world is reshaped and reorganized in the pursuit of profit. Given that capitalism operates globally, there is no natural confinement or pressure to stop the ruin of ecosystems, short of global collapse.[78]

Thus, the basic characteristic of capitalism "is that it is a system of self-expanding value in which accumulation of economic surplus – rooted in exploitation and given the force of law by competition – must occur on an ever-larger scale."[79] The accumulation of capital remains the primary objective in capitalist economies. Sweezy perceptively described the accumulation process and its relationship to nature, in stating,

> a system driven by capital accumulation is one that never stands still, one that is forever changing, adopting new and discarding old methods of production and distribution, opening up new territories, subjecting to its purposes societies too weak to protect themselves. Caught up in this process of restless innovation and expansion, the system rides roughshod over even its own beneficiaries if they get in its way or fall by the roadside. As far as the natural environment is concerned, capitalism perceives it not as something to be cherished and enjoyed but as a means to the paramount ends of profit-making and still more capital accumulation.[80]

In some respects, this is a self-propelling process, as the surplus accumulated at one stage becomes the investment fund for the next (such as technological development to expand or improve production). In this, the scale of capitalist operation is ever-increasing, driven by ceaseless economic growth. To sustain this process, capital requires constant access to, and an increasingly large supply of, natural materials (e.g., petroleum). Capital freely appropriates nature's supplies and leaves wastes behind.[81] As the economic system grows under capitalism, the throughputs of materials and energy increase and capital incorporates ever-larger amounts of natural resources into its operations.

The law of value remains central to understanding capitalism and the ecological crisis.[82] For Marx, "The earth ... is active as an agent of production in the production of a use-value."[83] But the value of a particular commodity under the capitalist system is measured in terms of abstract social labor. Any commodity's value is determined by its socially necessary labor time. Value is put forward in opposition to land and labor, the "original sources of all wealth."[84] For example, the value of oil is determined by the human labor embodied in the obtaining and processing of the oil and the capital invested in the operation. The value of oil has nothing to do with nature or natural cycles. A contradiction exists between the accumulation of value in the form of abstract social labor and value in the form of the accumulation of material processes. Under capitalism, money serves as the equivalent of value. It is the reification of universal labor-time, "the product of universal alienation and of the suppression of all individual labour,"[85] and "a form of social existence separated from the natural existence of the commodity."[86] Money mystifies labor and nature. In exchange, the qualitative dimensions of social production are erased. "Money 'solves,'' Burkett notes, "the contradiction between the generality of value and the particularity of use values by abstracting from the qualitative differentiation of useful labor as conditioned by the material diversity of human and extra-human nature – the true sources of wealth."[87]

There is no drive to maintain the social metabolism in relation to the natural metabolism (a measure of sustainability) under capital. Capital cannot operate under conditions that require the reinvestment of capital into the maintenance of nature. Short-term profits provide the immediate pulse of capitalism. Capital is dictated by the competition for the accumulation of wealth.[88] Money serves as a universal measure and means for international trade and aids capital in its international expansion, as it incorporates more people and nature into the global system. The monetary process comes to dominate the organization of the material processes of production. In this, capitalism successfully conquers the earth (including the atmosphere), taking its destructive field of operation to the planetary level. The exploitation of nature is universalized, increasingly bringing all of nature within the sphere of the economy, subjecting it to the rationality of profitability.[89] Capital is the systematic force organizing social production and driving industrialism to intensify the exploitation of nature. Given the logic of capital and its basic operations, the rift in the carbon cycle and global climate change are intrinsically tied to capitalism. In fact, the continued existence of capitalism guarantees the continuation of these events. "Short of human extinction, there is no sense in which capitalism can be relied upon to permanently 'break down' under the weight of its depletion and degradation of natural wealth."[90]

Numerous human activities contribute to the accumulation of CO_2 and global climate change, including deforestation, desertification, and expanded agricultural production, but the burning of fossil fuel is the primary source of greenhouse gases.[91] CO_2 is the most abundant greenhouse gas. Society adds "carbon to the atmosphere at a level that is equal to about 7 percent of the natural carbon exchange of atmosphere and oceans."[92] The increasing concentrations of greenhouse gases have contributed to the warming of the earth, making the mean global temperatures in the 1990s the "warmest ever recorded."[93]

Capitalism, organizing the social relations of commodity production, effectively plunders the historical stock of concentrated energy that has been removed from the biosphere only to transform and transfer this stored energy (coal, oil, and natural gas) from the recesses of the earth to the atmosphere in the form of CO_2. In this, capitalism is disrupting the carbon cycle by adding CO_2 to the atmosphere at an accelerating rate. At the same time, capital's constant demand for energy necessitates the continual plundering of the earth for new reserves of fossil fuel.[94] With over 23 billion metric tons of CO_2 released into the atmosphere per year, capitalist production is creating "waste emissions faster than natural systems can absorb them."[95] As a result, CO_2 is accumulating – as atmospheric waste – at alarming rates, warming the earth, and potentially causing dramatic climate change.

The Jevons paradox: A dilemma for ecological modernization

Scientific recognition of the accumulation of CO_2 and climate change has made CO_2 emissions a major social concern and culminated in social pressure throughout the world to reduce emissions. Capital and neoclassical economists attempt to assuage fears of environmental deterioration as an inherent part of capitalist economic operations. They typically assert that capitalist development will lead to improved technologies and efficient raw material usage, and that this will decrease emissions and environmental degradation. They argue there is an "environmental Kuznets curve" (EKC) for many types of environmental impacts. The EKC suggests that environmental impacts, such as pollution, increase in the early stages of development within nations as an industrial economy is established, but level off and eventually decline as economies "mature," because environmental quality is a luxury good, affordable only by the affluent.[96] Proponents of "green capitalism," such as Paul Hawken, advocate that if the value of nature were properly accounted for, capitalism would develop in an ecologically benign direction.[97] In other words, they argue that through innovative technological development and appropriate reformist government policy, the economy can be dematerialized, reducing the throughput of raw materials and energy that the system requires.[98]

Ecological modernization theorists follow this "socio-techno" optimism, claiming that the forces of modernization lead to the dematerialization of society and the decoupling of the economy from energy and material consumption, allowing human society, under capitalism, to transcend the environmental crisis.[99] In particular, ecological modernization theorists argue that rationality, a cornerstone of modernity, percolates into all institutions of "advanced" societies.[100] This process leads to the emergence of "ecological rationality," which focuses on the necessity of maintaining the resources and ecosystem functions upon which societies depend, and shifts the focus away from the pure economic rationality that prevailed in the early stages of modernization. Ecological modernization theory is at base a functionalist theory in that it does not see the emergence of ecological rationality as coming primarily from social conflict, but rather from ecological enlightenment within the key institutions in societies. Ecological modernization theorists contend, then, that radical ecological reform does not require radical social reform – i.e., the institutions of capitalist modernity can avert a global environmental crisis without a fundamental restructuring of the social order.

In the same vein, Boltanski and Chiapello argue that capitalism is a flexible system that is able to respond to social and natural barriers, social movements, and criticism. It is a system that can incorporate an interest for the common good of society into its operations. In fact, past criticisms of the system have helped direct capitalism in ways that allow it to flourish in order to meet social needs and desires. Expanding knowledge is seen as a force that propels bureaucrats and capitalists to respond readily to social concerns.[101]

Of course, Marxist scholars would not deny that capitalism is a dynamic system. However, the likelihood of capital pursuing the common or social good (and by extension environmental sustainability) is contested.

Nonetheless, ecological modernization theorists and others of this persuasion believe that capitalism is fully able to respond to climate change through pursuing socio-technical innovation, without challenging the prevailing political-economic structure. Our contention is neither that economic growth has not produced new technologies that are more efficient nor that improvements in technology that reduce some types of pollution have not taken place. Rather, we contend that the belief that these changes lead to benign ecological relationships needs further consideration, especially considering that capitalist expansion of commodity production – which includes energy sources as throughputs – has outstripped improvements in the efficiency of energy use. Empirical research suggests that carbon *efficiency* (economic output per unit of carbon emissions) may follow an EKC, but per capita emissions increase monotonically with economic development.[102] Ironically, the most efficient nations are often, in fact, the biggest consumers of natural resources.[103]

William Stanley Jevons, in *The Coal Question*, explained that improved efficiency in the use of coal made coal more cost effective as an energy source and therefore more desirable to consumers. Thus, he argued, greater efficiency in resource use often leads to *increased* consumption of resources.[104] This relationship has become known as the Jevons Paradox.[105] Jevons pointed to an observed relationship between efficiency and total consumption, but he did not explain why this was the case. He needed to connect this fact – that rising efficiency is associated with *rising* consumption, at least in the case of coal – with the drive for the accumulation of capital, which entails the continued material consumption of transformed nature to fuel its operations. Dowd explains how capitalist production for the accumulation of capital, rather than production to meet social needs and the demands of environmental sustainability, generates enormous waste throughout its operations. Given capital's "need for substantial economic expansion," it produces ever-greater amounts of waste, in concentrations that threaten the ecosystem.[106] Empirical research and other analyses support the contention that economic growth and expansion typically outstrip gains made in efficiency.[107]

Straightforward calculations based on aggregate data for a selection of "advanced" capitalist nations illustrate the paradoxical relationship between efficiency and resource consumption. Over the period 1975 to 1996, the carbon efficiency of the economy – economic output, measured in terms of gross domestic product (GDP), per metric ton

Table 1. Changes in the economic carbon efficiency (GDP per unit of CO_2 emissions), total CO_2 emissions, and CO_2 emissions per capita of four "advanced" capitalist nations between 1975 and 1996.

Nation	Carbon efficiency (change)	Total CO_2 emissions (change)	CO_2 emissions per capita (change)
United States	+ 34.0 percent	+ 29.7 percent	+ 5.9 percent
Netherlands	+ 30.1 percent	+ 24.3 percent	+ 9.1 percent
Japan	+ 64.0 percent	+ 25.9 percent	+ 12.0 percent
Austria	+ 50.2 percent	+ 11.6 percent	+ 4.9 percent

Note. The calculations are based on data presented by Matthews et al. (2000).

of CO_2 emissions – increased dramatically in the United States, the Netherlands, Japan, and Austria (see Table 1). However, over this same period, total CO_2 emissions, and even per capita emissions, *increased* in all four of these nations despite the improvements in efficiency (see Table 1).[108] Thus, gains in the efficiency of the use of fossil fuel have typically resulted in the expansion of their use in industrialized capitalist nations. As a result, carbon emissions generally increase with modernization and its concomitant "improvements" in technology and gains in efficiency.[109] It is noteworthy that Marx explained that capitalism prevents the truly rational application of new science and technologies because they are simply used to expand the operations of capital.[110]

Capitalism, at this stage of its development, depends upon massive quantities of fossil fuel in order to continue to operate at the current scale of production, to say nothing of an *increasing* scale of production. Thus, state market policies and carbon sequestration technologies are ploys to continue capitalist production as is, and they are unlikely to deal directly with global climate change. Market policies are simply rhetoric, and sequestration technologies would have their own ecological concerns and are likely too large-scale to operate and too expensive to fund in the capitalist economic system.[111] The recovery of agricultural nutrients has proven to be insurmountable under capitalism for over a hundred years. Thus, a massive quantity of artificial fertilizer and oil – which contributes to the accumulation of CO_2 – is needed to sustain food production. Recovering carbon waste from the atmosphere will likely prove to be a much more difficult task. The social structure of the capitalist system sets limits and constraints on what mitigating actions will and can be taken.[112] All the while, the rift in the carbon cycle continues to deepen, as CO_2 continues to accumulate in the atmosphere, while capital pursues profit. Thus the social project to mend the carbon rift is not simply a technological one, but it requires the struggle to establish an entirely new social metabolism with nature. In fact, this requires a new social system driven by human development (which by necessity must also be ecological to sustain the conditions of life), not the accumulation of capital.[113]

The disruption and flooding of carbon sinks

Since modern capitalist societies are emitting CO_2 into the atmosphere at an extraordinary and escalating pace, it is important to understand what happens to carbon when it enters the atmosphere. CO_2 has a long atmospheric lifetime, remaining in the atmosphere for up to 120 years.[114] As described earlier, carbon has an established cycle, where it moves through the biosphere, being absorbed by plants, to be used in the production of carbohydrates before being released back into the atmosphere through a variety of pathways. Oceans and forests serve as natural sinks, absorbing large quantities of CO_2.

The creation of a rift at one point in a cycle (i.e., the accumulation of CO_2 in the atmosphere) can generate system-wide crises. The gravity of the situation in regard to the carbon cycle in the current historical era is that capitalism is disrupting the carbon cycle at two points, further complicating matters. The circulation of carbon and the stabilization of it within certain parameters depend on the availability of carbon sinks and their ability to absorb CO_2. The oceans and forests are the largest and primary sinks for CO_2, but the amount of CO_2 in the atmosphere has exceeded the capacity of nature to absorb these gases. Thus, the sinks may be approaching the limits of their capacity to sequester carbon, as environmental destruction throughout the world degrades and depletes them. The oceans influence the concentration of CO_2 in the atmosphere, as the gas is continuously exchanged at the surface. In the water,

> CO_2 forms a weak acid that reacts with carbonate anions and water to form bicarbonate. The capacity of the oceanic carbonate system to buffer changes in CO_2 concentration is finite and depends on the addition of cations from the relatively slow weathering of rocks.[115]

The scale of anthropogenic CO_2 exceeds the supply of cations, and may come to exceed the saturation point in the water. In the long-run the capacity of the ocean to absorb CO_2 will likely decrease.[116] This rift may only deepen and further limit the sequestration of carbon, leaving more CO_2 in the atmosphere. Already the accumulation of CO_2 has led to the warming of the earth, which has increased the melting of glaciers (also historic sinks of CO_2), releasing even more CO_2 into the atmosphere.

With the ability of the oceans to absorb CO_2 potentially in decline, the absorption capacity of terrestrial ecosystems becomes particularly important. Forests are the primary carbon sink on land. Deforestation not only destroys a carbon sink, but leads to the emission of substantial quantities of CO_2 into the atmosphere when forests are burned. Dramatic deforestation, particularly in the tropics (given that many core nations have already destroyed the bulk of their forests and depend on wood imports from less developed nations), continues to decrease the absorption of CO_2 by terrestrial ecosystems. Worldwide, there was, on average, a net loss of over 90,000 square kilometers (an area approximately the size of Portugal) of forest each year during the 1990s.[117] Global deforestation appears to be driven, at least in part, by the increasing globalization of markets and the influence of global capital, where the natural environment of periphery nations is degraded in the extension of trade – especially in agricultural goods and natural resources – and as a result of the expansion of global poverty, as the poor and otherwise landless clear ground for survival.[118] The reduction in forest area and the potential carbon saturation of available forests only increases the accumulation of CO_2 in the atmosphere. Falkowski et al. note that sinks helped slow the accumulation of CO_2, but there is no "natural savior" waiting to absorb and assimilate all the CO_2 produced by capitalist processes. "Humans have affected virtually every major biochemical cycle" and sinks "cannot mitigate against continued accumulation of the gas in Earth's atmosphere."[119]

Global inequalities, per capita emission allowances, and biospheric crisis

At the planetary level, ecological imperialism has resulted in the appropriation of the global commons (i.e., the atmosphere and oceans, which are used as sinks for waste) and the carbon absorption capacity of the biosphere, primarily to the benefit of a relatively small number of countries at the center of the capitalist world economy. The core nations rose to wealth and power in part through high fossil fuel consumption and exploitation of the global south. Anthropogenic greenhouse gases emissions, while stemming from localized sources, are distributed throughout the atmosphere and accumulate as waste, which degrades the atmosphere and leads to further alteration of the biosphere, creating a global crisis.

Theorists from the world-systems perspective provide valuable studies regarding the unevenness of CO_2 emissions among nations. Non-core nations of the global economy emit significant amounts of CO_2 into the atmosphere, use inefficient energy technologies, and, in the case of China, burn primarily coal to meet their energy needs. All of this reflects inequalities in the global economy and the unevenness of capitalist development. But it is core nations that cause a disproportionate amount of emissions due to industries, automobiles, and affluent lifestyles. Roberts writes:

> Overall, the richest 20 percent of the world's population is responsible for over 60 percent of its current emissions of greenhouse gases. That figure surpasses 80 percent if our past contributions to the problem are considered.[120]

Thus, the affluent core nations of the global economy are primarily responsible for global climate change, whether it is in regards to emissions, the quantity of CO_2 in the atmosphere that floods the sinks, or the hegemonic economic forces that foster the destruction of sinks, such as forests.

The IPCC has estimated that at least a 60 percent reduction in carbon emissions from 1990 levels is necessary to reduce the risk substantially of further climate change substantially. The core nations' carbon output alone exceeds the world's total allowable amount. Agarwal and Narain suggest that any just and reasonable approach to determining how much carbon a nation can emit into the global commons must be based on emissions per head of population.[121] Simms, Meyer, and Robins calculated that "based on the 1990 target for climate stabilization, everyone in the world would have a per capita allowance of carbon of around 0.4 tonnes, per year."[122] But as time passes and the release and accumulation of gases continues, that allowance decreases, particularly as the human population continues to grow. Before too long the per capita allowance of carbon may be 0.2 tons per year. The severity of the situation and the extreme global inequalities are clearly seen when we consider that the per capita emissions of carbon for the United States are currently over 5.6 metric tons per year.[123] The per capita emissions for the G-7 nations are 3.8 metric tons per year; and the rest of the world has per capita emissions of 0.7 metric tons per year.[124] Furthermore, global shifts in production have brought an immense amount of capital to peripheral nations, where industrial production increasingly takes place. The profits are then transferred back to the core nations. Nevertheless, this relocation of productive operations to peripheral nations has increased their carbon emissions, despite few immediate economic gains.[125] Marx commented that "the more a country starts its development on the foundation of modern industry, like the United States, for example, the more rapid is this process of destruction."[126] While he was describing the social and environmental exploitation that takes place under capitalist agriculture, Marx's statement captures the social relations under capital in general, especially the human relationship with the biosphere.

Inaction creates an ever more difficult position for the future. In fact, if current trends continue, global warming could spiral out of control, potentially threatening the survival of human beings.[127] An "ecological discontinuity" can occur with few, if any, immediate warning signs.[128] Global climate change may cause extreme weather patterns (hurricanes, floods, droughts, etc.), which may disproportionately affect peripheral nations, despite their minor carbon contribution. Global warming will lead to a rise in sea levels, threatening many islands as well as some densely populated, low-lying countries, such as Bangladesh, with severe floods. CO_2 "will be responsible for more than half of the anticipated global warming over the next century."[129] Climate change will lead to changes in the distribution of plants on earth. Furthermore, some species respond better to higher CO_2 concentration than others and may, therefore, displace other plants. This will cause a decrease in biodiversity. Already there is concern that high-mountain ecosystems are experiencing higher temperatures, causing changes in the types of plants and animals that exist there, as plants from lower elevations move up the mountains.[130] All of this highlights how new constraints will be placed on life and its development. Vitousek warns that the changes that are forced on the world will not be smooth, as humans continue to "alter the structure and function of Earth as a system."[131]

Falkowski et al. caution that disruption of so many cycles and natural processes creates an immense amount of uncertainty and can create a series of feedback loops with devastating results.[132] Such a disruption in the carbon cycle could surpass a natural threshold and cause a sudden change in the global ecosystem. This shift to a new climate regime is known as abrupt climate change. The accumulation of carbon warms the planet. An acceleration of river runoff and melting ice increases the amount of freshwater that enters the North Atlantic, decreasing the salinity of the ocean waters. As a result, the thermohaline circulation, which moves warm, saline waters from the tropics to the north, before looping back, could collapse or be severely hampered in its operation. If this happens, the North Atlantic could cool quite quickly, creating harsh, icy winters, while expanding drought and the warming of the global south.[133]

The continuation of capitalist operations, which indicate an ongoing increase in carbon emissions, threatens to undermine the capacity of the biosphere to support life on earth. The accumulation of CO_2 in the atmosphere is causing a warming of the earth. The IPCC expectation of an increase in temperature of 1.5–6.0 °C during this century signifies a rift in the carbon metabolism, as carbon waste accumulates in the biosphere. Given the logic of capital, we know that it cannot mend the carbon cycle. Capital only has a productive cycle, which takes precedence over the maintenance of the natural world, in order to continue its accumulation of capital. Thus, capitalism continuously creates and deepens metabolic rifts, separating the social metabolism from the natural metabolism. As a result, the changes induced in nature feedback, influencing social conditions for humans. As Buell argues, we are currently living in an environmental crisis that threatens large-scale ecocide.[134]

Conclusion: The race to the inferno

Our argument is that global climate change in the current era is a form of capitalistic metabolic rift. We illustrate how the theory of metabolic rift provides the means to grapple with both the quantitative and qualitative relationships in the nature-society dialectic. The metabolic rift approach allows us to study natural cycles and economic processes, as well as the interaction between the two realms. At the same time, this theory allows us to conceptualize social relationships with nature and to evaluate empirical evidence. In studying climate change, we extended Marx's model of the metabolic rift, as developed by Foster, to the biosphere to understand how capitalism has created and expanded a rift in the carbon cycle, which leads to climate change. Geological and biological conditions removed large quantities of carbon from the biosphere by depositing them in the depths of the earth in the form of fossil fuel. Coal and oil are highly concentrated energy forms. Under the drive to expand commodity production for the accumulation of capital, technological developments advanced to a stage and scale where the burning of natural resources provided the fuel to power machinery. As a result, energy that is contained in coal and petroleum has been mined from the earth, transformed in form, and pooled back into the atmosphere, where they accumulate as CO_2 in the biosphere. The energy cannot be regained and concentrated on time-scales meaningful to humans since present stores of fossil fuels represent millions of years of accumulation of solar energy. The burning of fossil fuels has contributed large quantities of carbon to the atmosphere, while definitely breaking the "solar-energy budget." The carbon cycle is overwhelmed, as carbon emissions (waste) accumulate faster than the environment can absorb them. As a result, CO_2 accumulates in the biosphere, intensifying the greenhouse effect, potentially to our detriment.

Capitalism drives this rift with the biosphere. It is an inherently expansionary system, in pursuit of the accumulation of capital on an ever-greater scale. Capitalism is unable to maintain a sustainable relationship with nature. As Marxist ecologists have argued, its operations and processes maintain the production cycle, while disrupting natural cycles, despite capitalism's dependence on the natural world for its material operations. The theory of metabolic rift is able to account for how capitalism disrupts natural cycles, in relation to the accumulation of capital process. Capitalist production, despite advances in fuel efficiency and technological development, continues to draw upon stored energy, buried deep within the earth, only to pool this carbon back into the atmosphere in increasing quantities. It cannot surmount the Jevons paradox so long as the drive to accumulate operates. There is no natural containment of capitalist operations, short of human extinction. Natural limits are simply obstacles that capital attempts to transcend or work around, only to further the swath of environmental destruction. In this, capitalism undermines the conditions of the atmosphere by leading to the accumulation of carbon waste and the undermining of sinks through deforestation. Ultimately, capital operates as a disruptive force in the ability of the biosphere to sustain life in the long run.

Life was an essential component in the creation of the biosphere and the conditions that allowed for further evolution of life forms. Humans, via capitalism, are engaged in a process that may cause irreversible climate change and undermine the ability of human civilization to survive, given the scale and degree of environment degradation. Just like the mending of the metabolic rift in the soil nutrient cycle, addressing the carbon rift will require a transformation in society. Marx contended that systematic change was necessary to repair the rift generated by capitalism. He argued that a society of "associated producers" could "govern the human metabolism with nature in a rational way, bringing it under their collective control instead of being dominated by it as a blind power; accomplishing it with the least expenditure of energy and in conditions most worthy and appropriate for their human nature."[135] Other economic systems, especially in the future, may or may not be inherently in conflict with nature. This remains to be seen.

We do know that the rift in the carbon cycle continues to expand and deepen. Capital has robbed the global commons, which were used for the absorption of carbon, only to impoverish the future. Technological development cannot assist in mending the carbon rift until it is freed from the dictates of capital relations. Thus, changing the historical system offers the only possibility of slowing global climate change (and we state "slowing," simply because we will inherit the legacy of carbon that has already accumulated in the biosphere). The planetary nature of climate change and the global reach of capitalism require that efforts to transcend these issues involve global cooperation. Otherwise, the biospheric rift will continue to expand as we race to the inferno.

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41. Foster, "Marx's Theory of Metabolic Rift," 375–383.
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48. Barbara Freese, *Coal: A Human History* (Cambridge: Perseus Publishing, 2003).
49. Eugene A. Rosa and Thomas Dietz, "Climate Change and Society: Speculation, Construction and Scientific Investigation," *International Sociology* 13/4 (1998): 421–455.
50. Spencer Weart, "From the Nuclear Frying Pan into the Global Fire," *The Bulletin of the Atomic Scientists* 48 (1992): 19–27; Rosa and Dietz, "Climate Change and Society," 426–428.
51. Rosa, "Global Climate Change," 492–493; Gale E. Christianson, *Greenhouse: The 200-Year Story of Global Warming* (New York: Walker and Company, 1999).
52. R. Revelle, "Introduction: The Scientific History of Carbon Dioxide," in *The Carbon Cycle and Atmospheric CO_2 : Natural Variations Archean to Present*, E.T. Sundquist and W.S. Broecker, editors (Washington D.C.: American Geophysical Union, 1985), 1–4.
53. In 1840, Liebig firmly established the position that the carbon assimilated by plants was CO_2 from the atmosphere. See Revelle, "Introduction."
54. P. Falkowski, R.J. Scholes, E. Boyle, J. Canadell, D. Canfield, J. Elser, N. Gruber, K. Hibbard, P. Högberg, S. Linder, F.T. Mackenzie, B. Moore III, T. Pedersen, Y. Rosenthal, S. Seitzinger, V. Smetacek, and W. Steffen, "The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System," *Science* 290 (2000): 291–296. It should be noted that there have been natural climate variations in global temperatures through the centuries, which contributed to a "Little Ice Age," but there is widespread agreement among scientists that the accumulation of carbon in the atmosphere driving global warming is the result of human activities. For a discussion of the "Little Ice Age," see Richard H. Grove, *Ecology, Climate and Empire: Colonialism and Global Environmental History, 1400–1940* (Knapwell, Cambridge, UK: White Horse Press, 1997); Brian Fagan, *The Little Ice Age: How Climate Made History, 1300–1850* (New York: Basic Books, 2000); Jean Grove, *The Little Ice Age* (London; Methuen, 1988); John F. Richards, *The Unending Frontier: An Environmental History of the Early Modern World* (Berkeley: University of California Press, 2003). Scientists make great efforts to distinguish between natural variations and human induced variations within systems. For a brief discussion of scientific consensus on global warming, see Oreskes, "The Scientific Consensus on Climate Change." For a useful discussion of extra-human and human agency in environmental change, see Piers Blaikie and Harold Brookfield, *Land Degradation and Society* (London: Methuen, 1987).

55. Thomas R. Karl and Kevin Trenberth, "Modern Global Climate Change," *Science* 302 (2003): 1719–1723; also see Peter M. Vitousek, "Beyond Global Warming: Ecology and Global Change," *Ecology* 75/7 (1994): 1861–1876.
56. Falkowski et al., "The Global Carbon Cycle."
57. Rosa and Dietz, "Climate Change and Society"; Elizabeth Crawford, *From Ionic Theory to the Greenhouse Effect* (Nantucket, MA: Science History Publications, 1996).
58. Furthermore, the concentration of other greenhouse gases in the atmosphere, since preindustrial times, has increased: methane by 145 percent and nitrous oxide by 15 percent. See Intergovernmental Panel on Climate Change, *IPCC Second Assessment: Climate Change 1995*, 21; also see Karl and Trenberth, "Modern Global Climate Change."
59. York, Rosa, and Dietz, "A Rift in Modernity?"; Rudel, "Sequestering Carbon in Tropical Forests"; Foster, *Ecology Against Capitalism*; Foster, Magdoff, McChesney, "The Pentagon and Climate Change."
60. Foster, *The Vulnerable Planet*; Jared Diamond, *Guns, Germs, and Steel* (New York: W.W. Norton, 1999); Clive Ponting, *The Green History of the World* (New York: St. Martin's Press, 1991); Frederick Buell, *From Apocalypse to Way of Life*; Mike Davis, *Late Victorian Holocausts* (London: Verso, 2001); Franz J. Broswimmer, *Ecocide* (London: Pluto Press, 2002).
61. Moore, "*The Modern World-System* as Environmental History?"; for a detailed and useful study of the development of global capitalism, see Immanuel Wallerstein, *The Modern World-System I: Capitalist Agriculture and the Origins of the European World-Economy in the Sixteenth Century* (New York: Academic Press, 1974).
62. Foster, *Marx's Ecology*.
63. Foster and Clark, "Ecological Imperialism."
64. Capitalism is a dynamic system, but the drive to accumulate capital dictates throughout its history. Thus, in this discussion, we draw upon Marx to situate the logic of capital and understand how this fueled technological development. As capitalism developed and as capital was concentrated and centralized, the characteristics of monopoly capital came to dominate in the twentieth century, but still the drive to accumulate capital was central. In the larger discussion, we make use of work by Foster and Burkett, both of whom study political economy and the environment, to further understanding of the development of capitalism in relation to nature.
65. In addition to its place in the writings of Marx, Engels, and Liebig, the division between town and country remained a dominant concern in the work of social critics and activists. See Ebenezer Howard, *Garden Cities of To-morrow* (London: Swan Sonnenschein & Co., 1902); Peter Kropotkin, *Fields, Factories and Workshops: Or Industry Combined with Agriculture and Brain Work with Manual Work* (New York: G.P. Putnam's Sons, 1913); William Morris, *News from Nowhere and Selected Writings and Designs* (Harmondsworth, Middlesex, UK: Penguin, 1962); William Morris, *William Morris on Art and Socialism* (Minola, New York: Dover Publications, 1999); Raymond Williams, *The Country and the City* (New York: Oxford University Press, 1975).
66. Joyce notes that it is important to see that in cities people experienced new freedoms. Politics was a contested realm of moral positions, economic interests, and power. The relational aspect of social developments remains a central issue to be considered. See Patrick Joyce, *The Rule of Freedom*.
67. Boris Hessen, "The Social and Economic Roots of Newton's 'Principia'," in *Science at the Cross Roads*, N.I. Bukharin, editor (London: Frank Cass and Company, 1971); Robert K. Merton, *Science, Technology and Society in Seventeenth Century England* (New York: Harper & Row Publishers, 1970); Eric Hobsbawm, *The Age of Capital, 1848–1875* (New York: Vintage Books, 1996); Daniel R. Headrick, *The Tentacles of Progress: Technology Transfer in the Age of Imperialism, 1850–1940* (New York: Oxford University Press, 1988); Daniel R. Headrick, *The Tools of Empire: Technology and European Imperialism in the Nineteenth Century* (New York: Oxford University Press, 1981).
68. Marx, *Capital*, Volume 1, 497.

69. Ibid., 494–501.
70. Karl Marx, "Wages," in *Collected Works*, Volume 6 (New York: International Publishers, 1976), 431; also see Burkett, *Marx and Nature*, 108–112.
71. Karl Marx, *Capital*, Volume II (New York: Penguin, 1992), 218–219.
72. Marx, "Wages," 431.
73. Foster, *Ecology Against Capitalism*, 19.
74. Daly, *Steady-State Economics*, 23.
75. Ibid., 23.
76. Joseph A. Schumpeter, *Essays: On Entrepreneurs, Innovations, Business Cycles, and the Evolution of Capitalism* (New Brunswick, NJ: Transaction Publishers, 2000), 302.
77. Karl Marx, *Grundrisse: Foundations of the Critique of Political Economy* (New York: Penguin Books, 1993), 334–335.
78. Paul Burkett, "Natural Capital, Ecological Economics, and Marxism," *International Papers in Political Economy* 10/3 (2003): 1–61.
79. Foster, *Ecology Against Capitalism*, 36; also see Burkett, *Marx and Nature*; Elmar Altvater, *The Future of the Market* (London: Verso, 1993); Allan Schnaiberg and Kenneth A. Gould, *Environment and Society* (New York: St. Martin's Press, 1994); Paul Sweezy, *The Theory of Capitalist Development* (New York: Monthly Review Press, 1970); Paul A. Baran, *The Political Economy of Growth* (New York: Monthly Review Press, 1968); Paul A. Baran and Paul Sweezy, *Monopoly Capital* (New York: Monthly Review Press, 1966) for discussions of capitalism as a system of constant expansion.
80. Paul Sweezy, "Capitalism and the Environment," *Monthly Review* 56/5 (2004): 86–93.
81. Burkett, *Marx and Nature*; Paul Burkett, "Nature's 'Free Gifts' and Ecological Significance of Value," *Capital and Class* 68(1999): 89–110.
82. Burkett, "Natural Capital, Ecological Economics, and Marxism"; Moore, "The Crisis of Feudalism: An Environmental History."
83. Marx, *Capital* Volume III, 955.
84. Marx, *Capital* Volume I. Marx's adherence to the labor theory of value was not a shortcoming, but key to understanding the operations of capitalism both socially and ecologically. Marx illuminates how capital mystifies nature's contribution to wealth. Burkett argues that simply ascribing a social value to nature will not solve this contradiction, because "any attempt to directly attribute value to nature, without taking account of the historical specificity of wealth's social forms, results in an inability to specify the precise *value-form* taken by nature (value in terms of what, and for whom?) without running into serious theoretical difficulties." See Burkett, "Nature's 'Free Gifts' and Ecological Significance of Value"; Foster, *Ecology Against Capitalism*. Thus, Marx's critique of political economy indicates that part of transcending the capitalist system is transcending the labor theory of value itself.
85. Karl Marx, *A Contribution to the Critique of Political Economy* (New York: International Publishers, 1972), 47.
86. Marx, *Grundrisse*, 145.
87. Burkett, *Marx and Nature*, 84.
88. Marx noted in Volume III of *Capital* that capital only made efforts to reduce waste (or refuse) when it was profitable (195–198). Yet these efforts do not resolve the ecological crisis, because they only offer new ways to pursue the accumulation of wealth (in the short run), while increasing the demands placed upon the environment for further production, generating more waste. Thus, the pursuit of profit threatens the ability of nature to reproduce itself and to absorb waste and energy. See Foster, *Ecology Against Capitalism*; Barry Commoner, *The Closing Circle* (New York: Alfred A. Knopf, Inc., 1971); Doug Dowd, *The Waste of Nations* (Boulder: Westview Press, 1989).
89. Foster, *The Vulnerable Planet*.
90. Burkett, "Natural Capital, Ecological Economics, and Marxism," 47; also see Foster, "Capitalism and Ecology"; István Mészáros, *Socialism or Barbarism* (New York: Monthly Review Press, 2001).

91. Rudel, "Sequestering Carbon in Tropical Forests: Experiments, Policy Implications, and Climate Change"; Vitousek, "Beyond Global Warming."
92. Foster, *Ecology Against Capitalism*, 66.
93. Rosa and Dietz, "Climate Change and Society," 423.
94. Foster and Clark, "Ecological Imperialism"; Michael Perelman, "Myths of the Market: Economics and the Environment," *Organization & Environment* 16/2 (2003): 168–226; Harry Magdoff, *The Age of Imperialism* (New York: Monthly Review Press, 1969); Harry Magdoff, *Imperialism* (New York: Monthly Review Press, 1978).
95. Simms, Meyer, and Robins, *Who Owes Who?*
96. For a review of this literature, see Soumyananda Dinda, "Environmental Kuznets Curve Hypothesis: A Survey," *Ecological Economics* 49 (2004): 431–455; Theresa A. Cavlovic, Kenneth H. Baker, Robert P. Berrens, and Kishore Gawande, "A Meta-Analysis of Environmental Kuznets Curve Studies," *Agricultural and Resource Economics Review* 29/1 (2000): 32–42; and David I. Stern, "Progress on the Environmental Kuznets Curve?" *Environment and Development Economics* 3 (1998): 173–196.
97. Paul Hawken, "Forward," in *Natural Capital and Human Economic Survival*, Thomas Prugh, editor (Solomons, MD: International Society for Ecological Economics, 1995); Paul Hawken, Amory Lovins, and L. Hunter Lovins, *Natural Capitalism: Creating the Next Industrial Revolution* (Boston: Little, Brown, and Co., 1999).
98. Paul Hawken, "Natural Capitalism," *Mother Jones Magazine* (April 1997): 40–53, 59–62.
99. Arthur P. J. Mol, *The Refinement of Production* (Utrecht, Netherlands: Van Arkel, 1995); Gert Spaargaren, *The Ecological Modernization of Production and Consumption: Essays in Environmental Sociology*, Doctoral Dissertation, Wageningen University (Wageningen, Netherlands, 1997).
100. Arthur P. J. Mol, "Ecological Modernisation and Institutional Reflexivity: Environmental Reform in the Late Modern Age," *Environmental Politics* 5/2 (1996): 302–323; Arthur P. J. Mol, *Globalization and Environmental Reform* (Cambridge, MA: MIT Press, 2001).
101. This account depends upon Sebastian Budgen's review of Luc Boltanski and Ève Chiapello's book, *Le Nouvel Esprit de Capitalisme* (Gallimard: Paris, 1999). It should also be noted that, in concluding the review, Budgen states that Boltanski and Chiapello's belief that enlightened capitalists will pursue the development of a society premised on social needs and the common good is "the point at which it [their argument] deserts any sense of realism." See Sebastian Budgen, "A New 'Spirit of Capitalism,'" *New Left Review* (January-February 2000): 149–156.
102. Roberts, Grimes, and Manale, "Social Roots of Global Environmental Change"; Anqing Shi, "The Impact of Population Pressure on Global Carbon Dioxide Emissions, 1975–1996: Evidence from Pooled Cross-country Data," *Ecological Economics* 44 (2003): 29–42; York, Rosa, and Dietz, "A Rift in Modernity?"; York, Rosa, and Dietz, "STIRPAT, IPAT, and ImPACT."
103. Richard York, Eugene A. Rosa, and Thomas Dietz, "The Ecological Footprint Intensity of National Economies," *Journal of Industrial Ecology* 8/4 (2004): in press.
104. William Stanley Jevons, *The Coal Question; An Enquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-mines* (London: Macmillan, 1865).
105. Brett Clark and John Bellamy Foster, "William Stanley Jevons and *The Coal Question*: An Introduction to Jevons's 'Of the Economy of Fuel,'" *Organization & Environment* 14/1 (2001): 93–98; M. Giampietro and K. Mayumi, "Another View of Development, Ecological Degradation, and North-South Trade," *Review of Social Economy* 56/1 (1998): 20–36.
106. Dowd, *The Waste of Nations*; also see Baran, *The Political Economy of Growth*, and Baran and Sweezy, *Monopoly Capital*.
107. Richard York and Eugene Rosa, "Key Challenges to Ecological Modernization Theory: Institutional Efficacy, Case Study Evidence, Units of Analysis, and the Pace of Eco-Efficiency," *Organization & Environment* 16/3 (2003): 273–288; York, Rosa, and Dietz,

"A Rift in Modernity?"; York, Rosa, and Dietz, "STIRPAT, IPAT, and ImPACT"; York, Rosa, and Dietz, "Footprints on the Earth"; York, Rosa, and Dietz, "The Ecological Footprint Intensity of National Economies"; Foster, *Ecology Against Capitalism*; Schnaiberg and Gould, *Environment and Society*; Stephen Bunker, "Raw Material and the Global Economy: Oversights and Distortions in Industrial Ecology," *Society and Natural Resources* 9 (1996): 419–429.

108. Data used to make these calculations are from Matthews et al., *Weight of Nations*. GDP is measured in constant units of each nation's own currency. CO_2 emissions are those from combustion of fossil fuels, including bunker fuels. We present data for this selection of nations because Matthews et al. provide data for only these four nations and Germany. The data for Germany are problematic for this presentation since, for years prior to reunification (1990–1991), data are only presented for the former West Germany.
109. Anqing Shi, "The Impact of Population Pressure on Global Carbon Dioxide Emissions, 1975–1996"; York, Rosa, and Dietz, "A Rift in Modernity?"; York, Rosa, and Dietz, "STIRPAT, IPAT, and ImPACT."
110. Marx, *Capital* Volume I; also see Crenshaw and Jenkins, "Social Structure and Global Climate Change."
111. Foster, *Ecology Against Capitalism*; Loren Lutzenhiser, "The Contours of U.S. Climate Non-Policy," *Society and Natural Resources* 14 (2001): 511–523.
112. Crenshaw and Jenkins, "Social Structure and Global Climate Change."
113. Burkett, "Natural Capital, Ecological Economics, and Marxism," 27.
114. Roberts, "Global Inequality and Climate Change"; Karl and Trenberth, "Modern Global Climate Change."
115. Falkowski, Scholes, Boyle, Canadell, Canfield, Elser, Gruber, Hibbard, Högberg, Linder, Mackenzie, Moore III, Pedersen, Rosenthal, Seitzinger, Smetacek, and Steffen, "The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System."
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