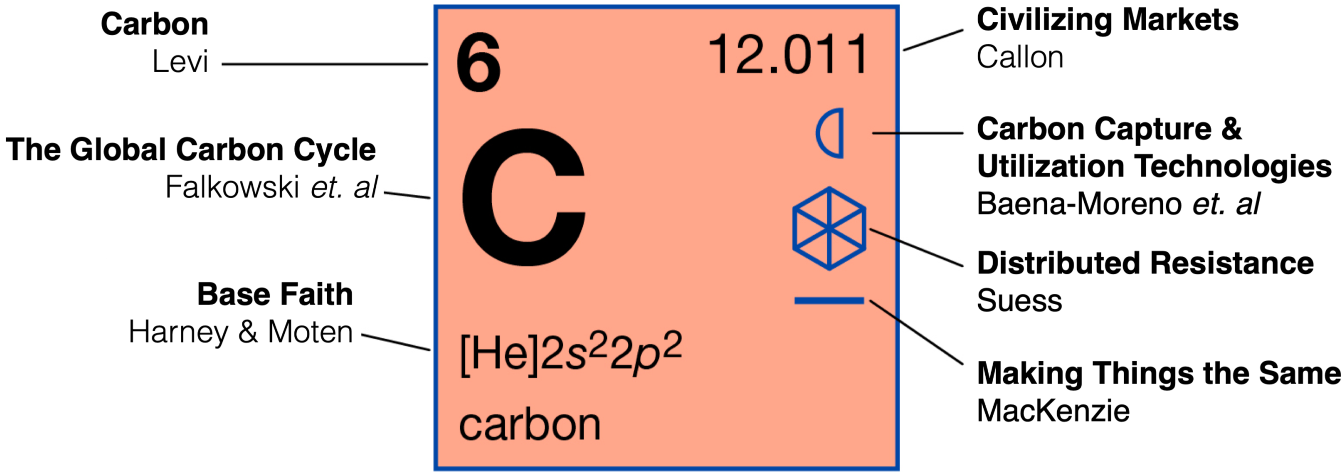


Carbon
Levi

The Global Carbon Cycle
Falkowski *et. al*

Base Faith
Harney & Moten

Civilizing Markets
Callon

Carbon Capture & Utilization Technologies
Baena-Moreno *et. al*

Distributed Resistance
Suess

Making Things the Same
MacKenzie

TRACE CARBON

22nd of May 2020

An online workshop for Art Meets Radical Openness 2020

22nd of May 2020
14:00-17:00

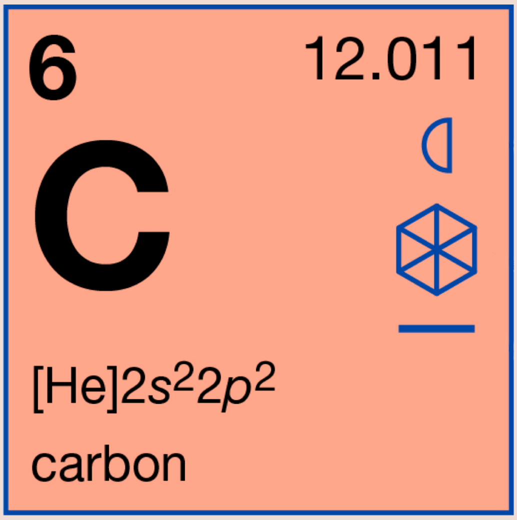
What's at stake
is the trace of perfume
that has been released

.

"Base Faith"
Harney & Moten

Jamie Allen
w/ Caroline Sinders

#cyclesofcirculation



The phrase “trace element” refers to materials and chemicals with very low concentrations. Carbon is literally everywhere on earth — it is anything but “trace” as an element — and yet tracking its flows and tracing its usage has become a global fixation, through marketisation, logistification, footprinting and storytelling. This traceability of materials — the ability to identify their history, distribution, location, and application — has become a main preoccupation of contemporary ecological, political, epidemiological, conspiratorial, and global supply chain practices (forming, for example, part of the ISO 9000 standard). A “trace amount” for the chemist is one whose average concentration is less than 100 atomic parts per million (ppm); for the biochemist it is a dietary element needed in extremely small quantities to sustain life; for the geochemist it is a quantity that makes 0.1% of a rock's composition.

The technologies we hope to account for, manage and engineer carbon (dioxide) are driven by the things that drive all human technological development — human impulses, desires, values, systems, institutions, economics, power equalities and inequalities. There are personal stories in the re-composition of carbon as a new kind of traceable currency, ambiguous stories of human attentions and passions, greed and interests, benevolence and care for the element number 6. If the road to hell is indeed paved with good intentions, the very least we can do is pave them with carbon sequestering cement.

The workshop Trace Carbon is largely a discussion format, framed around the markets and techniques for carbon measurement and management currently proposed and underway in environmental, ecological, governmental, industrial and technological contexts. There will be a short assignment and AFK reflections and assignments done by the group during the approximately 4-hour session. The workshop features presentations of ongoing related work, and a ‘reader’. The workshop itself will involve recordings of ‘carbon traces’ — stories by and with participants — to be published in some form through the Cycles of Circulation project, compiled and edited by Caroline Sinders.

Levi, P. (1984). “Carbon” from “The Periodic Table”. New York: Schocken Books. **p. 4**

“Carbon” by Primo Levi is one part of a book of short stories that Levi wrote — it’s a book of semi-autobiographical fictions based on scenes from his life as a chemist, called “The Periodic Table”. Described as a poetic fantasy, “Carbon” is one entry in this table, about the single life of an atom as its ‘main character.’

Falkowski, P., *et. al* (2000). The global carbon cycle: a test of our knowledge of earth as a system. Science, 290(5490), 291-296. **p. 11**

The cycling and measurement — containment, really — of carbon as an element tests the limits of what human knowledge is and can do. This is an academic paper on the increases of CO2 due to human activities, starting from the Industrial Revolution until now, outlining how far the scientific metaphor of ‘earth as a system’ can be taken.

Harney, S. M. & Moten, F. (2017). Base faith. E-Flux Journal, (86), 1. **p. 18**

A poetic, research based essay on processes and systems of the earth, in relationship to futures on the planet, pasts and futures of ownership and capital. “What’s at stake is the trace of perfume that has been released.”

Callon, M. (2009). Civilizing markets: Carbon trading between in vitro and in vivo experiments. Accounting, organizations and so- ciety, 34(3-4), 535-548. **p. 26**

This journal article by the famed ‘less radical’ Latour, Michel Callon talks about ‘carbon markets’, rather early in their consideration by people like Callon. Carbon markets set a limit or cap of emissions and then allow groups to trade their ‘left over’ emissions they have used. This essay focuses on carbon markets as ‘on-going collective experiments’, which they still are.

Baena-Moreno, *et. al* (2019). Carbon capture and utilization technologies: A literature review and recent advances. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 41(12), 1403-1433. **p. 41**

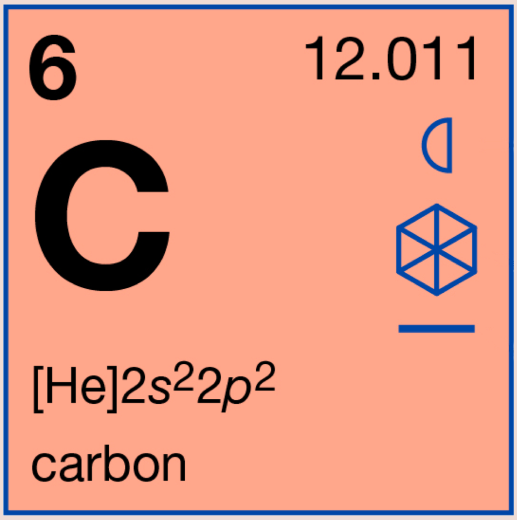
This is a straightforward, if technical academic paper on a list of carbon capture and utilization technologies and applications. The paper covers different ends of the carbon capture spectrum — from R&D, academic studies, to commercial uses of carbon dioxide.

Suess, S. Distributed Resistance, Streamlined Silk. Synoptique.ca, https://synoptique.ca/wp-content/up- loads/2019/03/8.1-Suess-1.pdf **p. 73**

This essay by Solveig Suess talks about globalised flows of materials, including carbon, particularly concerned with logistics and the tracing of this materiality. Suess deals as well with the conceptual tools of new materialism that focus on the mechanics which extract both logistics and industry for capital, and their impacts on environments.

MacKenzie, D. (2009). Making things the same: Gases, emission rights and the politics of carbon markets. Accounting, organizations and society, 34(3-4), 440-455. **p. 89**

A paper on the ways that markets level things out and create means of exchange for incommensurate elements, materials and value. MacKenzie’s work analyses carbon markets specifically, how these markets were created, and how something as ephemeral as atmospheric gases have come to be measured and analyzed through the “politics of market design.”



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“Carbon” by Primo Levi is one part of a book of short stories that Levi wrote — it’s a book of semi-autobiographical fictions based on scenes from his life as a chemist, called “The Periodic Table”. Described as a poetic fantasy, “Carbon” is one entry in this table, about the single life of an atom as its ‘main character.’

Carbon (excerpt)

The Periodic Table, Primo Levi

. . .

Is it right to speak of a "particular" atom of carbon? For the chemist there exist some doubts, because until 1970 he did not have the techniques permitting him to see, or in any event isolate, a single atom; no doubts exist for the narrator, who therefore sets out to narrate.

Our character lies for hundreds of millions of years, bound to three atoms of oxygen and one of calcium, in the form of limestone: it already has a very long cosmic history behind it, but we shall ignore it. For it time does not exist, or exists only in the form of sluggish variations in temperature, daily or seasonal, if, for the good fortune of this tale, its position is not too far from the earth's surface. Its existence, whose monotony cannot be thought of without horror, is a pitiless alternation of hots and colds, that is, of oscillations (always of equal frequency) a trifle more restricted and a trifle more ample: an imprisonment, for this potentially living personage, worthy of the Catholic Hell. To it, until this moment, the present tense is suited, which is that of description, rather than the past tense, which is that of narration—it is congealed in an eternal present, barely scratched by the moderate quivers of thermal agitation.

But, precisely for the good fortune of the narrator, whose story could otherwise have come to an end, the limestone rock ledge of which the atom forms a part lies on the surface. It lies within reach of man and his pickax (all honor to the pickax and its modern equivalents; they are still the most important intermediaries in the millennial dialogue between the elements and man): at any moment—which I, the narrator, decide out of pure caprice to be the year 1840—a blow of the pickax detached it and sent it on its way to the lime kiln, plunging it into the world of things that change. It was roasted until it separated from the calcium, which remained so to speak with its feet on the ground and went to meet a less brilliant destiny, which we shall not narrate. Still firmly clinging to two of its three former oxygen companions, it issued from the chimney and took the path of the air. Its story, which once was immobile, now turned tumultuous.

It was caught by the wind, flung down on the earth, lifted ten kilometers high. It was breathed in by a falcon, descending into its precipitous lungs, but did not penetrate its rich blood and was expelled. It dissolved three times in the water of the sea, once in the water of a cascading torrent, and again was expelled. It traveled with the wind for eight years: now high, now low, on the sea and among the clouds, over forests, deserts, and limitless expanses of ice; then it stumbled into capture and the organic adventure.

Carbon, in fact, is a singular element: it is the only element that can bind itself in long stable chains without a great expense of energy, and for life on earth (the only one we know so far) precisely long chains are required. Therefore carbon is the key element of living substance: but its promotion, its entry into the living world, is not easy and must follow an obligatory, intricate path, which has been clarified (and not yet definitively) only in recent years. If the elaboration of carbon were not a common daily occurrence, on the scale of billions of tons a week, wherever the green of a leaf appears, it would by full right deserve to be called a miracle.

The atom we are speaking of, accompanied by its two satellites which maintained it in a gaseous state, was therefore borne by the wind along a row of vines in the year 1848. It had the good fortune to brush against a leaf, penetrate it, and be nailed there by a ray of the sun. If my language here becomes imprecise and allusive, it is not only because of my ignorance: this decisive event, this instantaneous work *a tre*—of the carbon dioxide, the light, and the vegetal greenery—has not yet been described in definitive terms, and perhaps it will not be for a long time to come, so different is it from that other "organic" chemistry which is the cumbersome, slow, and ponderous work of man: and yet this refined, minute, and quick-witted chemistry was "invented" two or three billion years ago by our silent sisters, the plants, which do not experiment and do not discuss, and whose temperature is identical to that of the environment in which they live. If to comprehend is the same as forming an image, we will never form an image of a happening whose scale is a millionth of a millimeter, whose rhythm is a millionth of a second, and whose protagonists are in their essence invisible. Every verbal description must be inadequate, and one will be as good as the next, so let us settle for the following description.

Our atom of carbon enters the leaf, colliding with other innumerable (but here useless) molecules of nitrogen and oxygen. It adheres to a large and complicated molecule that activates it, and simultaneously receives the decisive message from the sky, in the flashing form of a packet of solar light: in an instant, like an insect caught by a spider, it is separated from its oxygen, combined with hydrogen and (one thinks) phosphorus, and finally inserted in a chain, whether long or short does not matter, but it is the chain of life. All this happens swiftly, in silence, at the temperature and pressure of the atmosphere, and gratis: dear colleagues, when we learn to do likewise we will be *sicut Deus*, and we will have also solved the problem of hunger in the world.

But there is more and worse, to our shame and that of our art. Carbon dioxide, that is, the aerial form of the carbon of which we have up till now spoken: this gas which constitutes the raw material of life, the permanent store upon which all that grows draws, and the ultimate destiny of all flesh, is not one of the principal components of air but rather a ridiculous remnant, an "impurity," thirty times less abundant than argon, which nobody even notices. The air contains 0.03 percent; if Italy was air, the only Italians fit to build life would be, for example, the fifteen thousand inhabitants of Milazzo in the province of Messina. This, on the human scale, is ironic acrobatics, a juggler's trick, an incomprehensible display of omnipotence-arrogance, since from this ever renewed impurity of the air we come, we animals and we plants, and we the human species, with our four billion discordant opinions, our milleniums of history, our wars and shames, nobility and pride. In any event, our very presence on the planet becomes laughable in geometric terms: if all of humanity, about 250 million tons, were distributed in a layer of homogeneous thickness on all the emergent lands, the "stature of man" would not be visible to the naked eye; the thickness one would obtain would be around sixteen thousandths of a millimeter.

Now our atom is inserted: it is part of a structure, in an architectural sense; it has become related and tied to five companions so identical with it that only the fiction of the story permits me to distinguish them. It is a beautiful ring-shaped structure, an almost regular hexagon, which however is subjected to complicated exchanges and balances with the water in which it is dissolved; because by now it is dissolved in water, indeed in the sap of the vine, and this, to remain dissolved, is both the obligation and the privilege of all substances that are destined (I was about to say "wish") to change. And if then anyone really wanted to find out why a ring, and why a hexagon, and why soluble in water, well, he need not worry: these are among the not many questions to which our doctrine can reply with a persuasive discourse, accessible to everyone, but out of place here.

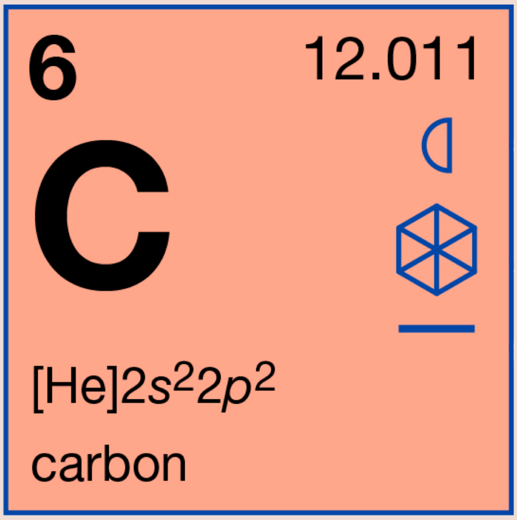
It has entered to form part of a molecule of glucose, just to speak plainly: a fate that is neither fish, flesh, nor fowl, which is intermediary, which prepares it for its first contact with the animal world but does not authorize it to take on a higher responsibility: that of becoming part of a proteic edifice. Hence it travels, at the slow pace of vegetal juices, from the leaf through the pedicel and by the shoot to the trunk, and from here descends to the almost ripe bunch of grapes. What then follows is the province of the winemakers: we are only interested in pinpointing the fact that it escaped (to our advantage, since we would not know how to put it in words) the alcoholic fermentation, and reached the wine without changing its nature.

It is the destiny of wine to be drunk, and it is the destiny of glucose to be oxidized. But it was not oxidized immediately: its drinker kept it in his liver for more than a week, well curled up and tranquil, as a reserve aliment for a sudden effort; an effort that he was forced to make the following Sunday, pursuing a bolting horse. Farewell to the hexagonal structure: in the space of a few instants the skein was unwound and became glucose again, and this was dragged by the bloodstream all the way to a minute muscle fiber in the thigh, and here brutally split into two molecules of lactic acid, the grim harbinger of fatigue: only later, some minutes after, the panting of the lungs was able to supply the oxygen necessary to quietly oxidize the latter. So a new molecule of carbon dioxide returned to the atmosphere, and a parcel of the energy that the sun had handed to the vine-shoot passed from the state of chemical energy to that of mechanical energy, and thereafter settled down in the slothful condition of heat, warming up imperceptibly the air moved by the running and the blood of the runner. “Such is life,” although rarely is it described in this manner: an inserting itself, a drawing off to its advantage, a parasitizing of the downward course of energy, from its noble solar form to the degraded one of low- temperature heat. In this downward course, which leads to equilibrium and thus death, life draws a bend and nests in it.

Our atom is again carbon dioxide, for which we apologize: this too is an obligatory passage; one can imagine and invent others, but on earth that’s the way it is. Once again the wind, which this time travels far; sails over the Apennines and the Adriatic, Greece, the Aegean, and Cyprus: we are over Lebanon, and the dance is repeated. The atom we are concerned with is now trapped in a structure that promises to last for a long time: it is the venerable trunk of a cedar, one of the last; it is passed again through the stages we have already described, and the glucose of which it is a part belongs, like the bead of a rosary, to a long chain of cellulose. This is no longer the hallucinatory and geological fixity of rock, this is no longer millions of years, but we can easily speak of centuries because the cedar is a tree of great longevity. It is our whim to abandon it for a year or five hundred years: let us say that after twenty years (we are in 1868) a wood worm has taken an interest in it. It has dug its tunnel between the trunk and the bark, with the obstinate and blind voracity of its race; as it drills it grows, and its tunnel grows with it. There it has swallowed and provided a setting for the subject of this story; then it has formed a pupa, and in the spring it has come out in the shape of an ugly gray moth which is now drying in the sun, confused and dazzled by the splendor of the day. Our atom is in one of the insect's thousand eyes, contributing to the summary and crude vision with which it orients itself in space. The insect is fecundated, lays its eggs, and dies: the small cadaver lies in the undergrowth of the woods, it is emptied of its fluids, but the chitin carapace resists for a long time, almost indestructible. The snow and sun return above it without injuring it: it is buried by the dead leaves and the loam, it has become a slough, a "thing," but the death of atoms, unlike ours, is never irrevocable. Here are at work the omnipresent, untiring, and invisible gravediggers of the undergrowth, the microorganisms of the humus. The carapace, with its eyes by now blind, has slowly disintegrated, and the ex-drinker, ex-cedar, ex-wood worm has once again taken wing.

We will let it fly three times around the world, until 1960, and in justification of so long an interval in respect to the human measure we will point out that it is, however, much shorter than the average: which, we understand, is two hundred years. Every two hundred years, every atom of carbon that is not congealed in materials by now stable (such as, precisely, limestone, or coal, or diamond, or certain plastics) enters and reenters the cycle of life, through the narrow door of photosynthesis. Do other doors exist? Yes, some syntheses created by man; they are a title of nobility for man-the-maker, but until now their quantitative importance is negligible. They are doors still much narrower than that of the vegetal greenery; knowingly or not, man has not tried until now to compete with nature on this terrain, that is, he has not striven to draw from the carbon dioxide in the air the carbon that is necessary to nourish him, clothe him, warm him, and for the hundred other more sophisticated needs of modern life. He has not done it because he has not needed to: he has found, and is still finding (but for how many more decades?) gigantic reserves of carbon already organicized, or at least reduced. Besides the vegetable and animal worlds, these reserves are constituted by deposits of coal and petroleum: but these too are the inheritance of photosynthetic activity carried out in distant epochs, so that one can well affirm that photosynthesis is not only the sole path by which carbon becomes living matter, but also the sole path by which the sun's energy becomes chemically usable. It is possible to demonstrate that this completely arbitrary story is nevertheless true. I could tell innumerable other stories, and they would all be true: all literally true, in the nature of the transitions, in their order and data. The number of atoms is so great that one could always be found whose story coincides with any capriciously invented story. I could recount an endless number of stories about carbon atoms that become colors or perfumes in flowers; of others which, from tiny algae to small crustaceans to fish, gradually return as carbon dioxide to the waters of the sea, in a perpetual, frightening round-dance of life and death, in which every devourer is immediately devoured; of others which instead attain a decorous semi-eternity in the yellowed pages of some archival document, or the canvas of a famous painter; or those to which fell the privilege of forming part of a grain of pollen and left their fossil imprint in the rocks for our curiosity; of others still that descended to become part of the mysterious shape-messengers of the human seed, and participated in the subtle process of division, duplication, and fusion from which each of us is born. Instead, I will tell just one more story, the most secret, and I will tell it with the humility and restraint of him who knows from the start that his theme is desperate, his means feeble, and the trade of clothing facts in words is bound by its very nature to fail.

It is again among us, in a glass of milk. It is inserted in a very complex, long chain, yet such that almost all of its links are acceptable to the human body. It is swallowed; and since every living structure harbors a savage distrust toward every contribution of any material of living origin, the chain is meticulously broken apart and the fragments, one by one, are accepted or rejected. One, the one that concerns us, crosses the intestinal threshold and enters the bloodstream: it migrates, knocks at the door of a nerve cell, enters, and supplants the carbon which was part of it. This cell belongs to a brain, and it is my brain, the brain of the me who is writing; and the cell in question, and within it the atom in question, is in charge of my writing, in a gigantic minuscule game which nobody has yet described. It is that which at this instant, issuing out of a labyrinthine tangle of yeses and nos, makes my hand run along a certain path on the paper, mark it with these volutes that are signs: a double snap, up and down, between two levels of energy, guides this hand of mine to impress on the paper this dot, here, this one.



Falkowski, P., et. al (2000). The global carbon cycle: a test of our knowledge of earth as a system. Science, 290(5490), 291-296.

The cycling and measurement — containment, really — of carbon as an element tests the limits of what human knowledge is and can do. This is an academic paper on the increases of CO2 due to human activities, starting from the Industrial Revolution until now, outlining how far the scientific metaphor of ‘earth as a system’ can be taken.

The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System

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P. Högberg,[9]‡ S. Linder,[10]‡ F. T. Mackenzie,[11]‡ B. Moore III,[8]‡ T. Pedersen,[12]‡ Y. Rosenthal,[1]‡
S. Seitzinger,[1]‡ V. Smetacek,[13]‡ W. Steffen[14]‡

Motivated by the rapid increase in atmospheric CO_2 due to human activities since the Industrial Revolution, several international scientific research programs have analyzed the role of individual components of the Earth system in the global carbon cycle. Our knowledge of the carbon cycle within the oceans, terrestrial ecosystems, and the atmosphere is sufficiently extensive to permit us to conclude that although natural processes can potentially slow the rate of increase in atmospheric CO_2, there is no natural "savior" waiting to assimilate all the anthropogenically produced CO_2 in the coming century. Our knowledge is insufficient to describe the interactions between the components of the Earth system and the relationship between the carbon cycle and other biogeochemical and climatological processes. Overcoming this limitation requires a systems approach.

Over the past 200 years, human activities have altered the global carbon cycle significantly. Understanding the consequences of these activities in the coming decades is critical for formulating economic, energy, technology, trade, and security policies that will affect civilization for generations. Given present trends in energy demands, ample fossil fuel reserves, a lack of global, concerted, alternative energy production strategies, and projections of human population growth, atmospheric CO_2 concentrations appear fated to increase throughout the coming century (*1*, *2*). The rate of change in atmospheric CO_2 depends, however, not only on human activities but also on biogeochemical and climatological processes and their interactions with the carbon cycle. Here we examine some of the changes in biogeochemical and climatological processes concomitant with alterations in the carbon and nutrient cycles in the contemporary world, and compare these processes with our understanding of the preceding 420,000 years of Earth's history.

Entering Uncharted Waters

Under the auspices of the International Geosphere-Biosphere Programme (IGBP), several large international scientific studies have focused on elucidating various aspects of the global carbon cycle over the past decade (*3*). These programs have helped address two major recurrent questions in the current debate about global change: Can we distinguish between anthropogenic perturbations and natural variability in biogeochemical cycles and climate? And what is the sensitivity of Earth's climate to changes in atmospheric CO_2? We consider the two questions in the context of the relatively recent geological history of Earth, for which we have robust paleoclimatological proxies.

Arrhenius recognized over 100 years ago (*4*) that atmospheric CO_2 plays a critical role in regulating Earth's temperature (*5*, *6*). Analyses of ice cores strongly suggest that over the past 420,000 years, the climate system has operated within a relatively constrained domain of atmospheric CO_2 and temperature (*7*, *8*) (Fig. 1). In the CO_2-temperature phase space that characterized the preindustrial world, CO_2 oscillated in 100,000-year cycles by approximately 100 parts per million by volume (ppmv), between about 180 and 280 ppmv. On millennial time scales, changes in CO_2 recorded in ice cores are highly correlated with changes in temperature (*9*). Although high-resolution analysis of ice cores suggests that there are periods in Earth's history when temperature can change relatively sharply without a discernible change in CO_2 (*7*), the converse does not appear to be true.

Comparison of the present atmospheric concentration of CO_2 with the ice core record reveals that we have left the domain that defined the Earth system for the 420,000 years before the Industrial Revolution (*10*) (Fig. 1). Atmospheric CO_2 concentration is now nearly 100 ppmv higher, and has risen to that level at a rate at least 10 and possibly 100 times faster than at any other time in the past 420,000 years. We have driven the Earth system from the tightly bounded domain of glacial-interglacial dynamics. Are we in a transition period to a new, stable domain? If so, what are the main forcing factors and feedbacks of this transition? What will be the climatological features of a new domain? What will be the responses and feedbacks of Earth's ecosystems? How and when can and should we return to the preindustrial domain?

The active carbon reservoirs and their strengths. Atmospheric CO_2 exchanges rapidly with oceans and terrestrial ecosystems (*11*). The ratio between the rate at which these two reservoirs absorb atmospheric CO_2 and the rate of emissions determines the overall rate of change of atmospheric CO_2. The sink strength of the reservoirs determines the capacity to absorb excess or anthropogenic CO_2. During glacial-interglacial transitions, for example, the atmosphere acts to transfer carbon between terrestrial ecosystems and the oceans. The remarkable consistency of the upper and lower limits of the glacial-interglacial atmospheric CO_2 concentrations, and the apparent fine control over periods of many thousands of years around those limits, suggest strong feedbacks that constrain the sink

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‡Members of the IGBP Working Group.

strengths in both the oceans and terrestrial ecosystems. The relatively rapid transition from glacial to interglacial states and the initially steep, but eventually gradual, transition into glacial periods (8) suggests that the rates of absorption and emission of CO_2 from the oceans and terrestrial ecosystems are asymmetrical. It should be noted that because of this asymmetry, the average atmospheric CO_2 concentration during the past 420,000 years was only ~220 ppmv, not 280 ppmv as usually ascribed (12).

How is atmospheric CO_2 regulated? The total of dissolved inorganic carbon in the oceans is 50 times that of the atmosphere (Table 1), and on time scales of millennia, the oceans determine atmospheric CO_2 concentrations, not vice versa. Atmospheric CO_2 continuously exchanges with oceanic CO_2 at the surface. This exchange, which amounts to ~90 gigatons (Gt) of carbon per year in each direction, leads to rapid equilibration of the atmosphere with the surface water. Upon dissolution in 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. Because the rate of anthropogenic CO_2 emissions is several orders of magnitude greater than the supply of mineral cations, on time scales of millennia the ability of the surface oceans to absorb CO_2 will inevitably decrease as the atmospheric concentration of the gas increases (*13*).

The concentration of total dissolved inorganic carbon in the ocean increases markedly below about the upper 300 m, where it remains significantly above the surface ocean-atmosphere equilibrium value in all ocean basins. The higher concentration of inorganic carbon in the ocean interior results from a combination of two fundamental processes: the "solubility pump" and "biological pumps" (*14*, *15*).

The efficiency of the solubility pump depends on the thermohaline circulation and on latitudinal and seasonal changes in ocean ventilation (*16*, *17*). CO_2 is more soluble in cold, saline waters, and sequestration of atmospheric CO_2 in the ocean interior is therefore controlled by the formation of cold, dense water masses at high latitudes, especially in the North Atlantic and in the Southern Ocean confluence. As these water masses sink into the ocean interior and are transported laterally, CO_2 is effectively prevented from re-equilibrating with the atmosphere by a cap of lighter overlying waters. Re-equilibration occurs only when waters from the ocean interior are brought back to the surface, decades to several hundreds of years later.

Coupled climate-ocean simulations (*6*, *18*) suggest that CO_2-induced global warming will lead to increased stratification of the water column. If this occurs, the transport of carbon from the upper ocean to the deep ocean will be reduced, with a resulting decrease in the rate of sequestration of anthropogenic carbon in the ocean (*19*, *20*). The combined effects of progressive saturation of the buffering capacity and increased stratification will weaken two important negative feedbacks in the carbon-climate system, thereby reducing the rate of oceanic uptake of anthropogenic CO_2. The magnitude of these feedbacks is critically dependent on how ocean circulation and mixing will respond to the climatic forcing.

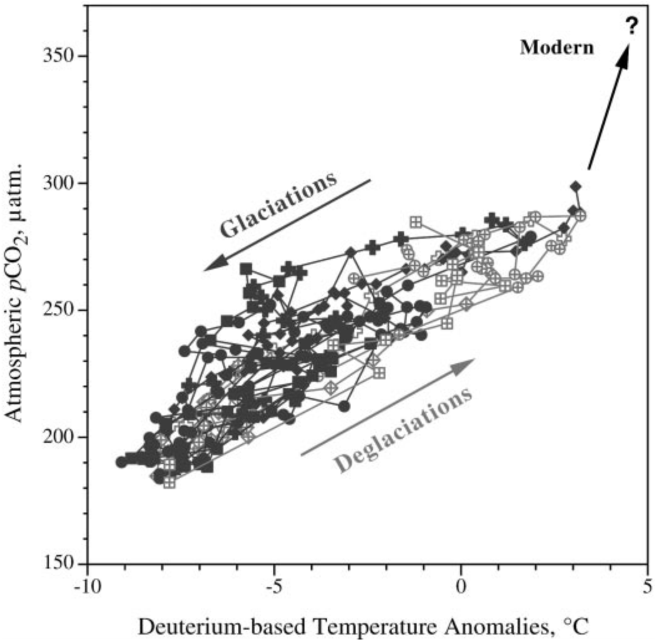

Fig. 1. A correlation between atmospheric partial pressure of CO_2 (pCO_2) and isotopic (δ_D) temperature anomalies as recorded in the Vostok ice core. The figure shows that climate variations in the past 420,000 years operated within a relatively constrained domain. Data are from (*8*).

Biological processes also contribute to the absorption of atmospheric CO_2 in the ocean. Phytoplankton photosynthesis lowers the partial pressure of CO_2 in the upper ocean and thereby promotes the absorption of CO_2 from the atmosphere. Approximately 25% of the carbon fixed in the upper ocean sinks into the interior (*21*, *22*), where it is oxidized through heterotrophic respiration, raising the concentration of dissolved inorganic carbon (DIC). The export of organic carbon from the surface to the ocean interior presently accounts for ~11 to 16 Gt of carbon per year (*23*). This process keeps atmospheric CO_2 concentrations 150 to 200 ppmv lower than they would be if all the phytoplankton in the ocean were to die (*23*, *24*). In addition to the organic biological pump, several phytoplankton and zooplankton species form $CaCO_3$ shells that sink into the interior of the ocean, where some fraction dissolves. This inorganic carbon cycle leads to a reduction in surface ocean DIC relative to the deep ocean and is therefore sometimes called the "carbonate pump." The process of precipitating carbonates, however, increases the partial pressure of CO_2 (*25*). Hence, on time scales of centuries, while the carbonate pump lowers DIC concentrations in the upper ocean, it simultaneously leads to the evasion of CO_2 from the ocean to the atmosphere.

Coupled climate-biogeochemical models suggest that the biological pumps tend to counteract the decrease in uptake caused by the solubility pump (*20*, *26*). If the biological pumps are to absorb anthropogenic CO_2 in the coming century, their efficiency must increase. In principle, this can be accomplished by any or all of four processes: (i) enhancing utilization of excess nutrients in the upper ocean, (ii) adding one or more nutrients that limit primary production, (iii) changing the elemental ratios of the organic matter in the ocean, and (iv) increasing the organic carbon/calcite ratio in the sinking flux (*27*). There are significant gaps in our knowledge that limit our ability to predict the magnitude of changes in oceanic uptake, but the likely changes in the biological pump are too small to counteract the projected CO_2 emissions in the coming century. Almost certainly, however, changes in oceanic ecosystem structure will accompany changes in physical circulation (and hence changes in nutrient supplies), lowered pH, and changes in the hydrological cycle. Our present knowledge of the factors that determine the abundance and distribution of key groups of marine organisms is so limited that it is unlikely we will be able to predict such changes within the next decade with reasonable certainty (*28*). These uncertainties affect our ability to predict specific responses, but not the sign of the changes in atmospheric CO_2 or the impact of this change on upper ocean pH. If our current understanding of the ocean carbon cycle is borne out, the sink strength of the oceans will weaken, leaving a larger fraction of anthropogenically produced CO_2 in the atmosphere or to be absorbed by terrestrial ecosystems.

Terrestrial ecosystems also exchange CO_2 rapidly with the atmosphere, but unlike in the oceans, there is no physicochemical pump. CO_2 is removed from the atmosphere through photosynthesis and stored in organic matter. It is returned to the atmosphere via a number of respiratory pathways that operate on various time scales: (i) autotrophic respiration by the plants themselves; (ii) heterotrophic respiration, in which plant-derived organic matter is oxidized primarily by soil microbes; and (iii) disturbances, such as fire, in which large amounts of organic matter are oxidized in very short periods of time.

On a global basis, terrestrial carbon storage primarily occurs in forests (*29*). The sum of carbon in living terrestrial biomass and soils is approximately three times greater than the CO_2 in the atmosphere (Table 1), but the turnover time of terrestrial carbon is on the order of decades. Direct determination of changes in terrestrial carbon storage has proven extremely difficult (*30*). Rather, the contribution of terrestrial ecosystems to carbon storage is inferred from changes in the concentrations of atmospheric gases, especially CO_2 and O_2, their isotopic composition, inventories of land use change, and models (*31–33*). The models require accurate knowledge of the oceanic uptake of CO_2 (*31*, *34*, *35*).

Terrestrial net primary production (NPP) (*36*) is not saturated by present atmospheric CO_2 concentrations (*37*). Consequently, as atmospheric CO_2 increases, terrestrial plants are a potential sink for anthropogenic carbon. The principal carbon-fixing enzyme in plants is ribulose 1,5-bisphosphate carboxylase/oxygenase (rubisco) (*38*). In C3 plants, the activity of rubisco increases with increasing CO_2 concentrations, saturating between 800 and 1000 ppmv CO_2, a concentration that will probably be reached early in the next century at the present emissions rate (*2*). Because the saturation function decreases as CO_2 increases, terrestrial plants will become less of a sink for CO_2 in coming decades. Some experimental evidence suggests that because of nutrient limitation (*39*), NPP may level off at only 10 to 20% above current rates, at an atmospheric CO_2 concentration of 550 to 650 ppmv, or double preindustrial concentrations (*40*). Furthermore, increased temperature will probably lead to higher microbial heterotrophic respiration, which may counteract and even exceed the enhancement of NPP (*41*). The combined effects of higher CO_2 concentrations, higher temperatures, and changes in disturbance and soil moisture regimes lead to considerable uncertainty about the ability of terrestrial ecosystems to mitigate against rising CO_2 in the coming decades (*42*). However, recent results from long-term soil warming experiments in a boreal forest contradict the idea that the projected rise in temperature is likely to lead to forests that are now carbon sinks becoming carbon sources in the foreseeable future (*43*).

Again, as in the case of marine ecosystems, we can predict that the negative feedback afforded by terrestrial ecosystems in removing anthropogenic CO_2 from atmosphere will continue; however, the sink strength will almost certainly weaken. The exact magnitude of the change in sink strength remains unclear.

Interaction of the carbon cycle with other biogeochemical cycles. All biotic sinks for CO_2 require other nutrients in addition to carbon. Humans have affected virtually every major biogeochemical cycle (Table 2), but the effects of these impacts on the interactions between these elemental cycles are poorly understood (*44*). The production of synthetic fertilizers, the cultivation of nitrogen-fixing crops, and the deposition of fossil fuel–associated nitrogen are collectively of the same order of magnitude as natural biological nitrogen fixation (*45*). These inputs will continue to rise with the projected increase in human population (*46*). Similarly, there has been an approximately fourfold increase in phosphorus inputs to the biosphere, primarily due to mining of phosphorus compounds for fertilizer.

At first glance, one might conclude that simultaneous increases in nitrogen fixation and phosphate production would stimulate the biological sequestration of carbon in terrestrial and marine ecosystems. Will such stimulation provide salvation from the continued anthropogenic emissions of CO_2 to the atmosphere?

It is estimated that by 2050, the total transport of fixed inorganic nitrogen from land to the coastal zone will have increased from the present value of ~20 teragrams (Tg) of nitrogen to ~ 40 Tg of nitrogen per year (*47*), concomitant with an increase in human population from 6 to 9 or 10 billion. Although nutrient loading has resulted in coastal eutrophication on a global scale (*48*), denitrification presently removes virtually all land-derived nitrogen before it can reach the open ocean (*49*, *50*). Coastal denitrification thus effectively decouples the terrestrial and oceanic nitrogen cycles. However, even if no denitrification occurred, the increased flux of land-derived nitrogen would sequester only 0.4 Gt of carbon per year (*48*), corresponding to about 5% of the present anthropogenic CO_2 emissions.

There is no evidence that phosphorus significantly limits primary production in coastal or open oceans on a global scale (*51*) or that phosphorus loading of the coastal oceans has significantly altered global primary production (*46*).

Iron is a micronutrient that limits both primary production (*52*) and nitrogen fixation in many areas of the ocean (*53*). Eolian (windborne) iron fluxes, a principal source of iron input to the open ocean, are coupled both to land use and the hydrological cycle (*54*). Episodic aridity affects eolian iron supplies, and in the coming decades, iron fluxes to the ocean could therefore increase because of increased evaporation of soil moisture or decrease because of increased precipitation (*55*). Increases in evaporation and increases in precipitation are expected in different parts of the land surface in response to increasing global temperatures. Thus, although increasing temperature and its potential influence on the availability of iron in the open ocean will affect the biological uptake of carbon in the ocean, at present we do not know the sign of the changes. However, even if iron fluxes were to increase to such an extent that oceanic nitrogen fixation were stimulated to the maximum, the maximum change in atmospheric CO_2 that could ensue would be about 40 ppmv. Although not insignificant, such an effect is unrealistic on time scales of centuries (*56*).

Eolian nitrogen inputs can also potentially enhance both terrestrial and marine uptake of anthropogenic CO_2 (*37*). In terrestrial ecosystems, the sink strength resulting from eolian nitrogen deposition depends on the carbon: nitrogen ratio of the stored organic mat-

Table 1. Carbon pools in the major reservoirs on Earth.

Pools	Quantity (Gt)
Atmosphere	720
Oceans	38,400
Total inorganic	37,400
Surface layer	670
Deep layer	36,730
Total organic	1,000
Lithosphere	
Sedimentary carbonates	>60,000,000
Kerogens	15,000,000
Terrestrial biosphere (total)	2,000
Living biomass	600–1,000
Dead biomass	1,200
Aquatic biosphere	1–2
Fossil fuels	4,130
Coal	3,510
Oil	230
Gas	140
Other (peat)	250

ter and the degree of nitrogen saturation of soils (*44*, *57–59*). Nitrogen deposition is predicted to continue and has the potential to enhance the carbon sink in nitrogen-limited ecosystems, but it will probably become decreasingly effective at doing so. Future nitrogen deposition will largely occur on already nitrogen-saturated soils, such as in the forests of Western Europe, China, and India, and on agricultural lands in the tropics, whose capacity to sequester carbon is intrinsically small and where soils are mostly limited by phosphate (*57*). In the context of the global carbon cycle, the eolian input of nitrogen to marine ecosystems is essentially irrelevant (*59*).

In addition to ecophysiological considerations, land use change plays a major role in the carbon source/sink dynamics. The increased pressure in the developing world to increase food and fiber production by converting forests to agricultural use effectively increases the flux of carbon to the atmosphere while simultaneously reducing the land area available for active sinks. Abandonment of agricultural land and regrowth of forests, largely in the temperate Northern Hemisphere, may be a significant terrestrial CO_2 sink at present (*34*) but cannot be sustained indefinitely. This sink can buy some time, but unless CO_2 emissions are reduced, it cannot mitigate against continued accumulation of the gas in Earth's atmosphere given projected emission scenarios.

Table 2. Examples of human intervention in the global biogeochemical cycles of carbon, nitrogen, phosphorus, sulfur, water, and sediments. Data are for the mid-1900s.

Element	Flux	Magnitude of flux (millions of metric tons per year)		% change due to human activities
		Natural	Anthropogenic	
C	Terrestrial respiration and decay CO_2	61,000		
	Fossil fuel and land use CO_2		8,000	+13
N	Natural biological fixation	130		
	Fixation owing to rice cultivation, combustion of fossil fuels, and production of fertilizer		140	+108
P	Chemical weathering	3		
	Mining		12	+400
S	Natural emissions to atmosphere at Earth's surface	80		
	Fossil fuel and biomass burning emissions		90	+113
O and H (as H_2O)	Precipitation over land	111×10^{12}		
	Global water usage		18×10^{12}	+16
Sediments	Long-term preindustrial river suspended load	1×10^{10}		
	Modern river suspended load		2×10^{10}	+200

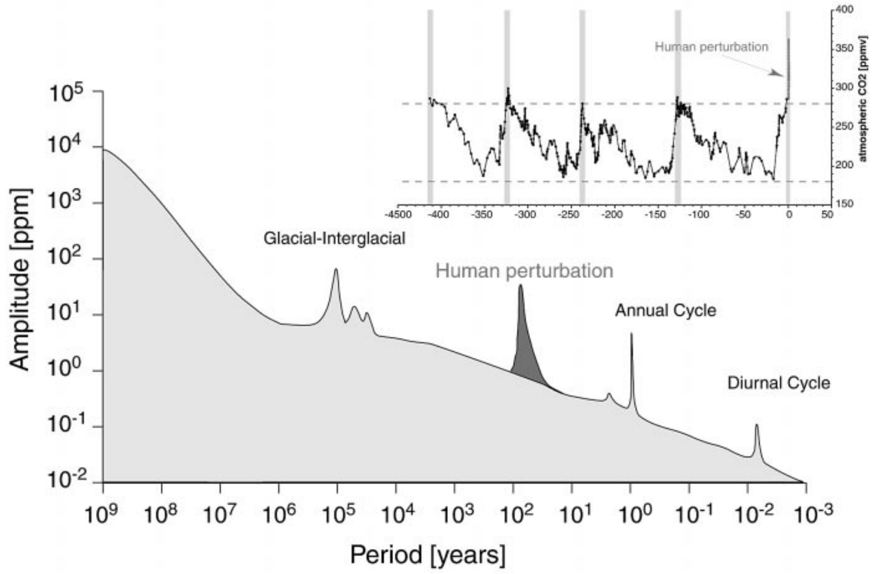

Fig. 2. Schematic variance spectrum for CO_2 over the course of Earth's history. Note the impact of human perturbations on the decade-to-century scale. (**Inset**) Changes in atmospheric CO_2 over the past 420,000 years as recorded in the Vostok ice, showing that both the rapid rate of change and the increase in CO_2 concentration since the Industrial Revolution are unprecedented in recent geological history.

The Need for an Integrated Systems Approach

The global carbon cycle is affected by human activities and is coupled to other climatological and biogeochemical processes. As discussed above, we have considerable information about specific aspects of the carbon cycle, but many of the couplings and feedbacks are poorly understood. As we drift further away from the domain that characterized the preindustrial Earth system, we severely test the limits of our understanding of how the Earth system will respond.

A look at the current understanding of glacial-interglacial CO_2 changes illustrates the problem. Perhaps surprisingly, there is no consensus on the causes of these changes. There are at least 11 hypotheses (*53*, *60*, *61*), which may be grouped into three basic themes: (i) physical/chemical "reorganization" of the oceans, (ii) changes in the ocean carbonate system, and (iii) changes in ocean nutrient inventories. Many of these hypotheses are not mutually exclusive. The interactions between marine and terrestrial ecosystems, changes in ocean circulation, radiative forcing, and greenhouse gases all probably interact in a specific sequence to give rise to the natural cyclic atmospheric and climatic oscillations. These interactions are not presently represented in detailed models of the glacial-interglacial transitions.

This example illustrates three points. First, in the recent history of Earth, the carbon cycle did not operate in a vacuum and was not constrained to a specific reservoir. Natural changes in the inventories of carbon, as inferred from the ice core records of glacial-interglacial transitions, are linked to other biogeochemical and climatological processes. Those linkages continue to the present, but the quantitative impacts in the coming century are obscured by simultaneous alterations of numerous biogeochemical cycles through human activities. Second, the scientific community has generally approached problems such as glacial-interglacial transitions from a disciplinary perspective. This approach has not produced completely satisfactory explanations for what is clearly a large natural perturbation in the global carbon cycle. Because of the disciplinary nature of research, interactions between components of the Earth system are not incorporated into present biogeochemical or climate models. When changes in isolated processes are considered, we usually understand the signs of feedbacks, if not the magnitudes of the responses. It is when processes interact that we have significant problems in reproducing the phenomena quantitatively. Clearly, a systems approach is needed. Third, reconstructions of the carbon cycle (for example, during glacial-interglacial transitions) provide testable hypotheses about the Earth system. Consensus on how a 100-ppmv change in atmospheric CO_2 can occur naturally within a 100,000-year time frame (*62*) would imply some understanding of the feedbacks within the Earth system. Knowledge of these feedbacks does not give us predictive capability for the coming decades or centuries, but it can help us develop the modeling tools needed to integrate the detailed information gathered from component studies of the contemporary world.

Our analysis above shows that although natural sinks can potentially slow the rate of increase in atmospheric CO_2, there is no natural savior waiting to assimilate all the anthropogenic CO_2 in the coming century. Although on geological time scales the anthropogenic emission of CO_2 is a transient phenomenon (Fig. 2), it will affect Earth's biogeochemical cycles for hundreds of years to come (*20*, *63*). Our present imperfect models suggest that the feedbacks between carbon and other biogeochemical and climatological processes will lead to weakened sink strengths in the foreseeable future, and the prospects of retrieving anthropogenic CO_2 from the atmosphere by enhancing natural sinks are small. This condition cannot persist indefinitely. Potential remediation strategies, such as the purposeful manipulation of biological and chemical processes to accelerate the sequestration of atmospheric CO_2, are being seriously considered by both governmental bodies and private enterprises. These mitigation strategies will themselves have unknown consequences and must be carefully assessed within the context of an integrated systems approach before any action is taken.

As we rapidly enter a new Earth system domain, the "Anthropocene" Era (*64*), the debate about distinguishing human effects from natural variability will inevitably abate in the face of increased understanding of climate and biogeochemical cycles. Our present state of uncertainty arises largely from lack of integration of information. Nevertheless, scientists' abilities to predict the future will always have a component of uncertainty. This uncertainty should not be confused with lack of knowledge nor should it be used as an excuse to postpone prudent policy decisions based on the best information available at the time.

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$$CO_2 + CaSiO_3 \underset{\text{metamorphosis}}{\overset{\text{weathering}}{\leftrightarrows}} CaCO_3 + SiO_2$$

where Mg can substitute for Ca. CO_2 is resupplied to the atmosphere by vulcanism [J. F. Kasting, O. B. Toon, J. B. Pollack, *Sci. Am.* **258**, 90 (1988)]. On time scales of decades, these processes are relatively insignificant in determining atmospheric CO_2 as compared with the exchanges of CO_2 between oceanic and terrestrial ecosystems.
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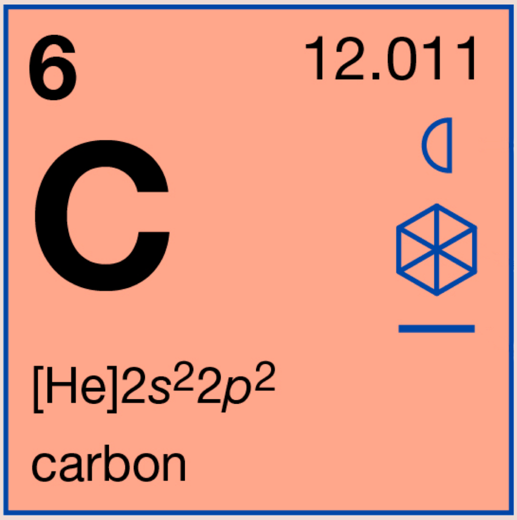

Harney, S. M. & Moten, F. (2017). Base faith. E-Flux Journal, (86), 1.

A poetic, research based essay on processes and systems of the earth, in relationship to futures on the planet, pasts and futures of ownership and capital. “What’s at stake is the trace of perfume that has been released.”

Stefano Harney and Fred Moten

Base Faith

The earth moves against the world. And today the response of the world is clear. The world answers in fire and flood. The more the earth churns the more vicious the world's response. But the earth still moves. Tonika Sealy Thompson might call it a procession. The earth's procession is not on the world's calendar. It is not a parade on a parade ground. It is not in the world's teleology. Nor is the procession exactly a carnival played to mock or overturn this parade, to take over its grounds. A procession moves unmoved by the world. The earth's procession around which all processions move struts in the blackness of time. And the earthen who move around, and move in earth's procession, move, as Thompson says, like Sisters of the Good Death in Bahia move, in their own time out of time. God is so powerful in this procession that he cannot exist. Not because he is everywhere in the procession but because we are. We are the moving, blackened, blackening earth. We turn each other over, dig each other up, float each other off, sink down with each other and fall for each other. We move in earthen procession swaying to base even as its beat alerts the world's first responders. These responders are called strategists. Strategy responds to the constant eruption of the earth into and out of the world. The response takes the form of a concept upon which form has been imposed, which is then imposed upon the earthen informality of life.

Some say it was Alfred Sohn-Rethel who first figured out how the concept was, in this interplay of formation and enforcement, stolen into ownership, abducted and abstracted, weaponized in strategy. He said the abstraction of exchange, and later the abstraction of money, led us to think in the suspension of time and space, the suspension of materiality, and this led to the propriation of the concept. But Sohn-Rethel only picks up the trail of this theft with the thief, the individual, already formed and ready for the strategized and immaterial concept, already formed and readied by it. He wants to convict this thief. We want to take him home.

We want to take him out 'cause out is home. We're at home in the prophetic churning of the earth on the move, the round run of the fugitive, visitation in our eyes, refuge on our tongues. Our unholy commune with those who keep moving and stay there, who keep out before they can be kept out. That's why the hellhounds of strategy are on our trail. They think they got the scent of our leader. But our leader is not one. Let's call her Ali, after Pasolini's “Profezia.” Ali Blues Eyes. Pasolini thought she was coming in the procession from Africa to teach Paris how to love, to teach London brotherhood, to march east with

A smiley face appears in a Hawaiian volcano's crater during an eruption during 2016.

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the red banners of Trotsky in the wind. But she never arrived because we went to chant in Palermo, fast in Alabama, meditate in Oaxaca. So Ali became Tan Malaka and we went to the fête, the jam, the study group.

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Ever since capital witnessed Lenin doing it better, capital has been running from strategy. Today when capital deploys a concept, everybody is supposed to buy it but no one is supposed to believe it. Capital might call this strategic universality. Or it might not call it anything because capital is not concerned with the dignity or the sovereignty of the concept. The concept served its purpose. And its main purpose now is to get out of the way of logistics or to become logistics' conduit. Its propriety and its proprietary commitments prepare it to be bought and sold into a roughened, airy thinness. Today's concepts in circulation are not the abstraction of or from the commodity; they are commodities and cannot, in their propriety and proprietary form, be used against the commodity-form. Their form is the air the commodity expels, containerized, as all but impalpable units of exhaust(ion). They are just another strategy. And strategy, though it is not abstract, does not really matter, either. What matters is logistics. Logistics, not strategy, provides the imperative. Strategy just provides the friction. Logistics moves the concept around in the circuits of capital. The world's only argument against the earth is logistical. It must be done. The earth's movement must be stopped, or contained, or weakened, or accessed. The earthen must become clear and transparent, responsible and productive, unified in separation. This is not a matter of deploying the concept, strategically or otherwise, but of force, forced compliance, forced communication, forced convertibility, forced translation, forced access. Capital does not argue, though many argue with it.

Capital just likes disruption. Capital's been running from strategy, running toward logistics, running as logistics, running into the arms of the algorithm, its false lover who is true to it. All that's left of strategy is leadership, the command you find yourself in after logistics takes over, when the unit comes into its own. For capital, strategy is a just a form of nostalgia, or proof that it has nothing to fear from its enemies who embrace it, proof that they are not enemies. They are the commanded, repeating commands. They call it policy. Ali was never in command. She's just made up of the hungry. She's just made up of plans.

In his desire to make capital claim its materiality Marx took Ali's. Tried to make her a leader. But Ali's prophesy was too crowded, too black, too late, too loud. Submerged in capital, the earthen buried strategy and detonated it. The first respondents told us we need to learn to be

Filmstill from Pier Paolo Pasolini's 1967 movie *Oedipus Rex.*

Cover art for Ornette Coleman’s third studio album *The Shape of Jazz to Come* (1959).

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more strategic. We will learn to need strategy, they say. But we know strategy is the delivery system for a concept, collateral and deployed. Indeed, strategy is itself just a concept in the world, the universal approach. But not even capital cares. Capital only wants things to run smoothly, which is to say universally. This is what disruption is for, and leadership, and open innovation. Capital does not fear strategy. It can barely remember it from the days of worldly concepts. Marx made capital a concept. Lenin saw his chance. So capital learned to be material again. No, capital doesn't fear strategy. Capital fears the earth's procession. Ali's blues black saint eyes.

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God has everything but faith; this is why He so brutally requires ours. He looked around and was so lonely He made Him a world. Rightly, He didn't believe in himself and, wrongly, He didn't believe in us. We were neither sempiternal nor parental, just generative and present, like a wave. In His case, (over)seeing was not believing. Faithlessness such as His demands a certain strategic initiative. Ever get the feeling we're being watched? Well, that's just God's property, the police, the ones who proclaim and carry out His strategic essentialism. They have some guns that look just like microphones. Sometimes they write books. They tell us what we need. Often, they are us. We're all but them right now but we're gonna try to fade back in and out as quickly as possible. Mattafack, let's sound it out, let's talk it over. If you could start talking over us right now we'd appreciate it.

Unremitting predication – what if this is our existence, given in and as a practice of chant, a ceaseless and ceaselessly inventive liturgy? You could call it the historicization of a veridical protocol in which the distinction between falsity and transformation, untruth and unchecked differentiation, is kept sacred. And it's not even vulgarly temporal in the way that seeing aspects, as Wittgenstein describes it, implies a timeline – first it was a duck and then it was a rabbit. There is, in the simultaneity of "it is a duck" and "it is a rabbit," a kind of music. Ornette Coleman calls it "harmonic unison" and we might follow him while also deviating from him but in and through him by calling it anharmonic unison, a differential inseparability. When essence leaves existence by the wayside, what ensues, for essence, is existential loneliness. What if the problem of the concept is the problem of separation? And what is the relationship between conceptual separation and individuation? What's at stake is the convergence of the body and the concept that is given in the transcendental aesthetic. Individuation and completeness follow. On the other hand, (en)chanted, (en)chanting matter, canted blackness (where flesh and earth converge beyond the planetary, in and as non-particulate differentiation). It's not about a return to some preconceptual authenticity so much as matter's constant aeration, its constant turning over, its exhaustion and exhaustive sounding, its ascentual and essentially and existentially sensual descent. The problem is the separation of the concept and our subsequent envelopment within it – this horrific sovereignty of the concept and its variously hegemonic representations. Did the invention of sovereignty require the concept or did the concept already bear the danger of sovereignty's brutal representation(s)?

Maybe the problem is the separability, the self-imposed loneliness-in-sovereignty, of the concept and its representations (as embodiment or individuation or subject or self or nation or state). How do we make sure that the concept still matters? How do we refuse its dematerialization, even if/when that dematerialization seems to have allowed the production of new knowledge, of new critical resources? This is a question that is explicitly for Marx. When the senses become theoreticians in their practice, in communism, which is here, buried alive, they ask questions of the one who brilliantly, and for us, both charts and re-instantiates the dematerialization that capital pursues in the separation of labor power from the flesh of the worker or of profit from that flesh in its irreducible entanglement with (the matter of) earth. Was that an instance of "strategic thinking"? If so, it demands that we rethink strategy. Is there a way to think the relation between strategy and improvisation that alloys the maintenance of a difference between immediacy and spontaneity? There is a deliberate speed of improvisation that is not simply recourse to the preconceptual. Maybe what's at stake is the difference between movement and *a* movement or *the* movement.

What's at stake is the trace of perfume that has been released. It is changed in being-sensual, depurified in being breathed. There is a socialization of essence that is given in and as sociality itself and maybe this is what Marx was talking about under the rubric of sensuous activity, but against the grain of his adherence to a logic and metaphysics of (individuation in) relation. All this makes you wonder what the difference is between strategy and faith. When we say difference, here, what we really mean is caress – how strategy and faith rub up against one another in a kind of haptic eclipse, or auditory submergence, or olfactory disruption, or gustatory swooning of the overview. In this regard, strategic essentialism is something like the soul feast's homiletic share or, more precisely, the ana- and anicharismatic sharing of the homiletic function in and by the congregation. When we say preach when we hear preaching we be preaching. It's like a conference of the birds – a constant rematerialization and proliferation of the concept; a constant socialization of the concept rather than some kind of expedient decree by some kind of self-appointed consultant who finds himself to have been gifted with the overlooking and overseeing power of the overview. The consultant's capture and redeployment of strategic essentialism is faithless and lonely. It exudes the sovereign religiosity of the nonbeliever. Let me tell you what we need or don't need, it says, always doubling down on you whenever it says "we" with a heavy, I/thou imposition, a charismatic boom that somehow both belies and confirms its sadness in the serial de-animation of its personal relationships, which is felt by us as the toxic solace of being spoken to and of by the one who is supposed to know. So maybe it's just a matter of where strategic essentialism, strategic universalism, or the concept, in general, are coming from. Unremitting predication bears a boogie-woogie rumble, where deferred dream turns to victorious rendezvous. Down here underground, where the kingdom of God is overthrown and out of hand and hand to hand, there's a general griot going on. His (and that of any of his representatives, the ones who must be representing us but can't) strategy is exhausted and surrounded by our plans.

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There's a movement of the earth against the world. It's not the movement. It's not even a movement. It's more like what Tonika calls a procession, a holy river come down procession, a procession in black, draped in white. The earth's procession sways with us. It moves by way of a chant. It steps in the way of the base, in the way of the dancing tao. It bows to the sisters of the good foot, carrying flowers from Caliban's tenderless gardens. The earth is on the move. You can't join from the outside. You come up from under, and you fall back into its surf. This is the base without foundation, its dusty, watery disorchestration on the march, bent, on the run. Down where it's greeny, where it's salty, the earth moves against the world under the undercover of blackness, its postcognitive, incognitive worker's inquest and last played radio.

The earth is local movement in the desegregation of the universal. Here's the door to the earth with no return home and who will walk through it is already back, back of beyond,

A selection of perfume is featured in this illustration from a Soviet commodity catalog published between 1956-61.

carried beyon', caribbean. Pasolini said Ali Blue Eyes will walk through the door over the sea leading the damned of the earth. Ali Blues Eyes. But we won't teach Paris to love. We can't show brotherhood to London. Ali took Trotsky's red banners and made something for us – a handkerchief, a bandage, a kiss.

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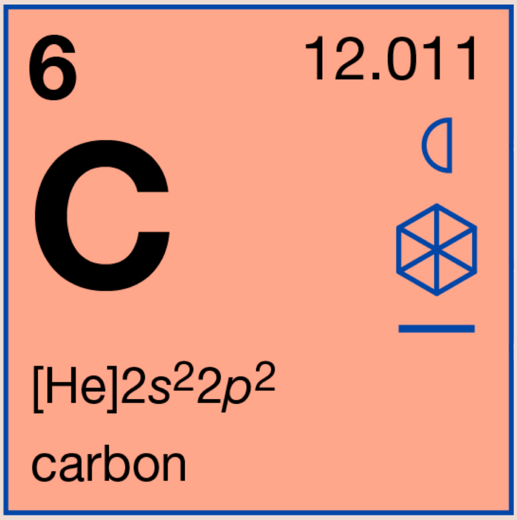

Callon, M. (2009). Civilizing markets: Carbon trading between in vitro and in vivo experiments. Accounting, organizations and so- ciety, 34(3-4), 535-548.

This journal article by the famed ‘less radical’ Latour, Michel Callon talks about ‘carbon markets’, rather early in their consideration by people like Callon. Carbon markets set a limit or cap of emissions and then allow groups to trade their ‘left over’ emissions they have used. This essay focuses on carbon markets as ‘on-going collective experiments’, which they still are.

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Civilizing markets: Carbon trading between *in vitro* and *in vivo* experiments

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Abstract

The creation of carbon markets is one of the solutions currently envisaged to meet the widely recognized challenge of global warming. The contributions in this special section of *Accounting, Organizations and Society* show that many controversies nevertheless exist on the ways in which these markets are organized, the calculative tools that are devised to equip them, and the role that they are supposed to play, especially in relation to other types of intervention which favour political measures or technological research. In light of these controversies, the article considers carbon markets as ongoing collective experiments. It is argued that carbon trading is an exceptional site for identifying the stakes involved in such experiments and for identifying better what the dynamics of civilizing markets could be.

In a recent interview on the BBC, Vaclav Klaus, the very neo-liberal president of the Czech Republic, stigmatized the red ecologists (sic), claiming that their actions were a threat to freedom. He added provokingly that the best way of dealing with environmental issues, especially the challenge of global warming or climate change, was to put all our trust in the market. As he sees it, the solution is not *less* but *more* market, the only appropriate policy being to remove all obstacles to its extension and development. The market frees initiatives, regulates the scarcity of resources and, in the long run, stimulates the innovations that will provide the solutions to humanity's problems. This extreme position, defended by a politician trained in the economics departments of US universities, has the advantage of explicitly raising the question of the role that markets should have in the global warming issue. But because it is limited to simply reasserting a general dogma, it says nothing about the only question that really matters, a question considered in detail in this special section of *Accounting, Organizations and Society*: the nature of the markets that should be set up and their forms of socio-technical organization.

Economists – not those who like Vaclav Klaus have lost all contact with academic research, but those who still think about the conditions of the functioning of real markets – fortunately show more perceptiveness and realism. They have not forgotten that economics has devoted a substantial part of its efforts to analysing market failures. Markets do indeed have unquestionable advantages that make them irreplaceable. Through the autonomy with which they endow economic agents, they stimulate creation and innovation. They are also a powerful

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tool for coordination. Finally, they facilitate adjustments and the search for compromises that are not as likely to emerge through other mechanisms such as plans. But there are two sides to every coin. Markets have intrinsic limits and their very functioning spawns matters of concern. From their first years at university, all economics student learn that markets are not well-suited to the production of public goods; they are a constant source of negative (sometimes irreversible) externalities which affect the existence of groups whose interests are not taken into consideration; they can do nothing or next to nothing about income inequalities; and they are not the best solution to guarantee everyone's access to certain goods such as healthcare. According to economists, these limits are real failures. Of course they do not doom markets as such, but they are an incentive to seek solutions and to introduce alternative means so that advantage can be taken of the benefits of markets while attenuating their negative and undesirable effects. Vaclav Klaus remembered only half of the lessons he had learned.

The global warming issue is a good illustration of what a reasonable approach, attentive to both the pros and the cons of markets, ought to be. This is for instance the approach adopted by Sir Nicholas Stern in his now famous report (Stern, 2007). He contends that global warming, of which the partially human origins have been established by scientific research, is the result of a huge shortcoming of economic markets. It is a perfect illustration of the damage that negative externalities can cause when they are produced on a large scale without the effects being felt immediately. Now that scientific research has made these externalities visible, tangible, measurable and predictable, the blindness of those who still chant on every note that *more* markets will save us from the weaknesses of existing markets is even more evident, for any extension of markets will naturally also entail new weaknesses. Stern's argument seems reasonable, at least in principle, as it excludes doctrinarian positions. The market is simply one solution among others, with its advantages and disadvantages; it should neither be diabolized nor considered as a panacea.

In my opinion this pragmatic attitude needs to be framed by two additional requirements. The first relates to the organization of activities concerning market design. In certain respects markets do indeed have unquestionable advantages and that is why it would be unreasonable not to take advantage of them. But their efficiency depends to a large extent on the socio-technical arrangements of which they are made (Callon, 1998; Callon, 2007; Callon & Muniesa, 2005; Callon, Muniesa, & Millo, 2007; MacKenzie, 2006; MacKenzie, forthcoming; MacKenzie & Millo, 2003). The design of these arrangements therefore becomes a strategic activity in its own right which is worth organizing after careful consideration. The second requirement, related to the first, pertains to the precautionary principle. No one, not even the best specialists, can be entirely sure in advance of the organizational forms and material *agencements* needed to establish a market's functioning. Concrete markets can be described and analysed *in vivo* only, which implies the establishment of devices for measuring, monitoring and watching them, to constantly keep an eye on the problems they pose and the way in which they react to certain interventions or adjustments. It is because a market is deployed in an uncertain world that it imposes this mixture of agnosticism and experimentation, of trials and errors, observation and evaluation of the effects produced, so typical of a precautionary approach – in this case applied to socio-technical artefacts and not only technological innovations.

The first requirement is fairly easy to acknowledge. Because markets are designed they should be designed well, with attention paid to quality so that all problems are properly identified. Social engineering has the same terms of reference as technical engineering and, like it, has to be organized formally. The second requirement, easy to accept in theory, is probably more difficult to put into practice. An experimental, agnostic approach, open to unexpected questions, prepared to carefully consider problems which arise and to hear voices raised, implies governance structures which are (still) cruelly lacking. Finally, the two requirements should not be considered separately. To be validated, design needs experimentation, and experimentation acts in turn on design (Roth, 2007). This tension between the two, on the basis of which markets are presented as reflexively designed devices and as on-going scale-one experiments, contributes to redefining relations between science, politics and economics, and to raising the question of the mechanisms through which boundaries are drawn between these different worlds. The aim of this introduction is to point out some directions for furthering our understanding of these mechanisms. From this point of view, reflection on the place, organizational forms and limits of carbon markets does not only have the practical advantage of examining how the challenge of global warming should be met; it is also a contribution to more general reflection on what civilized as well as civilizing markets could be.

Markets as on-going experiments

Recent studies have shown that a growing number of markets are the outcome of genuine processes of experimentation. The contexts in which these experiments take place vary. Using a metaphor borrowed from the life sciences, Muniesa and Callon (2007) distinguish between economic experiments run *in vitro*, that is, in a laboratory[1], and experiments run *in vivo*, that is, in scale-one real markets. A good example of *in vitro* experimentation is the design and organization of spectrum auctions by the Federal Communication Commissions (FCC). As Guala put it, this is a typical case of market engineering which starts with laboratory experiments and in which various economists with their different models are involved (Guala, 2007). As in any innovation process, made of negotiations and compromises, the results are then tested outside the laboratory, where new interests come into play and new problems arise. From the first laboratory tests, the market is envisaged not only as a nexus of procedures and rules. Material and especially computer devices are a key concern and their design and development fuel debates and reflection, very often of a theoretical nature. This passage via the laboratory is obviously not a general rule. Experiments can be carried out *in vivo* or, in other words, *in situ*, without being prepared in a laboratory. Mechanisms are set up to identify the effects produced, the bugs encountered, and the reactions triggered, so that they can be taken into account and the architecture of the markets under experimentation altered. This happens frequently in cases of financial markets, for instance when stock exchanges are computerized (Muniesa, 2003). Whether the experiments are *in vivo* or *in vitro*, what is designed, tested and evaluated is a socio-technical *agencement* that combines material, textual and procedural elements. That is why the notion of an experiment is fitting in such situations: the objects being tested are not very different from those that we find in university or industrial laboratories working in the natural or life sciences.

I do not know examples of economic experiments which were shifted several times from one site to another while they were under way, alternating between *in vitro* and *in vivo* settings. Market mechanisms designed and tested *in vitro* receive much care and attention when they are first transposed into the real world, but after that they are seldom monitored and the feedback that could contribute to making the theoretical models more realistic is by no means systematically capitalized on. Symmetrically, economic experiments run *in vivo* are usually designed without planning or even envisaging the *in vitro* phases that would allow for more in-depth reflection on certain mechanisms or fundamental problems. The *in vitro* and *in vivo* worlds are thus carefully kept apart. Yet studies on innovation have shown that the absence of exchange, interactions, feedback effects and cross-fertilization is particularly harmful to the innovation dynamic (Kline & Rosenberg, 1986) (Akrich, Callon, & Latour, 2002). In concrete terms, such interactions can exist, in the case of markets or any innovation, only if soundly structured networks organize relations between the sites at which *in vivo* experiments are conducted and those at which *in vitro* experiments are conducted. Such networks should allow for the joint and coordinated advancement of knowledge and theoretical models on markets, on the one hand, and of market material and institutional devices, on the other. They could provide the organized framework of coordination and information trading between economics and the economy.

Carbon markets prefigure what could be networks of experimentation on markets

Carbon markets are an interesting example of what these networks of experimentation with markets could be, mainly because they are clearly defined as experimental, at least in the EU.

As Anita Engels shows in her contribution, the actors themselves and especially industrial firms consider that the creation of a carbon market is likely to be a long process due to the high level of uncertainty surrounding it. This attitude, shared by most of the stakeholders, creates a climate favourable to critical reflection, negotiation, ongoing evaluation, and learning by doing, using and interacting. These are test markets or, to use a software term, markets whose beta versions are being

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[1] *In vitro* experiments include modelling activities as well as experimental economics.

tested. The EU has grounded its action in the same logic, with scheduled stages punctuated by reviews, and emphasis on the fact that certain measures or mechanisms are tentative, such as the distribution of free allowances rather than the organization of auctions to allocate them. This experimental approach is found at a more global level with the invention and establishment of Certified Emission Reductions (CER) in developing countries, as part of the Clean Development Mechanism. The CER are credits, not permits, but can be bought or sold and have a price and a market value. Unlike emission permits, these new 'products' do not seem to be the outcome of prior intense theoretical reflection. As fruits of the imagination of innovators in the wild seeking a compromise between the demands of the US and those of developing countries, they are perceived as forms of experimentation that are fiercely criticized and trigger numerous counter-proposals (Lohmann, 2005; Lohmann, 2006, this issue). For instance certain NGOs, having observed that labelled projects cause more environmental problems than they solve, suggest new evaluation or certification criteria (MacKenzie, this issue). The same uncertainties, trials and errors, and pragmatic approaches are found in the case of international organizations responsible for establishing accounting rules, which hesitate as to the categories to use to reveal these unusual products in firm's balance sheets (Cook, this issue). All in all, carbon markets seem to be experimental objects, all the aspects and components of which are tested, reflected on and critically evaluated.

Carbon markets also prefigure fairly accurately what interactive networks of experimentation could be, spread out in time and space. The various contributors to this section all refer to the theoretical and practical precursors of the European initiative (Braun, 2007). The origins of the constitution of carbon markets lie in certain economists' theories on the externalities produced by markets. Coase's seminal work immediately comes to mind, as well as that of all the authors who have discussed and enriched his analyses, especially Dales (1968). Without this contribution from economic theory, carbon markets would have been literally unthinkable. But the dissemination of models and their enforcement in concrete markets requires appropriate logistics. This is where networks of experimentation come in. Before they actually existed, carbon markets were not only conceived of in economics text books, they were also practised (as in rehearsed) on various occasions, in different places and forms – initially in the USA, with the first large scale experimental cap-and-trade programme (1995) for sulphur dioxide. Experiments have since proliferated, launched either by industrial companies like BP, or national governments, as in the UK, Norway and Japan. Significantly, all these sites, whether *in vivo* (universities) or *in vitro* (firms, nations, trans-national institutions), explicitly refer to one another. Interactions have been and are still organized, with capitalization on know-how and knowledge, and specialists circulating between sites. This is truly collective, distributed experimentation deployed in time and space, more or less chaotically or organized, but always explicitly. From this point of view the EU is a driving force: as the political history analysed in detail by Braun (2007) shows, it is a 'grand new policy experiment' that is being implemented. The intention is clearly to build up competencies, to develop a learning dynamic, and to construct networks of knowledgeable people and experts from all disciplines who commission studies and enrol both specialists and NGOs. This is how what can be called a community of practice (Amin & Roberts, 2008) or a collective of research and experimentation on carbon markets has come into being.

The advantage of studying carbon markets and their dynamics appears more clearly now. It can serve to further analysis and understanding of the more general process of constitution of collectives comprising large numbers of different actors from diverse temporal and spatial horizons, working on the conception and explicitation – mainly theoretical – of new market *agencements*. How, in these collectives, do theoretical models and practical solutions mutually interfere with and enhance one another? How is this collective work organized? What conflicts run through it? What mechanisms of coordination are used between the various protagonists or stakeholders? Alongside economics at large (including accounting, management science, etc.), what role does or could disciplines such as anthropology, the economic sociology, science and technology studies, and political science play? How are the different knowledge and know-how transported, experiences capitalized on, and evaluations conducted? How is professionals' work organized? What forms of inter-disciplinarity are set up, especially between the social sciences and the natural sciences (when models combine social and natural entities)? All these questions – and there are others that could be examined – concerning the modalities of collective experimentation, are relevant to the role of markets, their design, and the modalities of their functioning.

Experimenting by taking matters of concern into account

The gradual, tentative setting up of these experiments on markets is an indisputable fact. The question is nevertheless whether this trend should be reinforced. Are such difficult and costly experiments really necessary? Would it not be simpler to rely on economists' expertise to devise the required regulations, and then leave it up to the agents to organize their activities? Is it not contradictory to frame the design of markets, institutions which, precisely, rely on agents' inventiveness and rationality?

An examination, even superficial, of the process of creation *ex nihilo* of new markets, in which everything needs to be invented – from the characteristics of the goods to the algorithms of pricing or the delimitation of the agents concerned, etc. – shows that neither economists nor the usual economic agents can accomplish this gigantic task alone. Not only do they have to cooperate and to accept the fact that other actors are involved; in addition, in a climate of prevailing uncertainty, even total ignorance (regarding the behaviour of natural entities and human actors alike), the design process must necessarily consist of a long process of trial and error. The belief used to be that markets were quasi-natural realities, and theoreticians were content to identify the conditions of their viability (with economists playing the role of midwives – or rather midhusbands! – of markets). We now realize that they have to be sometimes created from scratch, and that they are in reality fragile and complicated socio-technical artefacts. It is therefore necessary to reconsider the following basic questions: what are markets made of? How can we ensure that they function satisfactorily? To these two complicated questions, the recent but rich adventure of the carbon market controversies provides the beginnings of an answer.

- The setting up of a European carbon market has revealed the diversity of actors involved in its construction and functioning. For perfectly understandable reasons, stylized representations of markets tend to reduce the circle of agents to take into account, sometimes settling for the basic distinction between producers, intermediaries and consumers. Real markets would however rapidly collapse if they consisted only of these three groups, and carbon markets are a striking illustration of the inadequacy of these models. Simply listing the actors who participate actively, in different ways, in their conception and in the experiments concerning them and their evaluation, reveals an infinitely richer and more diversified population. We find the usual suspects but also scientists – whether they be climatologists, biologists or geophysicists –, grouped together in organizations like the IPCC which weigh heavily in the debate, as well as international organizations or coordination structures such as OECD, UNCTAD (The United Nations Conference on Trade and Development), IEA (The International Energy Agency), or UNFCCC (The United Nations Framework Convention on Climate Change), professional accounting organizations, academic economists, think tanks, NGOs of various convictions and, last but not least, the complex EU administration in Brussels with its national ramifications, its squads of jurists, and its in-house economists and their models. Each of these agents can and should be considered as economic agents in their own right: the specialist on greenhouse gasses devises a model that constructs equivalence between the different gasses and directly participates in fixing the price of emission permits; the accountant explicates the effects of climate change on the calculation of costs and investments; the economist designs market architectures, and so on.

We could argue that not all these actors are genuine economic agents because they are situated on the fringes and not at the heart of markets. In my opinion this objection is ill-founded, for at least two reasons. First, the modalities of the organization of carbon markets (like other markets in an experimental phase) are particular. Their functioning includes design and evaluation activities that constantly trigger reforms and interventions without which the market would implode due to the large number of highly complex problems. As market failures are constituent parts of these markets, and occur constantly, they have to be dealt with all the time. Second, in stabilized markets many of the actors who tend to be considered as marginal or peripheral are clearly present and particularly active. In which sectors does one not find NGOs pointing out the ecological or humanitarian stakes, public- or private-sector economists, consultants, think tanks, government officials fighting for new rules of the game, or researchers directly involved in developing new products that generate controversies? Each of them, even if they are not directly engaged in commercial relations, actively participates in the design of markets and their functioning. The case of markets in the experimental phase seems to be appropriate for completing our description of market arrangements. No market is so stabilized, routinized, mechanized and purged of all uncertainty that it can entirely do without these design activities, including the framing and qualification of goods, the elaboration of rules of the game, the delimitation of agents to take into account, the construction of their calculative equipment, and so on. Once we have acknowledged this reality, we obtain a richer and more realistic picture, and at the same time a more complex one as we become more attentive to all the relations that form to enable a market to function. A car, a CER or an emission permit would not exist and could not enter into market exchanges without the anonymous crowds of humans and non-humans that have participated and still do participate in its conception, production, distribution and pricing, as well as the organization and supervision of all these relations.

- The multiple actors engaged in the functioning of markets all have their own expectations, conceptions, projects and interests, on the basis of which they promote different modes of structuring and organization. Through their disagreements over goods and their qualification, but also over the calculation of costs and prices, the evaluation of results or the taking into account of externalities and, more radically, their differences concerning the role of markets in controlling climate change, they reveal the potential diversity of forms of market organization. For example certain NGOs consider that the best solution is to leave carbon in the ground; others accept the idea of a market, at least as a partial solution, and think that clear criteria are needed to evaluate the demand for CER (gold standard); others refuse the idea that the market can be regulated or accompanied by taxes, and so on. These standpoints cannot be reduced to simple conceptions or ideological talk unconnected to a reality – that of concrete markets – seen to be external to them; they are, or tend to be, inscribed in devices which can be considered as experimental. Academic economists, who by no means agree on everything, are indeed important players, but they are clearly not the only ones to think and intervene. Carbon markets show that in a situation of uncertainty over the state of the market, the elements comprising it and the effects that it is likely to produce, one cannot judge its effectiveness and efficiency without taking into account all the assessments, points of view, projects and programmes developed by the actors who transform it in an on-going (open) experiment.

- What are these controversies about? What are the issues, the matters of concern, that markets produce and that the different actors involved in their functioning highlight, through the questions they raise? Studies inspired by STS, devoted to the analysis of market socio-technical *agencements* (Callon, 2007; Hardie & Mackenzie, 2007) are to my mind useful for introducing a tentative classification of these issues.

The first and most visible issue in the case of carbon markets, but one that concerns all markets, pertains to the framing and qualifications of the goods that are traded. In this case it is necessary to identify and characterize the various greenhouse gasses. As MacKenzie explains in the case of HFC 23, one of the problems is to measure in a unanimously acceptable way their impact on the climate (MacKenzie, this issue). Without the establishment of these equivalences, no economic valuation can be envisaged. MacKenzie shows the extent of the scientific, technical and metrological investments needed to stabilize the equivalences which, given the prevailing uncertainties, can be questioned at any time. A second issue pertains to the list of actors seen as taking part in the market. Agreement on this point is far from unanimous, as Lohmann illustrates so well. Unexpected actors, orphan or affected groups (to use the terminology that I have proposed in Callon (2008)), appear when no one was expecting them, for the good reason that they could hardly have existed as groups considering themselves to be concerned by the functioning of carbon markets before those markets were established. Here we see the dispossessed farmers; there the enraged neighbourhood inhabitants; elsewhere, in the countries of the North, spreading pollution caused by certain firms which increase their emissions after purchasing emission certificates in the South, etc. The proliferation of the actors concerned, whose emergence was impossible to foresee and who sometimes, directly or via spokespersons, end up becoming involved in the designing of markets, is a constant source of issues to take into account in adjusting the market architecture and specifying the modalities of its functioning. Calculative equipment, whether it serves to establish equivalences between chemical entities (for example to measure their effects on global warming), to price goods, to organize encounters between supplies and demands (auctions or other mechanisms), or simply to measure emissions, is also the subject of stormy debates and lies at the heart of the structuring of carbon markets. The list could be lengthened. It would show that each of the operations contributing to the formatting of the market socio-technical *agencements*[2] is found in a controversial and unstable form in the case of carbon markets. In other words, the description of the market and its functioning, that is, what the market is and what it does, cannot be separated from the multiple controversies concerning it, in which as many different versions are proposed.

Carbon markets thus invite us to enrich our conceptions of markets. Markets are not only devices enabling well-identified agents to defend their interests and to organize transactions so that they can reach satisfactory compromises efficiently. At the heart of markets we find debates, issues, feelings, matters of concern, dissatisfaction, regrets, and plans to alter existing rules, which cannot be internalized once and for all because they are linked to irreducible uncertainties, to what I have called framings which are never either definitive or unquestionable. This "hot" component of markets, which causes them to be in a constant state of disequilibrium, traversed by forces of reconfiguration, is not always present to the same degree but it always exists. The tension between the cold source and the hot source is a component of markets. In the case of those still in an experimental phase, such as carbon markets, the hot source is preponderant, for uncertainties are expressed through it. These markets, which act as magnifiers, show us that which is usually concealed or which we get rid of too readily by talking in terms of failures. I believe that it is more accurate and fertile to consider that any market includes both of these components. Carbon markets impose a new view of concrete markets. To the question: 'what are they made of?', they beg us to answer: of all the existing or emergent actors who are concerned by their functioning and involved in clarifying the problems and issues that they generate. To the question: 'what is a market that works correctly?', they suggest the following answer: it is a market which welcome and recognize as one of its most central constituent elements all the actors who demand to be taken into account, including those who are considered as marginal or on the verge of exclusion, with their points of view, their matters of concern, their proposed tools, framings and models. It is this dynamic tension, in which constant unexpected concerns are expressed and ask to be heard and to be taken into consideration, that defines a 'good' market (Law, 2004). The question here is obviously about the organization of this dynamic. It calls for specific solutions to each market, and finds answers only at the cost of an effort to organize the design and experimental activities of markets.

Politicization, economization and scientization: from (stem) issues to networks of specific and differentiated problems

A market which functions satisfactorily is one that organizes the discussion of the matters of concern produced by its functioning and the framings/overflowings that it entails. It takes those matters of concern into account and sets up procedures and devices designed not only to encourage the expression of problems which arise but also to facilitate the design and evaluation of theoretical or practical solutions to those problems. A definition such as this, which grants centrality to on-going open experiments and to the debates and controversies accompanying them, closely links distinctly economic activities and those that one would tend to qualify as political and that markets tend to exclude from their ambit. That is why the explicitation of problems revolving around the various framings/overflowings mentioned above and their "management" are not self-evident. Some think that it entails the risk of transforming markets into political arenas. Many others perceive it as a pollution of economic institutions by events that are out of place in them. Carbon markets show however how sterile this view of the economy can be. These markets can develop legitimately and efficiently only if they render such controversial events visible and debatable, as a source of material for experimentation. In short, for markets to function, in the sense defined above, there have to be arrangements, procedures and devices which are clearly not outside of them but, on the contrary, become an essential component of them (Callon, 2008).

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[2] Callon and Caliskan (submitted for publication) propose a provisional list of these framing activities, including: framing of passive goods and disentangling them from active human agencies; framing and qualifying calculating agencies; enframing the market encounter; producing the price; market maintenance; objectifying «The Economy».

To analyse these nascent market configurations in which economics and politics are combined, it would be tempting to say that in any market, as in any activity, whether economic or not, there are implicit politics that we could call sub-politics (Beck, 1992) and that need to be identified clearly if we are to get rid of them. In short, the aim would be to purify the market of the slag polluting it, to remove the unsolved political issues disrupting its functioning, to externalize them and then, after a political debate, to revert to that market to frame and regulate it better. Recent developments in the application of STS to the study of economic activities have however shown the counter-productive nature of this type of approach. The distribution between the political and the economic is not anterior to the market; it is the outcome of the functioning of markets, of which it is a by-product, in a sense. The short history of carbon markets clearly illustrates this point. Their construction is not primarily about the drawing of a boundary that clearly and unquestionably separates the political in their functioning from the economic. Carbon markets defy this type of division. They produce issues, matters of concern that no one is sure whether they should be addressed politically, economically or techno-scientifically.

The carbon market experiment can be described as a threefold process of joint problematizations at the end of which the problems to be treated by either markets or political institutions or scientific institutions will temporarily be distinguished. We know, and Nicholas Stern acknowledges this in his report, that all three treatments are inevitable, but we do not yet know with precision how the distribution will or should be made. This approach implies that neither economics nor politics nor science can be considered as realities that have been stabilized for once and for all. What an economic market is and what it can do are the result of on-going experimental processes and series of trials of strength, the outcome of which is not predictable. The same could be said for what can be qualified as political or scientific.

By adopting this point of view of economy, politics and science in the making, are we not likely to sink into confusion and relativism? A few comments are called for to reassure those who may be afraid of such an eventuality. Carbon markets are, once again, going to be very useful in helping us to understand why we are not condemned to choosing between the devil and the deep blue sea, between social constructivism (that which is considered as political, economic and scientific is simply the result of a clash between groups struggling to impose their own points of view) and essentialism (there are one or more definitions of politics, economics and science, which provide objective criteria enabling us to say, *a priori*, whether a behaviour, way of thinking or device is political, economic or scientific). Since they are markets in an experimental stage, which simply highlight a feature common to all markets, they are a remarkable site for studying this process of joint reconfiguration.

(Stem) issues and problematizations

As Marres (2007) shows, the best starting point for studying this process of politicization is the notion of an issue or matters of concern. In the case under study here, the issue – at the origin of the initiatives presented in this publication – is climate change and particularly one of its components, global warming. I propose to reserve the term *issue* for such situations of initial shock, where there is still no indisputable formatting enabling us, for example, to say with any certainty that it is a strictly (or primarily) political, economic or scientific issue. We will therefore talk of an issue when the available codes, irrespective of what they are, fail to answer the questions raised by this issue (Barry, 2001). This is indeed the case of global warming which defies all attempts to reduce it to a problem that is either strictly economic or political or scientific/technical. Of course those who try to perform such reductions are not discouraged by such polymorphism, but they all come up against overwhelming difficulties. Whoever accuses capitalism or the market of being the source of all our problems, and claims that global warming is above all an political problem requiring political solutions, is suddenly confronted with economic issues that strike back. Whoever thinks that the issue is at last scientifically and technologically under control is soon faced with political demands that point out the persistence of glaring injustices and the resulting economic waste. Global warming in its current state is an issue that is unqualifiable, not in theory but in practice, for no framing is able to embrace it in its entirety. As the roots of the word indicate, an issue always finds an exit enabling it to overflow. It is protean, constantly changing as it spreads, irrespective of the frame into which we try to fit and enclose it.

Issues can be compared to stem cells which, as we know, are not yet differentiated and are therefore described as totipotent. They are an original state from which all the cells comprising the organism derive. Depending on the circumstances and the trajectory followed, they become liver or heart muscle cells, for example, or neurons of the cerebral cortex. Before reaching this state, they go through various stages of specification (we talk of pluripotent, multipotent, unipotent and then specialized cells) at which they can veer off in a different direction towards other destinies and types of activity. Nothing in a stem cell determines its future as a liver or heart cell, for example. Moreover, the changes it undergoes do not seem to be irreversible, for stem cells can be obtained from highly specialized cells. Issues are very much the same: they have a multiplicity of fates, specifications, qualifications and regressions, all equally possible and probable, but some of which will materialize only later, depending on the circumstances and trials encountered. Global warming is an issue (we could say a stem issue!) that is gradually being split into a series of distinct problems, some of which are qualified as political and others as economic, technological or scientific. Let us call *problematization* this gradual process of fragmentation and division of issues that evolves into the joint formulation of a set of different problems which in a sense, at least partially, are a substitute for the initial issue (on the notion of problematization see Dewey (1916), Callon (1980) and Rabinow (2005); on the notion of the division of problems, see Barthe (2005)). Problematization is a multiform dynamic since, in general (and this is what is happening in the case of climate change), the questions (political, economic, etc.) it leads to are both distinct from and interdependent on one another. Instead of talking of global warming, people increasingly refer to market efficiency, negative externalities, developing countries' right to development, international politics, technological innovations to promote, research to undertake, and models to improve, with each of these topics being closely bound to the others.

The dynamic of problematization of (stem) issues is a complex process, probably even more complex than that of the differentiation of (stem) cells! The transformation of an issue into well-identified problems – which can be addressed by planning specific actions – is never completely consensual nor total. For instance, in the case of climate change, some are still convinced that global warming is simply one aspect of the more general issue of growth and its legitimacy. For those who think that all our problems stem from there, no problematization of global warming is acceptable. They demand that the issue not be divided up, and that it be put back into a more general issue that makes it even less divisible! The movement downstream, towards highly specifiable and treatable problems, is thus refused. Basically the demand is that the issue remain a stem issue, through a movement of amplification going upstream. Another, at least temporary, source of failure of problematization may stem from the opposition that it triggers: certain groups are opposed not to the division of the issue but to the way in which it is split up and reduced, like those who, for example, refuse the boundaries imposed by the Stern report between economic treatment and technological treatment of the abatement of greenhouse gasses.

When undertaken, this multiform problematization leads to the constitution of a network of problems (what I called a problematic networks: Callon, 1980) whose content and extension evolve in relation to the translations that are attempted between problems. It is contingent on the configurations in place when the (stem) issue becomes public. In other words, the division of (stem) issues into specific problems, some of which are qualified as technical and others as economic or political, as well as the formulation and explication of these problems, are not random. For example, the possibility of seeing the emission of greenhouse gasses as a consequence of market failure (negative externalities), stems from the state of economic theory, from what it says about the limits of any market but also about the existence of a largely common agreement on what economic markets are and the way they function (well or badly). Likewise, being able to contend without any fear of being contradicted, that it is conceivable to develop technologies to abate emissions, proves that science and technology have reached a degree of maturity, robustness and objectivity that makes the legitimacy of certain evaluations and projects unquestionable and inevitable (at least in the fields concerned). We would need to continue this inventory to show in detail and convincingly how the instituted configurations weigh on current problematizations. In turn – and this is an open research question – the way in which problems are eventually formulated, the treatment chosen and the solutions proposed and implemented, act on the existing configurations and contribute to changing them. The way in which the organization and functioning of economic markets are designed will most certainly emerge profoundly changed from the multiple and complex experiments in the European carbon market. Likewise, what we know or think we know about technologies, equivalences between greenhouse gasses, or the dynamics of climate change and of the distribution between anthropic and non-anthropic causes, will be altered drastically by the research undertaken in coming years and consequently what might be considered as scientific or technical questions will be redefined. Even the limits between established spheres will be revised: markets which constantly take into account the multiple externalities that they produce – especially the constitution of concerned groups scattered across the globe, unable to be heard and suffering from the effects of economic measures intended to abate greenhouse gas emissions – will no longer resemble markets as we know them today. They will force us not only to revise our market theories and our common conceptions of their functioning but also, above all, to alter our ways of distinguishing political and economic processes. As I have shown elsewhere (Callon, 2008), these markets of a new kind, which seem more open and civilized than those to which we are accustomed, combine devices that we previously attributed either to the economy or to expression and political action. This redefinition of the boundaries between categories of problems and activities, as the problematization advances, seems inevitable even if we have very few ideas on how it happens and the conditions favouring or impeding it.

I am convinced that carbon markets are an exceptional opportunity for furthering our knowledge of these mechanisms and studying the transformation of (stem) issues into networks of problems, the resolution of which is attended by a (partial and limited) reconfiguration of economics, politics and science, and relations between the three. Take, for example, the multiple and interdependent framings proposed by the Stern report with its careful delimitation of what has to be treated by either the market or political institutions or the technosciences. Do we accept this division and try to address economic problems, for example by deciding to somehow combine taxes and the auctioning of emission allowances? This is where we immediately stumble against issues that flow over the set frame (even if we have decided to concentrate only on economic aspects), such as the question of equivalences between the different greenhouse gasses. MacKenzie (this issue) shows that this measure, based on scientific modelling and metrological innovation, impacts on carbon pricing. Hence, the economic problem rapidly becomes a complex technico-scientific problem. The machine producing interdependent problems is running again. Sir Stern's nice neat framings become jumbled and call for the definition of new boundaries. The same creative confusion occurs if we start with a question such as: how can we scientifically evaluate, and thereby economically value, the effects in terms of greenhouse gas abatement of replanting a forest in a rural area of Brazil? Driven by attempts to make this protean issue of climate change manipulable and manageable, the formulations of problems proliferate and react to one another. Instead of a shock, trauma or complex issue, a dense network of problems appears, constantly moving as each problem is borne by one or more actors who identify with it. Carbon markets are an ideal site for studying the dynamics of this (never ending) process of joint problematization.

Trajectories of problematizations?

It is this multiform process of problematization of (stem) issues that we need to follow and study, so that we can avoid the two stumbling blocks mentioned above, essentialism and relativism, for the networks of problems stretch between the two. Dependent on existing categories but not determined by them, they are powerful machines of social reconfiguration. The dynamics of problematization does not obey a logic set in advance; in other words, there are no natural trajectories that, in one way or another, the problematization of (stem) issues follows. This is where the analogy between issues and cells stops, for cells change by following paths that may be unpredictable but consist of predetermined steps. We can nevertheless posit (as a provisional hypothesis) that the process of problematization of issues, in so far as it is contingent and singular, obeys rules which are generally describable.

The fact that (stem) issues do not follow typical trajectories that a natural history of issues could describe, is illustrated by the case of global warming and carbon markets. The context in which the climate change issue appears and the nature of the institutions that host and promote it (the IPCC, the Rio Conference, the Kyoto Conference, European multilevel governance) orient its treatment in certain directions which depend on on-going controversies and experiments. Greenhouse gasses do not disturb the world and do not contribute to changing it in the same way as GMOs or over-fishing in the Atlantic Ocean. To be sure, carbon markets are a good laboratory for studying social redifferentiation, but we must be careful not to seek general laws on the evolution of issues therein. Our focus should rather be on devising analytical categories for understanding the processes of problematization that these markets amply illustrate.

As experimentation progresses, new forms of organization and socio-technical *agencement* of markets are invented, for unexpected questions arise, to which answers and at least temporary solutions are needed. I have already mentioned several of them, presented in the articles in this section: a possible combination of carbon taxes and emission trading; the invention of certificates to enable developing countries to participate in the collective emission-abatement programme; the development of pricing tools; compromise between free allocation of allowances and auctioning; and modalities of treating allowances in firms' accounting. We could also mention (Braun, 2007) the debate on whether it is preferable to organize carbon trading upstream or downstream, and on the interesting point of who should be imputed with the responsibility of emissions and therefore the allocation of allowances (is China responsible for its industry's emissions, or the consumers in the US who buy its cheap products?). These problems, peculiar to the 'global warming' issue and to the particular circumstances in which it appears and prevails, stimulate the inventive and creative capacities of actors who are prompted to devise appropriate solutions.

This creative activity, whose outcome is strongly dependent on the specific nature of issues and problems that are being debated, is the main source of the new differentiations proposed and tested during the problematization process. Those who design and implement carbon markets by answering the questions that appear to them (or are put to them), try not to remain locked in existing frames. They test the fault lines or the biggest weaknesses of the existing *agencements* and, by following the gradients of resistance favourable to them, distinguish between that which will be considered as political and that which will be taken in charge and delegated to the market and thus to the economy. The consequence is an at least partial redefinition of the territory of economics, its rules of functioning and its organization. The effects are felt all the way through to the theoretical activity of market analysis. They affect economic modelling itself, which is thus confronted with problems that it had not entirely solved or even perceived (for instance equivalence or non-equivalence, in terms of market efficiency, between carbon taxes and the auctioning of emission allowances). Thus, step-by-step, a complicated political economics is constructed, which takes current problematizations into account. By ricochet, politics itself is at least partially redefined. Procedures of consultation are transformed, to take just this one, now well-documented example (Callon, Pierre, & Yannick, 2001). NGOs become legitimate and unavoidable partners, and the emergent concerned groups who demand, through spokespersons, to be heard and taken into consideration, can no longer be completely ignored. The way of organizing the international public sphere and of making visible problems qualified as political, changes as the organization of markets evolves. Science ends up being transformed and redefined: first, in its content, for models explicitly combine economic with climatologic and geophysical variables, and there is no reason for this interdisciplinary integration to stop; and second, in its organization, with the constitution of a world parliament of specialists (the IPCC) who, like any political assembly, negotiate the content of their reports among themselves and vote on scientific facts before making them public and passing them on to policy-makers. One day, for sure, this parliament will have to break open the circle of professional expertise; it will have to bring into the research collective researchers in the wild attentive to the events affecting emergent concerned groups. The shock of climate change has already triggered a series of other changes, of a different nature, in the way of designing and doing economics, politics and science, but also of distributing problems between the three. This threefold process which, through the treatment of issues and their multi-problematization constitutes a joint process of politicization-economization-scientifization, constantly produces new differences from existing ones and attributes new significations to economics, politics or science.

These reconfigurations, designed to deal with global warming as a very specific issue, could turn out to have a more general impact, so that the solutions tested in this specific case can be adapted and transposed to other situations. That is why it is interesting to consider, at least in simple terms, for exploratory purposes, whether these reconfigurations and the redistributions that they entail can be characterized in general terms.

Market organization could henceforth explicitly include a set of actors who were formerly on the fringes of markets and are now at their centre. Carbon markets provide what is, in my opinion, a fairly good idea of that list mentioned above, which includes scientists, specialists in the natural sciences (such as climatologists or geophysicists) or the social sciences (such as economists, anthropologists or sociologists), accompanied by a squad of experts and representatives from NGOs, think tanks, international bodies and other political administrations. To be considered as efficient, a market should pay very careful attention to the numerous matters of concern that it creates, and to the groups that express and promote them, thus becoming economic agents in their own right. This surely requires that the usual market mechanisms (revolving around, for example, rules of competition, circulation of information, etc.) be completed by a set of procedures and devices designed to compile the list of actors to involve, but also to make an inventory of matters of concern, to make them explicit and debatable, and to organize experiments and evaluation of solutions devised and then adopted.

The political devices that take shape before our eyes could also be transformed by this still emerging reconfiguration of markets. In their new form they are destined to include actors who ask questions not only on the role of the market (in the singular), which is not unusual, but above all on the actual organization and on the effects of particular market*s* (in the plural). The social engineering of markets could thus become an explicitly political issue. This could lead to actors hitherto excluded from or considered as external to the world of politics being granting an unusual place and role in the debates but also in decision-making processes. For this to happen, the creation of procedures that we have proposed to call dialogical could be demanded. The idea would be to allow for all the actors concerned by the design and functioning of a particular market to be identified and to express themselves, and then for their analyses and proposals to be compared. Active participation in the negotiations and debates by scientists and experts, whether they are confined researchers or researchers in the wild, would be encouraged (Callon et al., 2001).

The way of practising science and producing knowledge could likewise be affected profoundly. The creation of the IPCC – a radical innovation in the organization of research and the procedures for validating scientific facts – as well as the engagement of a multitude of experts from a wide variety of organizations (mainly NGOs), point to a new type of community or rather a research and innovation collective which, I predict, will spread through many sectors if the appropriate adjustments are made.

In this emergent configuration – which has inherited from the preceding one but is also reshaping it profoundly –, with markets thus revamped, political devices and procedures rearranged, and research and innovation collectives redesigned, the same actors regularly participating in all three forms of activity remain distinct but are now explicitly inter-related. It is moreover this overlapping that allows for the multi-problematization of issues and their treatment ‘in batches’, as they are sliced up into as many specific problems to solve. It might be that we are moving away from a world broken up into spheres, with a two-way trade between them; but the new world we are entering into has not for all that abolished the differences: it simply distributes and treats them differently.

Conclusion

I hope that the articles in this special section will convince the reader that carbon markets are an exceptional field for furthering our understanding of the joint processes of economization, politicization and scientification through which the forms of organization of economic, political and scientific activities, their mutual relations and the challenges they are designed to meet, are redefined. In the establishment of carbon markets we are witnessing a redistribution of economics, politics and science, which does not eliminate differences but, by maintaining these distinctions, refuses to consider that their content is immutable. The social sciences, along with the knowledge elaborated by the actors, are stakeholders in these processes of experimentation consisting of constant feedback on the significance and impact of what is under way and on the measures to take (which will affect current differentiations between economy, politics and science). I think that they could be instrumental in clarifying the new models whose emergence and establishment we are witnessing and, why not, in their possible generalization and transposition. How, in these conditions, can a civilizing process not come to mind, since in the final analysis this is a matter of plunging markets back into the social fabric which they help to create and which, in turn, constitutes the framework of the questions, expectations and needs to which they try to respond. The challenge of climate change could be one of the first opportunities on a planetary scale to raise the question of how to better civilize markets. The term civilizing markets, which I have chosen, following MacKenzie, as a title for this introduction, is even richer in meaning (Latour, forthcoming). Not only do markets need to be civilized, that is, to be included in this multi-problematization that is a living source of questions, research and the invention of satisfactory answers; but simply by participating in this movement they can act also as a civilizing force in politics and science. Civilization may be this never-ending effort to transform unsolvable issues into solvable problems, and thus to prove right Marx's claim that humanity never asks itself questions that it cannot solve. But we still need to establish why it asks itself certain questions rather than others, and that, in my opinion, is the whole point of studying civilizing markets.

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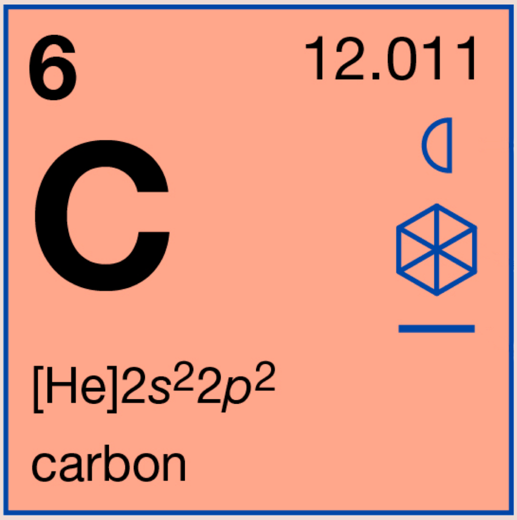

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This is a straightforward, if technical academic paper on a list of carbon capture and utilization technologies and applications. The paper covers different ends of the carbon capture spectrum — from R&D, academic studies, to commercial uses of carbon dioxide.

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Carbon capture and utilization technologies: a literature review and recent advances

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ABSTRACT

This paper presents a comprehensive list of Carbon Capture and Utilization technologies and applications, ranging from lab-scale R&D activities reported in academic papers to commercially established uses of carbon dioxide. Carbon dioxide, as a source of carbon, has the potential to be used as a solvent, as a raw material in the manufacturing of fuels, carbonates, polymers, and chemicals, or as a recovery agent in techniques such as enhanced oil recovery or enhanced coal bed methane. In this paper, a literature review and recent advances of each technology are explained. To finish, most relevant Life Cycle Assessment studies carried out by experts in this field are included. Among the different alternatives studied for the use of carbon dioxide, the processes of carboxylation, consisting the synthesis of carbonates and carboxylates, have stood out. Both the production of salicylic acid as well as that of dimethyl carbonate and mineral carbonation are presented as the most likely applications of carbon dioxide, at least, in the short term.

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Introduction

The concern for climate change is one of the key agendas stated by world leaders and experts on the subject, as well as in the daily conversations or the media every day. Carbon dioxide (CO_2) emissions are considered the main cause of this concern. Therefore, it is logical to think that the solution to this problem lies in the reduction of these emissions (Aresta 2010; European Comission 2016; Hatzigeorgiou, Polatidis, and Haralambopoulos 2010). Figure 1 represents monthly CO_2 concentration values.

As can be seen in Figure 1, CO_2 emissions have increased by approximately 2 parts per million per year. Currently, the direct reduction of the aforementioned emissions is complicated in the short term, due to the established technologies in different industries, based mainly on the use of fossil fuels. As a consequence, the concept of Carbon Capture and Storage (CCS) emerges as an attractive idea for the reduction of emissions, where, among others, absorption has been proved as an efficient technology to achieve a high capture yield with different solvents, such as monoethanolamine (MEA) or piperazine (PZ) (Li and Zhang 2018; Vega et al. 2017; Zhang 2016; Zhang et al. 2018a), but with certain technical and economic limitations like, for instance, the high energy penalty mainly due to the thermal regeneration of the mentioned solvents (Bilgen 2016; Zhang et al. 2018b). On the other hand, a common issue for all CCS technologies is the high requirement of CO_2 gas storage capacity (IPCC 2005).

Carbon Capture and Utilization (CCU) seeks not only to reduce the volume of emissions to the atmosphere but also to obtain a benefit through the use of CO_2 in different types of industrial processes, replacing conventional raw materials (Aresta 2010; Bilgen 2016). These methods will not be enough to achieve the desired objective, but they could be the key to complement the use of carbon-free renewable technologies, together with the awareness of the population (Princeton University 2015). This paper

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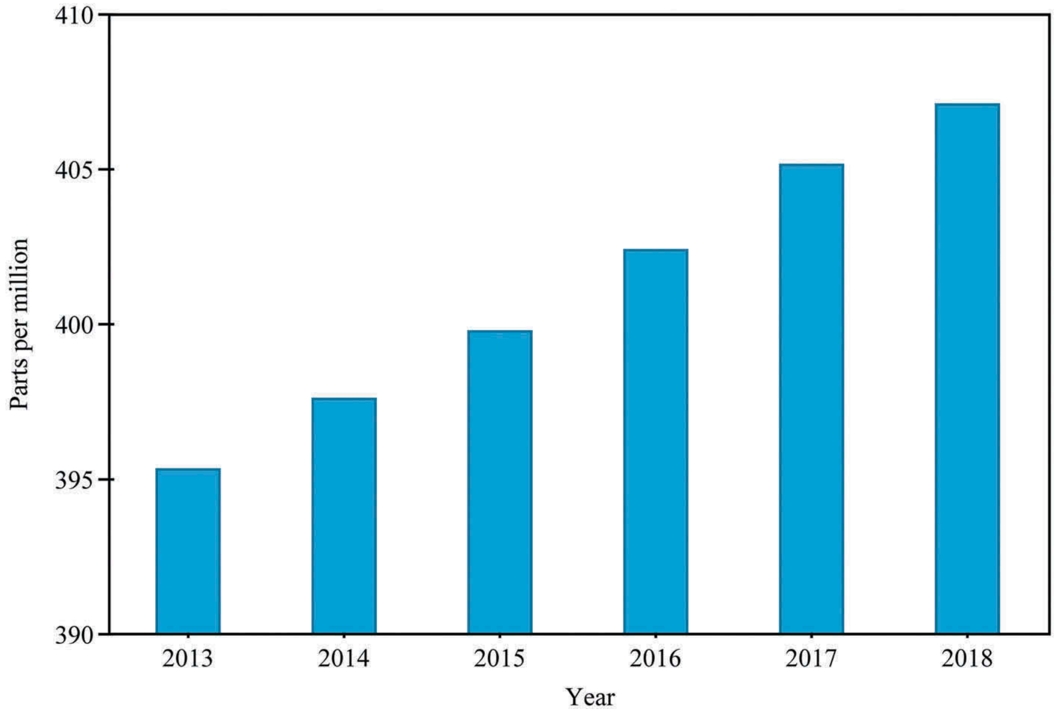

Figure 1. Monthly record of the concentration of CO_2 in the atmosphere. Adapted from Scripps Institution of Oceanography (2018).

analyzes the main available CCU technologies, as well as the innovative studies carried out so far by experts in this area. Finally, some Life Cycle Assessments (LCA) that have been done by other authors for promising CCU options are presented. The studied technologies have been grouped in four categories as shown in Figure 2: CO_2 as a solvent, Chemicals from CO_2, Fuels from CO_2, and Enhanced Oil Recovery (EOR) & Enhanced Coal Bed Methane (ECBM).

CCU technologies

The use of CO_2 can be technological, biological or chemical, and all of them seek to improve or replace traditional processes with the incentive of contributing doubly to curb climate change: it would reduce CO_2 emissions into the atmosphere and could lead to a reduction in the extraction of

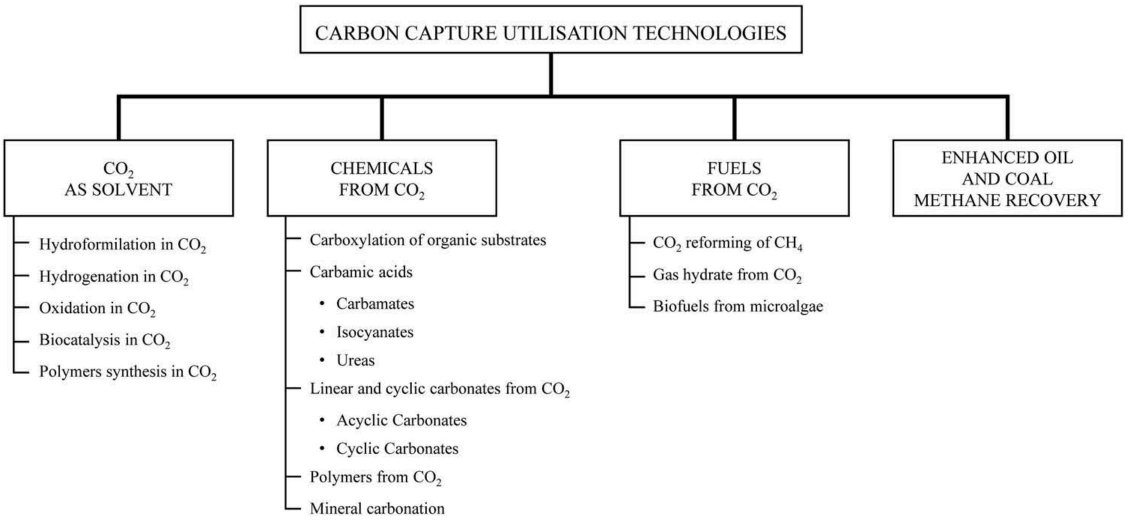

Figure 2. CCU technologies included in this study.

CO_2 from fossil fuels, as well as an economic saving for companies that consider their use (Abdeen et al. 2016a; Aresta 2010; Aydin 2014; Cuéllar-Franca and Azapagic 2015). On the one hand, the direct or technological use of CO_2 includes applications such as the extraction of compounds with supercritical CO_2 ($scCO_2$), dry cleaning, water treatment, and food industry uses, among others. In the case of the food industry, CO_2 is utilized as a replacement for the toxic elements used for food disinfection (e.g. n-hexane) as well as a replacement of the organic solvents in the extraction of compounds and finally replacing dangerous acidic species in water treatment (Aresta 2010). On the other hand, for the biological use, it is worth mentioning the direct fixation of CO_2 in fast-growing biomass. This can help to reduce the accumulation of CO_2 in the atmosphere much quicker than would naturally occur. This procedure can be used both for the manufacture of chemical products and for the production of energy, for example, converting that biomass into gaseous or liquid fuels instead of directly burning the biomass. A clear example of this fast-growing biomass is photosynthetic microorganisms or microalgae (Aresta 2010; Cuéllar-Franca and Azapagic 2015). Finally, the chemical use consists of the conversion of CO_2 into other products, such as methanol, acetic acid, carbonates, and polymers, among others (Aresta 2010).

CO_2 as a solvent

The use of solvents in the chemical industry involves large costs, both environmental and economic. The use and separation of solvents entail the use of many unit operations in the manufacturing of chemical products, representing a high percentage of the energy consumption of the process. From the environmental point of view, the organic solvents used in the chemical industry generate a negative impact, due to its flammability, smog formation, its toxicity, and the risk of inhalation, also affecting human health. This is why a considerable amount of research in the field of sustainable chemistry revolves around the development of new ecological solvents. The ideal solvent would be non-flammable, non-toxic for both humans and the environment, abundant, renewable, highly stable, low cost, easy to prepare, and separate from the final product (Albo et al. 2013; Aresta 2010; Lee et al. 2017; Marriott, Jessop, and Barnes 2014; Wang et al. 2016a). Under these conditions, CO_2 appears as a possible candidate, which seems to meet all the criteria, except that related to global warming. Even so, this CO_2 does not generate this effect directly, since it is a recycled material obtained from a waste. However, the contribution to global warming would be generated by the use of the energy necessary to compress the CO_2 to a liquid or supercritical state. This operation involves a generally high cost, which must be taken into account when comparing it with the energy consumption of conventional solvents (Beckman 2004; Boyère, Jérôme, and Debuigne 2014; Cuéllar-Franca and Azapagic 2015; Marriott, Jessop, and Barnes 2014).

CO_2 can be used as a solvent in both liquid (lCO_2) and $scCO_2$ states. A pure gaseous component is considered in a supercritical state when its temperature and pressure exceeds its critical values, for CO_2 these are 304.1 K and 7.4 MPa, respectively (Boyère, Jérôme, and Debuigne 2014). Its easily accessible critical point, high diffusivity, low viscosity, and surface tension make CO_2 even more attractive as a solvent (Albo et al. 2013; Aresta 2010; Boyère, Jérôme, and Debuigne 2014; Lee et al. 2017; Linstrom and Mallard 2014; Marriott, Jessop, and Barnes 2014; Wang et al. 2016b). Properties of the solvents can be expressed through different parameters such as dipole moment, dielectric constant, refractive index or solubility degree. $ScCO_2$ has characteristic properties of non-polar solvents, such as n-hexane. Table 1 shows some properties of lCO_2 and $scCO_2$.

Table 1. lCO_2 and $scCO_2$ physical properties. (Hyatt 1984; Marriott, Jessop, and Barnes 2014).

Solvent	Density (kg/L)	Viscosity (Pa· s)	C_P (25°C) (kJ/kg· K)	Reichardt Scale Polarity	Dielectric Constant (F/m)
$scCO_2$	0.956 [a]	1.060×10^{-4} [C]	0.846 [C]	0.090 (Var)	1.10–1.50
lCO_2	1.000 [B]	1.200×10^{-4} [E]	3.140 [D]	0.090 (Var)	1.50

[a] 40°C and 400 bar [B] 20°C and 65 bar [C] 40°C [D] 10°C [E] 25°C

Dielectric constant of $scCO_2$ and lCO_2 is similar to n-hexane (2.00 F/m) (Mopsik 1967). However, the solvency power measured on the Reichardt scale suggests that $scCO_2$ and lCO_2 are more polar than n-hexane (0.09 vs 0.009 presented by n-hexane) (Marriott, Jessop, and Barnes 2014; Ren et al. 1999). Initially, $scCO_2$ was proposed for extractions and fractionation in the field of natural product processing. Some of the commercial processes that began to be performed with CO_2 were the extraction of hops, decaffeination of coffee and tea, and the extraction of flavors, spices, and essential oils from botanical material. Even so, it has not been until the last twenty-five years when there has been an increasing interest in the use of this unconventional solvent as a substitute for liquid organic solvents (Aresta 2010; King and Bott 1993). One of the most important studies related to this subject focused on the extraction of various natural aromatic raw materials through different procedures, namely, solid/liquid extraction and solid/$scCO_2$ extraction (Pellerin 2003). One of the reported advantages of the use of CO_2 is that the amount of $scCO_2$ needed is relatively small and typically in the same order as the amount of raw material whereas the amount of conventional solvent needed are values from 3 (continuous reactor) (Aresta 2010) up to between 10 and 20 (batch reactor) (Marriot, Jessop, and Barnes 2014) times the amount of raw material. In addition, the elimination of waste with the use of conventional solvents cost up to € 380 per ton of waste (Marriot, Jessop and Barnes, 2014), while in the case of CO_2, if the waste has not been in contact with organic solvents, it can be re-used for other purposes. Finally, it was estimated that the equipment cost would be higher using CO_2 rather than conventional process, but, due to energy savings, environmental safety, and impact parameters, the use of $scCO_2$ was a better option in this comparison. The presence of $scCO_2$ in reactions with gaseous reagents makes it possible to operate in single-phase conditions, thus increasing the kinetics of mass transfer. This is due to the fact that the existing gas-liquid interface when using liquid solvents is avoided and the supercritical media have properties that favor the matter transport (Aresta 2010). The reactions where the use of $scCO_2$ has been most developed are hydroformylation, hydrogenation, oxidation, biocatalysis, and polymers synthesis (Aresta 2010)

Hydroformylation in CO_2

Hydroformylation is an industrial process of great importance in the manufacturing of aldehydes, obtained from olefins and syngas. This process involves the addition of CO and H_2 to a carbon-carbon double bond, forming the aldehyde that contains a number of carbons greater than the starting olefin. Hydroformylation can be carried out by both homogeneous and heterogeneous catalysis, the latter being easy to recycle (Bektesevic et al. 2006). Most investigations on the hydroformylation of olefins or alkenes in $scCO_2$ have been carried out in homogeneous catalytic systems, where the solvent is used to recover the catalyst after the reaction, what involves a great effort and a significant expense when traditional solvents are used. The results obtained with high molecular weight olefins have been quite satisfactory (85% yield) since these cannot be hydroformylated in aqueous bases with rhodium catalyst due to their low solubility in water (Aresta 2010; Bektesevic et al. 2006; Marriott, Jessop, and Barnes 2014).

Hydrogenation in CO_2

Hydrogenation in $scCO_2$ is one of the few processes that have been successfully developed on an industrial scale, taking place in both fluid and gaseous phases. While the biphasic hydrogenation reactions use a homogeneous catalyst, the three-phase ones use a heterogeneous catalyst in addition to the reactive liquid and hydrogen gas. Some hydrogenation reactions in $scCO_2$ are listed in Table 2.

It can be seen that the main advantages of using $scCO_2$ are the high yields and selectivity obtained in the different hydrogenation reactions. Other studies have been conducted in which the use of CO_2 as a solvent favors hydrogenation. For example, in the hydrogenation of nitrile to primary amines, undesired dialkylamines are usually generated, but in expanded CO_2 media, the primary amines are stabilized through a reaction easily reversible with CO_2, obtaining carbamate salts. On the other hand, the hydrogenation of the oleic acid catalyzed by platinum at 35°C stops at a conversion of 90% even with long reaction times of more than 25 h. However, at the conditions of 55 bar of expanded CO_2, the reaction achieves a 97% conversion after only one hour (An et al. 2009; Anastas and Zimmerman 2013; Devetta et al. 1997; Marriott, Jessop, and Barnes 2014; Mayadevi 2012; Wang et al. 2018).

Table 2. Hydrogenation reactions in $scCO_2$. Modified from Mayadevi (2012).

Reaction	Catalyst	$scCO_2$ Advantage
Biphenyl Hydrogenation	Rh/C, Ru/C	Yield > 99%
Furfural Hydrogenation	Pd/C	Switchable selectivity of 5 different products varying the operating conditions
2-butylene-1,4-diol Hydrogenation	5% mass Pd/C	100% selectivity for butane-5,6-diol
Styrene oxide to 2-phenyl-ethanol	Pd/Cu encapsulated with polyurea	100% selectivity and yield

Oxidation in CO_2

Another reaction that has been the target of several investigations, is the selective oxidation of organic substrates in dense CO_2. One of the key aspects that CO_2 presents as a good solvent for this type of reaction is that it cannot be oxidized. This means that it will not lead to the formation of byproducts or unwanted compounds while generating a solvent consumption that would have to be replaced which is the case for most organic solvents (Aresta 2010; Marriott, Jessop, and Barnes 2014).

Some of the most recent studies (Ribeiro et al. 2017a; Sutradhar et al. 2017) have analyzed the results obtained from the oxidation of cyclohexane using different catalytic complexes in different solvents. For example, comparing the action of molybdenum complexes in acetonitrile, ionic liquid, and $scCO_2$ has concluded that cyclohexanol has the highest selectivity in $scCO_2$ (98%) (Sutradhar et al. 2017). However, using Fe (II) scorpionate complexes, the highest selectivity of the cyclohexanone was given for a mixed solvent medium of $scCO_2$ and an ionic liquid ([bmim] [PF6]), reaching values up to 96%, while the maximum obtained in pure solvents was 77% (Ribeiro et al. 2017b). The partial oxidation of alcohols to obtain carbonyls or carboxylic compounds are of high industrial interest. Thus, $scCO_2$ was investigated as a reaction medium for the partial oxidation of aliphatic, unsaturated, aromatic, and benzylic acids with different catalytic systems based on noble metals, both in continuous and discontinuous reactors. The results obtained using palladium and gold catalysts for the oxidation of benzyl alcohol to benzaldehyde were very promising, achieving selectivities greater than 90% (Aresta 2010; Hou, Theyssen, and Leitner 2007; Wang et al. 2014).

Biocatalysis in CO_2

Another field in which $scCO_2$ can be used as a solvent is biocatalysis. The capability of being adjusted in its properties and its previously mentioned characteristics make the $scCO_2$ especially suitable for use in organic synthesis. The attractive idea of combining natural catalysts such as enzymes with a natural solvent such as CO_2 has been an incentive for research in this field, since it seems to be the perfect union between a highly selective and active sustainable catalytic system, and an ecological solvent with excellent transport properties. Thus, $scCO_2$ is presented as an alternative solvent for biocatalysis under non-aqueous conditions, which allows an easy recovery of the products and the enzyme, in addition to providing a similar yield to that observed in organic solvents such as n-hexane and cyclohexane. Although theoretically, this technology seems to have a high potential, the use of biocatalysts in $scCO_2$ has tried to be avoided due to the interactions between the solvent and the catalyst, which lead to the generation of carbamates (Du et al. 2008; Marriott, Jessop, and Barnes 2014; Matsuda 2013).

Polymers synthesis in CO_2

$ScCO_2$ is the main candidate to replace traditional solvents in the synthesis of polymers due to its environmental advantages that have been exposed previously. However, the use of $scCO_2$ as a solvent in polymerization reactions has a drawback, since high molecular weight compounds, especially polymers, are generally poorly soluble in $scCO_2$ under relatively soft conditions ($T < 373$ K, $P < 35$ MPa) (Boyère, Jérôme, and Debuigne 2014; Jo et al. 2017; Vert et al. 2009; Zhang et al. 2015a). Polytetrafluoroethylene (PTFE) was synthesized in a heterogeneous CO_2 medium, using a water-soluble persulfate initiator, achieving rapid polymerization kinetics, yield values of up to 90% and high molecular weight. PTFE was also produced in a medium based on dry $scCO_2$, both in the absence and in the presence of stabilizers, obtaining morphology of fibrillated PTFE, which could be particularly interesting for the manufacture of hydrophobic microporous membranes without solvents (Giaconia et al. 2008; Romack, DeSimone, and Treat 1995).

Chemicals from CO_2

As can be seen below, CO_2 could also be employed to produce chemicals. This can be achieved through carboxylation reactions where CO_2 plays a fundamental role as a precursor for organic compounds.

Carboxylation of organic substrates with CO_2

The reaction of CO_2 with organic substances can lead to the formation of carbon-carbon bonds for the production of carboxylic acids or the formation of carbon-heteroatom bonds for the production of carbonates or carbamates in which the first type is called carboxylation reaction (Senboku and Katayama 2017; Yuan et al. 2017; Zhang and Hou 2017). Carboxylic acids are organic compounds in which a carbon atom is linked to an oxygen atom by a double bond and a hydroxyl group by a single bond, forming the carboxyl group (-COOH). They are widely used in food, chemical, and pharmaceutical industries. Its applications include the production of detergents, pharmaceuticals, antibacterials, plastics, dyes, textiles, perfumes, and animal feed. Currently, other advanced applications of carboxylic acids can be found, such as in the production of biopolymers, being additives for lubricating oils, in drug administration, and in tissue engineering. Most carboxylic acids are produced on an industrial scale by chemical synthesis (Djas and Henczka 2018). The synthesis of aromatic hydroxycarboxylic acids with CO_2 turns out to be one of the most studied industrial syntheses. Since the carboxylation reaction of Kolbe-Schmitt is the traditionally used process, it is also currently a standard commercial method for the preparation of said aromatic acids (Lindsey and Jeskey 1957). Subsequently, this sparked research into variations of this reaction such as Iijima and Yamaguchi (2008a). They carried out several studies proposing different promoters of the reaction to obtain salicylic acid from phenol and $scCO_2$. In the first place, the direct synthesis of hydroxybenzoic acid (HBA) was carried out under optimal conditions, at 473 K and 8 MPa of CO_2, using several types of basic metal oxides as catalysts, such as γ-alumina, zirconia, and ceria. They were also tested with Lewis acids such as SiO_2 and $ZrO\text{-}SO_4^{2-}$ which were identified to be ineffective catalysts for the reaction. Other basic oxides such as CaO and MgO were equally unsuitable for this type of reaction. When investigating the effect of various carbonates of alkali and alkaline earth metals on the synthesis of this acid, it was observed that the catalytic activity of K_2CO_3 was the highest among the catalysts studied, followed by that of $KHCO_3$, having yields of 36% and 17%, respectively. Table 3 represents an extract of the results produced in two studies for HBA obtaining.

As can be seen in Table 3, except for K_2CO_3, none of the catalysts result in the formation of 4-hydroxybenzoic acid (p-HBA). An increase in salicylic acid formation was observed up to a yield of 68% with the use of 30 mmol of K_2CO_3, although an optimum amount of K_2CO_3 of 10 mmol was

Table 3. Extract of results obtained for the two studies on the direct synthesis of HBA (Iijima and Yamaguchi 2008b, 2008a).

Catalyst	Yield (% mol)	o-HBA yield (% mol)	p-HBA yield (% mol)	o- HBA selectivity (%)
Study: Direct synthesis of salicylic acid from phenol and supercritical CO_2 with K_2CO_3 as a catalyst (Iijima and Yamaguchi 2008b)				
K_2CO_3	36.57	36.02	0.55	98.5
Rb_2CO_3	0.54	0.54	0.00	100.0
$CaCO_3$	0.39	0.39	0.00	100.0
$KHCO_3$	17.06	17.06	0.00	100.0
Study: Effective regioselective carboxylation of phenol to salicylic acid with supercritical CO2 in the presence of aluminum bromide (Iijima and Yamaguchi 2008a)				
ZnCl2	5.20	5.20	0.00	100.0
ZnBr2	12.90	12.90	0.00	100.0
AlCl3	2.70	2.70	0.00	100.0
AlBr3	55.90	55.90	0.00	100.0

suggested, since the greatest increase in HBA formation occurs at this amount (Iijima and Yamaguchi 2008b). Although the traditional method previously explained has been widely used, some of the pioneering studies in the synthesis of carboxylic acids are taking place in the field of electrochemistry. One of the advantages of the organic compounds reduction in presence of CO_2 is the efficient fixation of CO_2 to organic molecules, forming C-C bonds under soft conditions. CO_2 electroreduction could be presented as a worthy alternative to these processes that involve intensive use of energy as well as the replacement of toxic reducing agents by electrons. It has been shown that the resulting carboxylic acid is obtained with high efficiency by using reactive metals such as magnesium or aluminum galvanic or sacrificial anode, which also has its drawbacks, which will be discussed later (Matthessen et al. 2014; Senboku and Katayama 2017). Some authors studied the electrolysis by divergent pairs of diacid precursors and diol, from the cathodic carboxylation and the simultaneous anodic acetoxylation of conjugated dienes (Matthessen et al. 2015, 2014; Senboku et al. 2015; Tateno et al. 2015). In their studies, an innovative methodology is defined that allows a conversion of CO_2 using a durable and inert anode. This process results in the formation of dicarboxylate salts and diacetate esters, from cathodic carboxylation and anodic acetoxylation, respectively. Trifluoroacetate (TFA) and tetraethylammonium (TEA) were used both as supporting electrolytes and as reagents for acetoxylation, forming their corresponding salts in the solution. The electrolysis of other diene substrates was also carried out under the same conditions as in the previous case. It should be mentioned that in the case of 1,3-butadiene, the CO_2 pressure was 10 bar. It can be observed that by carrying out the electrolysis of 1,3-cyclohexadiene with nickel cathode and graphite anode, in a solution of CH_3CN with TEA and TFA, under a pressure of 1 bar of CO_2, a carboxylation yield of 35% and an acetoxylation yield of 49% were obtained (Matthessen et al. 2015).

Another application of electrochemistry is ionic liquids. Since the compatibility of ionic liquids with $scCO_2$ is known, they have been frequently used in the electrochemical carboxylation of both supporting electrolyte and reaction medium. One of the examples reported consisted in the electrocarboxylation of a wide range of halogenated aromatic hydrocarbons, such as bromobenzene, iodobenzene, or chloronaphthalene, using a platinum cathode and a magnesium anode in the ionic liquid DEME-TFSI reacting with $scCO_2$. Moderate yields of approximately 50% were obtained, which leaves a considerable range for improvement in these processes. In spite of the obtained yields, it turns out to be an alternative more respectful towards the environment and simpler in terms of being able to purify the products by means of simple column chromatography. Therefore, it is a field still under study (Kathiresan and Velayutham 2015; Senboku and Katayama 2017; Tommasi and Sorrentino 2009, 2006, Zhao et al. 2014).

It is concluded that the use of CO_2 in carboxylation processes is interesting to meet the economic and environmental requirements, and provides an alternative to traditional CO_2 coupling reactions that require organometallic reagents, with a great future of electrocarboxylation, and especially, that is free of sacrificial anodes (Luo and Larrosa 2017; Senboku and Katayama 2017).

Carbamic acids from CO_2

CO_2 has a particular affinity for interacting with various nitrogen nucleophiles, such as ammonia or amines. This fact is of great synthetic relevance since it is a key step towards the carbonylation of the said nucleophile and the synthesis of N-carbonyl compounds. The fixation of CO_2 by amines can produce carbamic acids, carriers of the carbamate group ($RR'NCO_2$). Nowadays, the interest in the reaction between amines and CO_2 continues, since in addition to its traditional uses, such as in the Solvay process or in the synthesis of urea from ammonia and CO_2, new applications with synthetic relevance have emerged, such as the synthesis of esters from carbamates, isocyanates, and ureas (Quaranta and Aresta 2010).

Carbamates. The carbamate esters (urethanes) are fundamental structural elements for the development and obtaining of therapeutic agents, such as drugs or agrochemicals (Vessally et al. 2018). One of the most important methodologies for the preparation of organic acyclic carbamates from CO_2 involves the reaction of three components: amines, alkyl halides, and CO_2. Firstly, the tricomponent reaction of amines with alkyl halides and CO_2 is a highly known synthetic route for the synthesis of acyclic carbamates, being the object of several investigations. Salvatore et al. have proved the treatment of several aliphatic, aromatic, and heteroaromatic amines with alkyl halides in the presence of Cs_2CO_3 as a base, tetrabutylammonium iodide as an additive, and Dimethylformamide (DMF) as a solvent, under a CO_2 atmosphere, obtaining the corresponding carbamates with yields of up to 98%. This same research group extended its methodology with the use of benzyl chloride, observing reasonable results, with yields from 60% to 96% (An et al. 2014; Salvatore et al. 2002, 2001).

Hooker et al. (2009) demonstrated that 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) can efficiently catalyze the carboxylate coupling of amines with alkyl halides and CO_2. Various radio-labeled carbamates were obtained by the treatment of $[^{11}C]$ CO_2 with a mixture of amines and alkyl chlorides in the presence of DBU as a base, in DMF. The reactions were carried out with amine, alkyl chloride, and DBU at a concentration of 100 mM each, in 300 ml of DMF, with yields from 60% to 77%. Kong et al. (2011) have demonstrated that a range of carbamate esters can be obtained from the reaction of the corresponding aliphatic and aromatic amines with a variety of alkyl and CO_2 halides in very soft conditions, at atmospheric pressure of CO_2 and at room temperature, using K_2CO_3 as a base in polyethylene glycol 400 (PEG 400) as solvent and catalyst while considering a more ecological procedure for the production of organic carbamates. The obtained yields from this process varied from 29% to 93%. Xiong et al. (2015) developed a methodology for obtaining O-aryl carbamates from the reaction between aliphatic amine, diaryliodonium salts, and CO_2. Under the right conditions, the reaction was carried out for a wide variety of functional groups on the aryl ring of the diaryliodonium salts, such as fluorine, chlorine, bromine, and nitrile. The yields obtained were 63%, 38%, 20%, and 75%, respectively. With asymmetric salts of aryl-(phenyl)-iodonium as functional groups, yields of up to 91% were reported. More recently, Riemer et al. (2016) were able to synthesize different amino acids protected with carboxybenzyl (Cbz) from amino acids with benzyl bromide and CO_2 at atmospheric pressure, using Cs_2CO_3 as a base in Dimethyl sulfoxide (DMSO). The reaction provided the carbamates corresponding to the said amino acids in favorable yields, between 70% and 90%. Yang et al. (2017) developed a generation of aniline carbamates with nitrile, reacting aniline with 2-ethylbenzonitrile bromides and CO_2 under soft basic conditions, obtaining yields of 80–86%. New substituents were obtained that turned out to be excellent guiding groups for the activation of anilines with C-H meta-bonds for the construction of new C-C and C-O bonds in metal-catalyzed reactions.

There are also studies on the synthesis of carbamate esters promoted electrochemically (Feroci et al. 2003, 2007). Some of the conclusions were that the aliphatic amines gave better yields than the aromatic amines and that the secondary aliphatic amines are more reactive than the primary amines. Thus, it is concluded that carboxylate coupling of amines with alkyl halides and CO_2 is one of the most useful synthetic routes for the biologically and synthetically most important carbamate esters. The key features of this procedure are that the raw materials turn out to be cheap and easily accessible, non-toxic byproducts, reasonable yields, and their production from common bases under very soft operating conditions. These results clearly show the possible application of this chemical fixation of CO_2 at an industrial level. Despite this, the number of studies reported on this subject continues to be limited, making this field of research still open.

Isocyanates. The second key point of this section is the isocyanates, carriers of the RNCO group. Isocyanates are compounds of great industrial importance, since their application reaches various fields. They are used as raw material for the manufacture of phytosanitary agents, pesticides, dyes, resins and plastics, textile waterproofing agents, detergents, bleaches, and adhesives (Germain et al. 2016; Quaranta and Aresta 2010; Wang, Liu, and Deng 2017). One of the phosgene-free alternatives for the synthesis of isocyanates consists of two steps: first, a catalytic synthesis of carbamates from nitrile or amino compounds and CO_2, followed by a thermal cracking that provides the corresponding isocyanates. There is no chloride involved in this specific route, leading to the simplification of the separation and purification operations, hence increasing the quality of the products. Despite its apparent advantages, few studies were reported on the direct synthesis of isocyanates from CO_2, amines, and alcohols (Wang, Liu, and Deng 2017).

Table 4. Summary of studies on the synthesis of carbamates to obtain isocyanates from CO_2 (Ammar et al. 2017; Choi et al. 2002; Wang, Liu, and Deng 2017; Yan et al. 2011).

Catalyst	Operating Conditions	Yield (%)
Bu_2SnO	200 ºC, 24 h, 30 MPa CO_2	14
Bu_2SnO	$Me_2C(OEt)_2$, 200 ºC, 24 h, 30 MPa CO_2	84
$Ni(OAc)_2$-bipiridina	200 ºC, 24 h, 30 MPa CO_2	67
Cs_2CO_3	200 ºC, 24 h, 2.5 MPa CO_2	44
CeO_2	150 ºC, 12 h, 5 MPa CO_2	91
MnO_x(0,03)-CeO_2	150 ºC, 12 h, 5 MPa CO_2	82

The synthesis of carbamates by reacting CO_2, amines, and alcohols were tested in Abla, Choi, and Sakakura (2004)'s work. Initially, they used tin-based catalysts at pressures of 30 MPa of CO_2 and 200°C. After 24 h of reaction, the conversion of n-butylamine was only 16%, which could be improved to 100% using acetal in large excess as a dehydrating agent. Due to the toxicity of tin, they used nickel-based catalysts, less harmful and more active, but this methodology was unsatisfactory by industrial standards (Abla, Choi, and Sakakura 2001, 2004). Honda et al. (2011) used commercial CeO_2 as a heterogeneous catalyst to synthesize methyl benzyl carbamate in one step from CO_2, benzylamine, and methanol. Under a pressure and temperature of CO_2 of 5 MPa and 150°C, after 12 h of reaction, a greater conversion of 99% of benzylamide was obtained, with the selectivity of the methyl-benzylcarbamate of 92%, obtained without using dehydrating agents. In addition, it had the advantage that the catalyst could be reused after calcination at 600°C for 3 h. More recently, a catalyst of cerium and manganese (MnOx-CeO_2) was prepared, which showed high activity in the synthesis of aliphatic carbamates from CO_2, aliphatic amines and methanol, reaching carbamate yields of up to 82% and the catalyst can be reused up to four times for a simple recycling process (Zhang et al. 2015a). Although there have been several studies conducted in recent years regarding the use of CO_2 for the synthesis of isocyanates which are also summarized in Table 4, most are still in pilot scale (Wang, Liu, and Deng 2017).

Undoubtedly, phosgene is the most effective carbonylation agent and its technology is too established to be replaced, due to its high efficiency and profitability. Even so, its environmental and health risk makes it increasingly necessary to search for alternative routes for the synthesis of phosgene-free isocyanates. The key to finding the methodology that increases the performance of isocyanates lies in three points. Firstly, choose a suitable carbonyl source, for example, CO_2; although it represents a great challenge. Secondly, develop an efficient catalytic system and finally, search for an integrated production system that takes advantage of the resources used.

Ureas. In this section, the manufacturing of urea from CO_2 will be looked into. The synthesis of urea is currently the main consumer of CO_2 in organic synthesis. Urea, ($CO(NH_2)_2$), is the most widely produced nitrogen fertilizer and is commonly marketed. It is produced at industrial level via the reaction of ammonia with CO_2, a two-stage process where ammonia and CO_2 react to form ammonium carbamate, which is then dehydrated producing urea. This industrial method is based on the Bosch-Meiser urea process, developed in 1922. This reaction is exothermic and the process requires operating conditions between 150°C and 250°C with pressures of 5–25 MPa (Wang, Xin, and Li 2017; Xiang et al. 2012).

The apparent need to employ high pressure and temperature is what led Xiang et al. (2012) to investigate a way based on a negative corona discharge. They demonstrated for the first time that, although the reduction of CO_2 by NH_3 in urea at environmental conditions was not feasible through conventional processes, by making these gases available under said discharge urea could be synthesized at room temperature and pressure. Thus, without using any metallic catalyst, they achieved a conversion of 82% under a pressure of 1 atm and at 20°C. They observed that the yields of the solid mixture of urea and ammonium carbamate increased with the reduction of temperature and with the increase of the molar ratio NH_3/CO_2 and the frequency of discharge. Recently, the use of metal salts of oxalates as catalysts for the synthesis of N, N'-dialkylureas from CO_2 and amines was described (Sun et al. 2016). They compared the use of metal salts of sodium oxalates, nickel, manganese, iodine, cesium, and zirconium, in addition to other salts of yttrium of borate, carbonate and citrate, and yttrium oxide, resulting in $Y_2(C_2O_4)_3$ being the catalyst that provided higher yields. Under the optimal conditions, which were found to be 20 atm of CO_2, 10 atm of NH_3 and at a temperature of 150°C, in N-methyl-2-pyrrolidone (NMP), high conversions of 71–86% were obtained. However, the secondary amines and aromatics showed to be incompatible with this carbonylation reaction. In addition to the target product, byproducts were also formed: N, N'-dialkyloxamide, N-alkynylcyanate, and N-N'-dialkyl carbodiimide. A recent method for the production of ureas in which primary amines and CO_2 were used in the absence of additives and solvents was described. Research on temperature and pressure revealed that there is a point of equilibrium of both factors. At more than 180°C the yield gradually decreased, which could be attributed to the reversibility of the reaction. The inclusion of additional additives in the system did not improve the performance considerably. Under the optimal reaction conditions (180°C and 10 MPa of CO_2), the aliphatic primary amines react gently with CO_2 to give ureas of different types, with a selectivity of 100% and yields that in some cases reached up to 97% after 24 h of operation (Wu et al. 2010). From the point of view of profitability and green chemistry, the use of a cheap, stable, and recyclable catalyst without a stoichiometric excess of dehydrators in the synthesis of urea is very attractive. This implies that researchers must still look for new concepts and technologies of dehydration for the synthesis of urea, especially based on the new mode of activation for CO_2, amines or carbamates so to be able to take them as soon as possible on a large scale.

Linear and cyclic carbonates from CO_2

Among the various chemical conversion processes that involve the transformation and consumption of CO_2, an actively investigated field is the production of organic carbonates, of linear, acyclic, and cyclic type, in addition to their use for the synthesis of polycarbonates. This synthesis of carbonates, which is environmentally friendly, could be an exit from the conventional use of toxic chemicals such as phosgene ($COCl_2$) and carbon monoxide (CO) (Lim, Lee, and Jang 2014; Martín, Fiorani, and Kleij 2015).

Acyclic carbonates. In recent decades, the synthesis of CO_2 based acyclic carbonates such as dimethyl carbonate (DMC), diethylene carbonate (DEC), and diphenyl carbonate (DPC) has attracted attention in various studies. Especially, the DMC has been one of the most active focuses in this field, since it represents a molecule with a wide variety of applications such as apolar solvent, fuel additive, electrolyte in lithium-ion batteries and carbonylation reagent, methylation, and methoxycarbonylation (Prat et al. 2016; Pyo et al. 2017). More than 90,000 tons of DMC are consumed worldwide annually, being destined to the production of polycarbonates, approximately 50%, and up to 25% of its total use is as a solvent. Traditionally, DMC has been produced from the reaction between methanol and phosgene, a method that has led to disuse being replaced by less toxic routes that involve the oxidative carbonylation of methanol (Garcia-Herrero et al. 2016; Kindermann, Jose, and Kleij 2017). Most acyclic carbonates are synthesized from alcohols and CO_2 by heterogeneous catalysis using metal oxides, zeolites, and metal complexes. Although in comparison with many effective homogeneous catalysts, heterogeneous catalysts have the advantage of being superior in stability and reuse. However, they also have deficiencies: the catalytic activity is usually unsatisfactory, so it is necessary to use solvents to improve the activity and selectivity, in addition to require dehydrating or efficient drying to obtain carbonates with high yields (Honda et al. 2014a; Dai et al. 2009).

Some of the studies carried out on homogeneous catalytic systems for the formation of DMC from methanol and CO_2 investigated the use of titanium, zirconium and nionium compounds, as well as complexes of tin and other organometallic compounds, whose efficiency was quite low (Kizlink and Pastucha 1995). Furthermore, using ortho-esters as a dehydrating agent and $[Bu_2Sn(OMe)_2]$ as a catalyst, a yield and selectivity of the DMC of 48% and 85%, respectively, were obtained. This was achieved under high pressures of approximately 300 atm of CO_2 and 180°C, resulting in a problem concerning ortho-esters including difficult recycling (Sakakura et al. 2000). The use of acetal as a drying agent was also studied, since it was considered more sustainable when regenerating, achieving higher yields in DMC (58%) in the presence of the tin catalyst (Sakakura et al. 1999). Organic desiccants were also used, which made zeolites, considered inefficient at high temperatures, achieved yields of up to 45% in DMC from methanol (Choi et al. 2002). Despite the different options studied, significant advances were achieved only with the addition of desiccant or dehydrating agents. The use of nitriles, compounds capable of regeneration through the formation of amides and subsequent conversion to nitriles, was proposed. The results were not expected when using acetonitrile as a desiccant for the synthesis of DMC from methanol and CO_2 with CeO_2 as a catalyst, since at 0.5 MPa of CO_2 and 150°C, the yield of DMC after 48 h reached only 9%, with a selectivity of 65%. Improved results were obtained when using benzonitrile, increasing the yield and selectivity of the DMC up to values of 47% and 75%, respectively, after 86 h of operation under a pressure of 1 MPa and at 150°C (Honda et al. 2011).

After making a classification of different dehydrators based on nitrile, it was concluded that 2-cyanopyridine was the nitrile that produced the best results when used with cerium oxide. The yield (94%) and the selectivity (96%) of the DMC reported in this system after 12 h of reaction at 5 MPa of CO_2 and 120°C were surprisingly high. In addition, the use of 2-cyanopyridine as a desiccant had the advantage that its dehydration by Na_2O and SiO_2 was feasible, although its efficiency could be improved (Honda et al. 2013; Honda et al. 2014b). Due to the excellent results in performance and selectivity registered when combining CeO_2 with 2-cyanopyridine, this system appears as a promising candidate for its application in the industrial and commercial field. In 2014, the first continuous flow process with fixed bed reactors was developed by means of this system, represented in Figure 3.

Briefly, in this process, a system capable of carrying out reactions from atmospheric pressure to 400 bar was used. Pumps were used both for the feed of the methanol and 2-cyanopyridine mixture and for the supply of liquid CO_2, while the CO_2 gas was introduced into the system by means of a thermal mass flow controller. In addition, the lines after the reactor were maintained at temperatures above 180°C to avoid the formation of solids. Tests at various temperature and pressure conditions were made presented in Table 5.

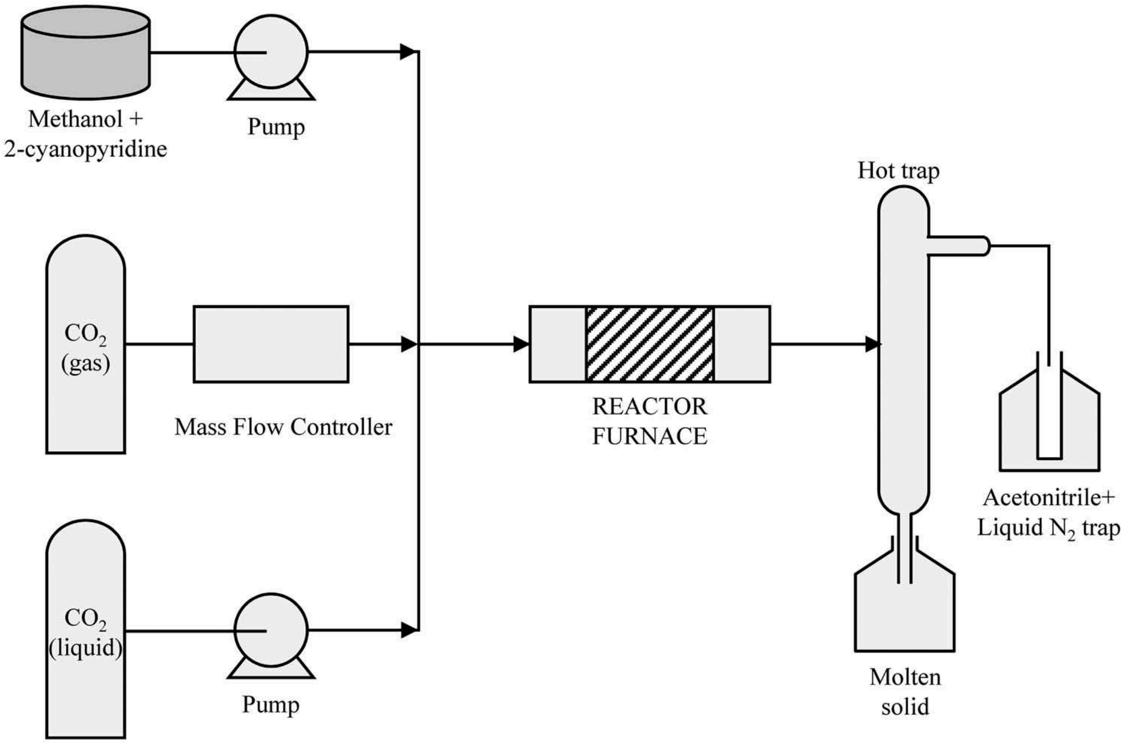

Figure 3. Flowchart of the continuous process for the production of DMC. Adapted from Bansode and Urakawa (2014).

Table 5. Results of the analysis of the effects of temperature and pressure in the continuous production process of DMC from CO_2 and methanol, with 300 mg of catalyst. (Bansode and Urakawa 2014).

Study	T (°C)	P (bar)	Methanol Yield (%)	DMC Selectivity (%)
Pressure Effect	120	1	27	96,5
		30	92	>99
		>30	92	>99
Temperature Effect	80	200	17	>99
	120		92,4	>99
	140		94	98
	160		90	93

It was concluded that the efficiency of the reaction reached a maximum and remained practically constant from 30 bar of CO_2, and that the optimum operating temperature was 120°C, as presented in Table 5. A key finding reached in a previous study was the existence of a delicate balance between temperature, pressure, and residence time required to achieve an excellent catalytic performance leading to the appearance of new opportunities in heterogeneous catalysis that promotes the investigation of the possibility of transforming traditional discontinuity in continuous processes, since batch processes are especially limited by the balance and the presence of water (Bansode and Urakawa 2014). Given its good results, it is not surprising that research has intensified in this field. Alongside this, the reuse of the cerium oxide catalyst has been studied, which is eventually deactivated by adsorption of the amide formed by 2-cyanopyridine. Furthermore, this system is not only limited to the formation of acyclic carbonates, but also for the synthesis of cyclic carbonates, carbamates, cyclic and acyclic urea derivatives, and even for the preparation of polymeric materials from CO_2 and diols (Tamura et al. 2016; Honda et al. 2014c). The synthesis of acyclic carbonates free of metals has also been reported through the use of organic promoters. To avoid the problem of dehydration and promote an effective and direct coupling of alcohols and CO_2, the Mitsunobu reagent was introduced, through which it was possible to convert primary, secondary, and even tertiary alcohols into acyclic carbonates. The product yields are from 70% to 98% in less than 8 h of operation, working between 90°C and 100°C (Chaturvedi, Mishra, and Mishra 2007). Moreover, the use of DBU was studied for the synthesis of organic carbonates, both acyclic and cyclic. Through this method, moderate performance (48%) was achieved at relatively soft conditions (70°C and 10 bar CO_2) for the DMC. In these same conditions, it was possible to obtain a yield of 69% for the synthesis of dibenzyl carbonate, another acyclic carbonate (Lim, Lee, and Jang 2014). Another method reported for the manufacture of DMC is the electrochemical synthesis from methanol, CO_2 and propylene oxide in an ionic liquid (bmimBr). Under optimum conditions; temperature of 30°C, atmospheric pressure of CO_2, with a molar ratio of methanol/propylene oxide of 11.5:1 and after 48 h of reaction, 97% conversion of methanol as well as the yield of the DMC of 75.5% was obtained (Yan et al. 2011).

Cyclic carbonates. The production of cyclic carbonates from CO_2 synthesis is a well-established field. One of the most investigated reactions in this field is the addition of CO_2 to epoxides which has also been used on an industrial scale for the manufacture of cyclic carbonates and polycarbonates (PC) (Martín, Fiorani, and Kleij 2015). For the reaction of epoxides with CO_2, catalysts have been developed based on alkali metal salts, metal oxides, transition metal complexes, organic bases, and ionic liquids. Studies are still emerging that raise other alternative procurement systems, such as, for example, the use of proteins for the catalysis of this reaction. It was demonstrated that amino acids can become a reaction catalyst for cycloaddition of CO_2 with epoxides. Relatively adverse conditions, more than 6 MPa of CO_2 at 130ºC for 48 h, were necessary to obtain satisfactory results from the use of amino acids (Saptal and Bhanage 2017). Even so, when combining alkaline metal salts with amino acids, excellent results were reported, reaching a propylene oxide conversion of 99% after one hour of operation at a temperature of 120 ºC and 2 MPa of CO_2 (Yang et al. 2014).

Table 6. Results of PC synthesis from different catalysts. Modified from Chang et al. (2018).

SwithOut WP		WITH WP	
CO-CATALYST	PC YIELD (%)	CO-CATALYST	PC YIELD (%)
KI	7	KI	94
KBr	3	KBr	29
KCl	Traces	KCl	13
DBU	6	DBU	20
DMAP	Traces	DMAP	15
TBAI	30	TBAI	81

Chang et al. (2018) recently proposed the use of wool powder (WP) as a catalyst for the coupling of epoxides with CO_2. By having hydroxyl, carboxyl and sulfonic acid groups, which turn out to be activators of epoxides while amino groups are the activator of the CO_2 molecule, it seems to be a good candidate to catalyze this type of reactions. Using CO_2 with a purity of 99.99% and propylene oxide as reagents, PC synthesis was studied using WP alone and with other co-catalysts: potassium iodide (KI), potassium bromide (KBr), potassium chloride (KCl), tetrabutylammonium (TBAI), DBU, and N, N-dimethylaminopyridine (DMAP). After 3 h of operation at 120°C and 1.5 MPa of CO_2, and without the use of any solvent, the results obtained are shown in Table 6.

When WP was exclusively used, PC performance was only 12%, while as can be seen in presented Table 6, using KI had the performance of 7%. Surprisingly, the combination of both in the same reaction gave a yield of 94% of the desired product. The dependency of the yield with the reaction time was studied, observing that it increased rapidly in the first 3 h, reaching its maximum in 94%, practically constant even when the operating time increased (Chang et al. 2018).

The direct carbonylation of glycerol and CO_2 to obtain glycerol carbonate (GC) is a very interesting and challenging route, since it would involve converting two materials considered as waste into valuable products for the chemical industry (Mohd et al. 2017). One of the most recent studies about the synthesis of GC, deals with the carbonylation of glycerol with CO_2 on cerium oxide catalysts, using as a desiccant agent of 2-cyanopyridine. Under optimized operating conditions of 150°C, 4 MPa of CO_2, 10 mmol of glycerol, 30 mmol of 2-cyano-ridin and 10 mmol of CeO_2 producing GC with the yield of approximately 79% after 5 h of reaction (Liu et al. 2016). Using the same system of CeO_2 and 2-cyanopyridine, PC synthesis was developed from propylene glycol (PG). The influence of 2-pridine turned out to be decisive due to the fact that the yield of PC produced went from less than 0.3% to more than 99% by the addition of 100 mmol of 2-cyanopyridine and only one hour of operation, at a temperature of 130 °C and 5 MPa of CO_2 while using 20% molar of catalyst (Honda et al. 2014a).

Given the current situation in the field of the synthesis of carbonates, both acyclic and cyclic, certain points can be concluded. One of the crucial characteristics for the optimization of these processes continues to be the regeneration of the desiccant species since, if it can be regenerated efficiently, the process would have a greater potential for its large-scale application and commercial exploitation. On the other hand, although the systems that use organic catalysts are more attractive for the environment, the activity shown by the metal complexes is considerably greater, so it is necessary to continue developing organometallic systems capable of equaling and even exceeding the activity promoted by the catalysts based on metals. As mentioned, the study of catalysts capable of facilitating high conversions of epoxides and alcohols at low CO_2 pressures is a field of great interest. It is worth mentioning that the research alongside the different routes reported in the last twenty years about the synthesis of the carbonates has made it possible to use more ecological and sustainable catalytic methods in pharmaceutical production and bulk chemistry.

Polymers from CO_2: polycarbonates and polyurethanes

The use of CO_2 to obtain polymers would not imply a substantial reduction in emissions, since the emission from the consumption of fossil energy is several orders of magnitude higher compared to the reduction that would be produced through the use of CO_2 in this industry. Even so, its use would make this sector meet the requirements of sustainable development through the utilization of versatile raw materials in the synthesis of polymers. It is important to note that the polymers generated from CO_2 are biodegradable (Qin and Wang 2010; Trott, Saini, and Williams 2016). Polycarbonates obtained from CO_2 and epoxides copolymerization, usually show inferior mechanical properties, in addition to a moderate chemical and thermal stability in comparison with the polycarbonates produced from bisphenol. Although these characteristics limit their industrial application as plastics, the biodegradability and sustainability of the synthesis of these polymers stimulated both the search for new applications and research to improve their properties and the efficiency of their synthesis (Taherimehr and Pescarmona 2014).

The most widely studied CO_2-based copolymers are propylene polycarbonate (PPC) and cyclohexene polycarbonate (PCHC), synthesized from propylene oxide (PO) and cyclohexene oxide (CHO), respectively (Engels et al. 2013). Different investigations have focused on the search for catalysts that increase the efficiency and selectivity of the desired product, as in most fields where the use of CO_2 is treated, due to its high stability (Xu, Feng, and Song 2014). Much of the catalytic systems investigated are homogeneous complexes based on metals combined with a nucleophile, which is often an organic salt. Since this reaction produces both cyclic carbonates and polycarbonates, the selectivity of these will be determined by the operating conditions, taking into account different factors. On the one hand, depending on the type of epoxide used, the formation of the polymer product will be more or less favored. Obviously, the operating temperature will also have an influence, favoring the high temperatures the synthesis of the cyclic product, since it is the thermodynamic product. On the other hand, due to intermolecular reactions, the higher the ratio between the nucleophile and the metal, the greater the selectivity of the cyclic product (Machado, Nunes, and Da Ponte 2018). The homogeneous catalysts can be classified into two types: bicomponent catalysts, which consist of the use of metal (III) complexes with other co-catalysts and dinuclear or bimetallic catalysts, which are metal complexes (II/III). Catalysts of the first type are usually metal complexes of Co (III), Cr (III), Mn (III) or Al (III), coordinated with ligands such as salicilimine or porphyrins. The co-catalysts employed are typically ionic salts, such as bis(triphenylphosphine)iminium chloride (PPNCl) or Lewis bases such as 4-dimethylaminopyridine (DMAP) (Trott, Saini, and Williams 2016). Some of the highest activities in the synthesis of PPC were reported using bifunctional catalysts substituted with ionic groups, reaching a conversion frequency (TOF) of up to 26,000 h^{-1} with low catalyst loads (ratio [catalyst]/[PO] = 1: 25000) (Na et al. 2009). Lee et al. (2005) were pioneers in the use of a series of complexes of bis(anilido-aldimine) and Zn (III), which showed considerably high activities (TOF = 2860 h^{-1}) with very low catalyst loads (ratio Zn/Epoxide = 1:50000). Kember et al. (2012) prepared a series of di-cobalt halide catalysts with several neutral co-ligands, such as pyridine, methylimidazole, and DMAP. They were used at a moderate temperature and at 1 atm of CO_2 for the synthesis of PCHC from CHO. In many cases, the registered activities were from good to excellent (TOF from 16 to 480 h^{-1}), taking into account the low pressures under which the reaction was executed.

Heterogeneous catalysts have also been reported in this area of study, such as zinc glutarate or other carboxylates, and double metal cyanides, highlighting $Zn_3(CoCN_6)_2$. In some cases, they are used industrially as epoxide homopolymerization catalysts, although for their use in CO_2 copolymerization much stronger conditions are required than for homogeneous catalysts. They need high CO_2 pressures and generally produce polyether carbonates instead of polycarbonates (Sebastian and Srinivas 2013; Trott, Saini, and Williams 2016). The disadvantage of this type of catalysts is their implicit toxicity when containing metals, whose use is strictly restricted, as well as the fact that their presence should not be detected in the final biodegradable polymers. It is for this reason that several efforts have been made to achieve metal complexes that are more respectful with the environment, but with high catalytic activity. Some of these metals are Fe, Zn, Mg, and Ti. For example, Wang et al. (2015) designed a binary complex of titanium salts for the synthesis of PCHC, which compared its tetravalent counterpart and increased its activity from 41 to 557 h^{-1}. Although all these systems showed polymer formation from CO_2 and CHO, in the CO_2/PO system the corresponding cyclic carbonate is produced and the propylene polycarbonate has a very low activity, this polymer being one of the most used industrial level (Liu and Wang 2017).

The synthesis of polyurethane (PU) has been another field of study during the last years. PU currently has multiple applications: elastomer, foam, adhesive, packaging, and sealant. This last generation polymer is synthesized on the basis of the reaction between isocyanates and polyols. Due to the decrease in the price of isocyanate in recent years (less than 2000 $/ton since March 2015) (Liu and Wang 2017), the challenge to reduce the cost associated with the synthesis of PU is focused on the price of polyols, which initially were cheap. This is where polyether carbonate polyols or CO_2 polyols come into play providing a promising way to lower costs of raw material, which is a substitute for polyols from polyether or polyester. Some of the main advantages have already been analyzed: polyether carbonate polyols with a CO_2 content of 20% mass reduce greenhouse gas emissions by 11–19%, with the saving of fossil resources that implies (13–16%) (von der Niklas and Bardow 2014). In addition, the PU synthesized from these polyols presents an improved resistance to oxidation and hydrolysis with respect to that based on polyether polyol (Wang et al. 2016b). Thus, both from the economic and technical point of view, the CO_2 polyols are presented as a substituent with great potential of conventional polyols, whose overall production in 2016 was approximately 9.4 Mt.

The initiator of the reaction is another important parameter to determine the characteristics of the polyols of synthesized CO_2. Thus, when employing oligomeric alcohol initiators, the required copolymerization time will be higher and producing polyols with low average molecular mass (MN) and high content of carbonate units (CU) will be difficult (Trott, Saini, and Williams 2016). To reduce this problem, the use of organic dicarboxylic acids as initiators has begun to be carried out. Using sebacic acid as an initiator, a controlled synthesis of CO_2-diol was achieved, with a catalyst activity of 1 kg of polymer/g of catalyst, a controllable MN below 2000 g/mol was achieved, although the content in CU could modify between 40% and 75% (Gao et al. 2012). The CO_2-triol was synthesized in a similar way using 1,3,5-benzene tricarboxylic acid (TMA) as an initiator, providing an MN between 1400 and 3800 g/mol and a content of CU somewhat lower than for the CO_2-diol (20–54%) (Liu et al. 2014). When the initiator represents approximately 10% of the total weight of the raw material for the copolymerization reaction to take place, its cost must be considered when choosing which initiator to use (Trott, Saini, and Williams 2016). That is why oxalic acid has been selected as the initiator, since it turns out to be the cheapest organic dicarboxylic acid. One of the most recent studies has reported the synthesis of CO_2-diol as a flame retardant from the use of bisphenol A as an initiator. The resulting polyol was obtained with a content in CU of 42% and an MN of 2400 g/mol, with a productivity of 2.4 kg of polymer/g of the catalyst after 6 h of operation at 2 MPa of CO_2 and 75°C (Ma et al. 2016). Due to the great improvement of the efficiency of these systems, a production line of 10000 tons per year of CO_2 polyols have been built in the city of Nantong, Jiangsu province, located in China, carried out by the company Huasheng Polymer Co. On the other hand, Covestro invested up to 17 million dollars for the configuration of a factory of CO_2 polyols with a capacity of 5000 tons per year, becoming doubly awarded in 2017 for the use of CO_2 for the synthesis of polyurethane foams, generating sustainable material and even reducing the use of fossil raw materials consumed previously by up to 20% (Alex 2015; Covestro 2017).

As it has been observed, this field of research is continuously active with much still to be improved however, studies are progressing in the right direction. Another addition to the study of these reactions would be the substitution of reactive epoxides for ones that are bio-derived, and not generated on the basis of fossils. Thus, the production of polycarbonates could be totally renewable. The main drawback is that these bio-derived species are generally highly substituted epoxies, so they are more challenging to present a more complex structure and considerably less reactivity.

Mineral carbonation

Mineral carbonation will be treated in this section, a chemical process in which CO_2 reacts with a metal oxide, such as magnesium, calcium or iron for the formation of stable carbonates such as calcite ($CaCO_3$) and magnesite ($MgCO_3$). Both calcite and magnesite are of great interest for their wide variety of applications in the pharmaceutical, cosmetic, explosives, paints, inks, resins, rubber, detergents, construction industries, and in particular, $CaCO_3$ is used for the surface treatment of plastics (Cuéllar-Franca and Azapagic 2015; Gao et al. 2018).

The great potential of using this type of processes can be easily understood when analyzing that the amount of carbon in the atmosphere currently involves around 870 Gt (NOAA/ESRL 2017), while approximately 39 million Gt of carbon is present in the carbonated rocks of the earth's crust, such as marble, limestone or chalk (Abdeen et al. 2016b; Oelkers and Cole 2008). Thus, to generate this reaction of mineral carbonation, the use of silicates based on magnesium seems to be indicated due to its availability in large quantities throughout the world, being the main sources of these natural magnesium silicates the olivine, the forsterite, and the serpentine. In the case of calcium silicates, wollastonite and anortite are usually employed (Oelkers and Cole 2008; Olajire 2013). There are also alternative resources as a source of calcium and to a lesser extent, magnesium which is an industrial alkaline waste. Its main advantages are its availability at low cost, high reactivity compared to that of natural minerals, proximity to CO_2 sources, and the possibility of improving environmental quality by encapsulating potentially toxic elements. However, these wastes are usually available in smaller quantities than minerals, making their use feasible at the individual plant level only. Some of the alkaline residues studied for use in mineral carbonation since 2008 are shown in Table 7 (Gao et al. 2018; Olajire 2013).

Wastes with the highest CaO/MgO content were ashes from coal-fired power plants and stainless steel slag, due to the industrial process from which they come. This carbonation process can be carried out *ex situ* in a chemical processing plant after the extraction and processing of the silicates or in situ, by injecting CO_2 directly into geological formations rich in silicates or alkaline aquifers (Olajire 2013). When dealing with this project of using CO_2 to obtain useful chemical products, only ex situ carbonation will be developed (Figure 4) (Mazzotti et al. 2005).

As can be observed in Figure 4, in *ex-situ* mineral carbonation the CO_2 generated is sent to a mineral carbonation plant, where resulted carbonated compounds are stored for its re-use or final disposal. The routes of the mineral carbonation process are a combination of the treatment of minerals and the CO_2 capture in them. The pretreatment usually consists of the extraction, crushing, and grinding of minerals before carbonation. The main objective of these actions is to increase the reactive surface, thus increasing the reaction rate of carbonation. Thus, mineral carbonation methods can be divided into direct and indirect (Helwani et al. 2016). In the direct methods the mineral is carbonated in a single step, while in the indirect, the reactive metal oxides are first extracted from the ore matrix to be carbonated in a later step, obtaining in this way high purity carbonates (IPCC 2005; Mazzotti et al. 2005; Olajire 2013). Within the direct routes, initially, the gas-solid route can be found, where gaseous CO_2 directly affects the mineral or alkaline solids. This method is simple, but the reaction rates were very low, that is why its development has not continued. There is also direct aqueous carbonation, which involves three phases coexisting in a single reactor. Firstly, the CO_2 dissolves in an aqueous solution obtaining a slightly acidic medium with HCO_3. On the other hand, there are the leachates of Ca or Mg from the mineral matrix that, together with the solution, cause the carbonate to precipitate. A lot of studies have been developed in this area (Baciocchi et al. 2013, 2011; Lombardi et al. 2012, 2011; Olajire 2013). Regarding indirect routes, there have been many proposed methods with different minerals. First of all, the multistage gas-solid method stands out. In this method, the Ca/Mg silicates are converted into hydroxides or oxides ($Ca/Mg(OH)_2$ and Ca/MgO) which will be transformed into the corresponding carbonates by its dry carbonation with CO_2 (Wang et al. 2017). Regarding the carbonation of minerals, despite being thermodynamically favorable, it is not easy to carry on an industrial scale. The main challenges to be faced in this type of reactions lie in the gigantic scale needed to reduce real CO_2 emissions and be able to carry out this mineralization, in addition to the need to accelerate the formation of carbonate to make it more efficient. The question whether this process would significantly affect the reduction of emissions has to take into account two opposite aspects: treatments such as transport, heating or cooling

Table 7. Industrial waste suitable for mineral carbonation (Gao et al. 2018; Olajire 2013).

INDUSTRIAL WASTE	CaO – MgO PRESENCE
Ashes from coal-fired power plants	65% mass CaO
Bottom ash from solid waste incinerators	20% mass CaO
Fly ash from solid waste incinerators	35% mass CaO
Paper recycling ash	35% mass CaO
Stainless steel slag	65% mass CaO+ MgO

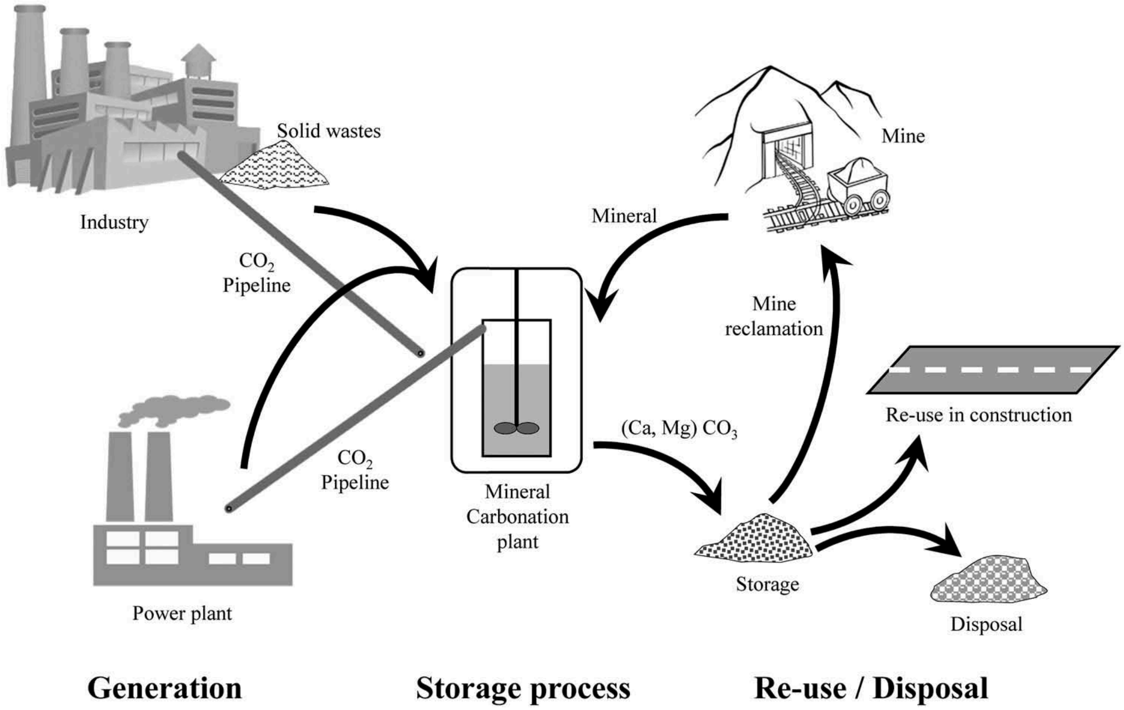

Figure 4. Ex situ mineral carbonation process. Adapted from Mazzotti et al. (2005).

of CO_2 would not be entirely necessary, since carbonation would take place around the emitting plant of this gas. On the other hand, the extraction, transport, and preparation of minerals also consume energy, but this is something that could be solved with the use of alternative raw materials such as wastes from different industries. Thus, the main advantage of mineral carbonation is the formation of stable carbonates capable of storing CO_2 for long periods of time, without the risk of leakage as in other CCS. Due to these qualities, it is presented as one of the most interesting and favorable technologies for the reduction of CO_2 emissions on a large scale.

Fuels from CO_2

Converting CO_2 into fuels generally requires a reforming reaction, typically, hydrocarbon and carbon reforming reactions and hydrogen reforming reactions (hydrogenation) (Jiang et al. 2010; Styring et al. 2011). The main processes to obtain fuels from CO_2 are syngas from reforming of CH_4, gas hydrates, and biofuels from microalgae.

CO_2 reforming of CH_4

Three different processes have been proposed to obtain syngas via reforming of methane used for the synthesis of syngas: steam reforming (SRM), partial oxidation (PO) and dry reforming (DRM). The SRM is the conventional technology used for the production of hydrogen from hydrocarbon fuels

(Abdullah, Ghani, and Vo 2017). Approximately 75% of the hydrogen produced is obtained by this process, due to its higher performance compared to the other two alternatives (Fan et al. 2016). The differences among SRM, PO, and DRM for syngas production are based on the kinetics and energy of reaction, the ratio of synthesis gas produced (H_2/CO) and the used oxidant: water in SRM (1), oxygen in PO (2) and CO_2 in DRM (3) (Abdullah, Ghani, and Vo 2017; Ebrahimi, Sarrafi, and Tahmooresi 2017).

Thus, of all these technologies, DRM is the most promising since it uses two abundant greenhouse gases for the manufacture of a useful product and of great importance in the industry, at the same time that it is presented as a possible method to reduce the net emission of these gases into the environment (Selvarajah et al. 2016). This process is also more economical than others, since it eliminates the gas separation process of the final products. Additionally, biogas (CO_2, CO, and CH_4) can be reformed through this process and the synthesis gas product is even considered as a storage of solar and nuclear energy. The use of catalysts in the dry methane reforming process is of great importance to maximize the production of syngas by altering and improving the reaction rate. Being an endothermic reaction, high temperatures are required to be carried out effectively, which can be lowered due to the presence of catalysts (Aramouni et al. 2018; Egawa 2018).

$$CH_4 + H_2O \rightarrow CO + 3 \cdot H_2 \qquad \Delta H_{298K} = +228 kJ/mol \qquad (1)$$

$$CH_4 + \tfrac{1}{2} \cdot O_2 \rightarrow CO + 2 \cdot H_2 \qquad \Delta H_{298K} = -22,6 kJ/mol \qquad (2)$$

$$CH_4 + CO_2 \rightarrow 2 \cdot CO + 2 \cdot H_2 \qquad \Delta H_{298K} = +247 kJ/mol \qquad (3)$$

Among the numerous possible materials to be used as catalysts for CH_4 reforming with CO_2, it has been found that the catalysts supported by noble metals show a promising performance in terms of conversion and selectivity towards the synthesis gas. Particularly Ru, Rh, and Ni are classified as active metals. Most of the catalysts used in this synthesis are based on nickel, which has reported long-term deactivation problem due to the deposition of coke, causing the conversion of reagents to decrease (Abdullah, Ghani, and Vo 2017; Aramouni et al. 2018; Egawa 2018). Several authors concluded that the main and desired reaction of the dry reformate is favored thermodynamically at temperatures above 730°C, although to achieve an H_2/CO = 1:1 mixture ratio of the synthesis gas obtained with a minimum formation of coke and a CO_2/CH_4 feed-rate of the unit, temperatures higher than 900 ºC are required (Abdullah, Ghani, and Vo 2017; Egawa 2018; Nikoo and Amin 2011; Selvarajah et al. 2016). At this high temperature, secondary reactions responsible for the formation of coke were not favored, except for the decomposition of methane to be endothermic. Thus, the maximum carbon formation usually occurs at temperatures between 100 and 300 ºC, which is favored by a CO_2/CH_4 ratio greater than unity, due to the presence of H_2 (Aramouni et al. 2018). Recently, Hassani et al. conducted a study where they showed, among other effects, the H_2/CO ratios produced in the DRM reaction at different temperatures under a pressure of 1 atm, using a Ni/Al_2O_3 nanocatalyst and with a CO_2/CH_4 = feed ratio of 1. They observed that as the temperature increased, the H_2/CO ratio increased with it, which is due to the endothermic nature. Under the conditions specified to obtain an H_2/CO ratio of the unit in the synthesis gas produced, temperatures higher than 850 ºC were necessary, thus giving the greatest conversion of reagents and the best performance (Hassani et al. 2016). Another very recent study analyzed the activity and selectivity of Ni catalysts with natural clay base for the DRM reaction. The effectiveness of catalysts with natural clay support ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$), clay modified with Fe and clay modified with Cu were checked. The methane and CO_2 conversions recorded were greater than 75% at temperatures above 800°C for all catalysts, except for the clay modified with Fe, which reached a maximum conversion at this temperature of 50% and 55% for CH_4 and CO_2, respectively (Liu et al. 2018a).

Despite its great environmental potential, DRM is not considered an industrially mature process. The extremely high endothermic reaction requires a lot of energy, along with the rapid carbon formation that ultimately leads to the deactivation of the catalyst, long reaction time, and the requirement of pure CO_2. These disadvantages make the DRM an impractical process that still needs additional developments. Future research in this field will probably revolve around catalysts based on bimetallic nickel like the Co-Ni catalyst. This is due to the fact that these catalysts have shown stable activity and high resistance to deactivation, even though carbon deposition is generated. The combined reforming reactions, such as DRM and partial oxidation, should also be considered and studied in greater depth, since the heat released by partial oxidation may be the heat supplied for DRM, which may lead to minimizing the operating cost.

Gas hydrates from CO_2

Gas hydrates are non-stoichiometric crystalline forms of water that are filled with small-sized gas molecules in its molecular cavities via hydrogen bonding at low temperatures and high pressures. Among the gases that could form a hydrate compound (methane, ethane, carbon dioxide, and nitrogen), CH_4 hydrates are expected to be an important energy resource in the near future, due to the fact that it is estimated that there are about 20,000 trillion m^3 of CH_4 hydrate below the ocean, which is more than all of the current fuel sources combined (Collett 2002; Pan et al. 2018). Many researchers in the past decades have studied the recovery of CH_4 hydrate from the ocean floor at various conditions (Fujioka et al. 2003; Collett 2002; Pan et al. 2018; Liu et al. 2018a), and more recently the idea of the replacement of CH_4 in the hydrate with high-pressure CO_2 emerges as a long-term storage of this gas and a way to keep the ocean floor stabilized after recovering CH_4 gas (Ota et al. 2005). Also, the direct use of CO_2 hydrate in oil production pipelines has been reported by some authors, as well as CO_2 hydrate-technology which is growing in relative to transportation processes (Jiang et al. 2016; Sabil, Azmi, and Mukhtar 2011; Veluswamy et al. 2018; Yu et al. 2008).

The advantages of CO_2 hydrate as a way of capturing are numerous. Firstly, the main chemical compound needed for CO_2 formation is water, which makes the process cheap and green since a solvent such as MEA or sodium hydroxide is not required. Secondly, it has been studied that the reduction of energy requirements for hydrate formation is possible by employing some chemicals in low concentrations (Liu et al. 2018b; Mooijer-Van Den Heuvel, Witteman, and Peters 2001). Among their uses, the feasibility of seawater desalination via hydrates was developed industrially and demonstrated that could be economically beneficial with the use of a promoter (Englezos 1993; Javanmardi and Moshfeghian 2003). Studies have been conducted where the feasibility of employing eutectic freeze crystallization with CO_2 hydrates for the separation of highly soluble salts from aqueous solutions has been shown (Güner 2015; Sabil, Azmi, and Mukhtar 2011; Vaessen, Ham, and Witkamp 2006). Also, CO_2 hydrates have been studied as cold distribution agent and phase-change material, due to the fact that the melting temperatures are consistent with the temperature needed in these applications and the dissociation heat is suitable for refrigeration application as well as easily regenerable. CO_2 hydrate based process can also be a good alternative to freeze-crystallization processes to concentrate water-rich streams which require relatively low temperatures (Sabil, Azmi, and Mukhtar 2011). Another usage of CO_2 hydrate is to increase CO_2 concentration in culturing algae, where its addition to algal culture systems can increase algal biomass effectively (Nakano et al. 2014).

Biofuels from microalgae

Microalgae cultivation can be carried out in submerged areas, infertile lands, and seawater (Mashayekhi et al. 2017; Singh, Nigam, and Murphy 2011). The cultivation of algal biomass, apart from providing biofuel feedstock, has a favorable environmental impact by reducing the concentration of greenhouse gases because it uses large amounts of CO_2 (Demirbaş 2009; El-Sheekh et al.

2017). To choose a desired type of microalgae, a selection strategy should be considered based on various criteria such as growth rate, quantity of lipids that can be produced and its quality, response to external changes in the environment, temperature variations, nutrient input and light source, absorption speed, and affinity for nutrients, and particularly CO_2, nitrogen, and phosphorus (Amaro, Guedes, and Malcata 2011; Singh, Nigam, and Murphy 2011; Ugwu, Aoyagi, and Uchiyama 2008).

There are three different sources of CO_2 for microalgae: atmospheric CO_2, industries emissions of CO_2 and CO_2 from soluble carbonates (Wang et al. 2008). Moreover, there are two kinds of possible ways to carry out microalgae cultivation: in open raceway ponds or photo-bioreactors (flat-plate, annular or tubular) (Brentner, Eckelman, and Zimmerman 2011; Styring et al. 2011). Economically, bioreactors are more expensive than open-bond systems and recent research have tried to make this process cheaper in terms of capital cost and energy requirements (Brentner, Eckelman, and Zimmerman 2011). The main problem of microalgae cultivation is that a large land area is required. Also, process control is difficult, what makes the productivity to be limited (Cuéllar-Franca and Azapagic 2015). Microalgae cultivation does not compete to food markets that makes them especially interesting for futures researches. This research should be lead towards a reduction of the cultivated area needed and a reduction of general costs (Tan et al. 2018). Figure 5 presents a block diagram of the process needed to convert microalgae to biofuels. In this process, after converting a carbon source in a flue gas, a microalgae cultivation stage is employed to obtain a wastewater biomass that will be dry before its transformation into biofuels.

Enhanced oil and coalbed methane recovery

Throughout the life of an oil production field, there are three stages. Firstly, at the beginning of production, the oil flows naturally to the surface due to the pressure difference existing alongside the deposit. In the second phase, when the pressure in the reservoir falls, water is typically used to increase it while displacing the crude and continuing extracting it. Finally, in a third stage, the remaining oil can be recovered through various technologies with the injection of either steam or

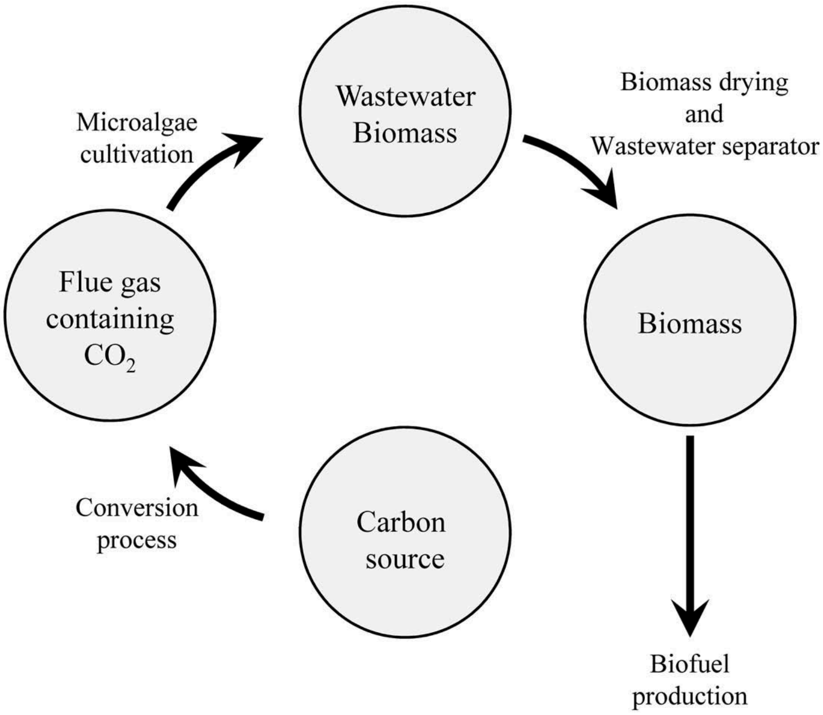

Figure 5. Biofuels from microalgae process. Modified from Tan et al. (2018).

CO_2 being the most common (Ghoodjani and Bolouri 2015). The use of CO_2 as an oil or natural gas recovery agent in techniques such as EOR and ECBM, respectively, has been investigated for many years. Outcomes from both laboratory scale and industrial studies show that CO_2 is an efficient agent displacing oil and natural gas (Panwar et al. 2017).

EOR with CO_2 injection is the second most improved hydrocarbon recovery technique after water injection according to the International Energy Agency (IEA 2015). Its application is preferable in oil fields with a depth greater than 800 m that have at least between 20% and 30% of the original oil, in which there have been previously applied secondary recovery methods (Godec, Kuuskraa, and Dipietro 2013). The injection of CO_2 is not only valid for specific gravities of medium or light oils, but it has also been increasing its application year after year for the recovery of heavy oils. The flexibility of the CO_2 injection process allows it to be used in a miscible or immiscible manner, depending on the existing conditions (pressure, temperature, and composition of the oil in the deposit) (Hertwich et al. 2008; Sweatman, Parker, and Crookshank 2009). Lately, EOR studies assessed the impact of various methods for allocating CO_2 system emissions and the benefits of sequestration under a number of different scenarios (Godec, Kuuskraa, and Dipietro 2013; Jaramillo, Griffin, and McCoy 2009). Also, some studies developed some methodologies for the identification and screening of oil reservoirs that are suitable for CO_2 flooding (Bachu, Shaw, and Pearson 2004; Dai et al. 2014). Moreover, Li et al. (2016) modified these applications for estimating CO_2 sequestration capacity at depletion as well as under enhanced oil recovery.

Regarding ECBM process, studies focused on economic issues as well as potential storage in mixed gas while studying the best places to apply this during these recent years (Saghafi 2010; Jikich et al. 2004; Busch and Gensterblum 2011; BarBaran et al. 2014; Hamelinck et al. 2002). EOR has been practiced for long periods of time in countries such as the United States or Canada. However, ECBM is under test phase (IPCC 2005). The information collected in this section argues that CO_2-EOR deserves to be a major part of a worldwide carbon management strategy. According to IEA, growth in production from CO_2-EOR is now limited by the price of CO_2 (IEA 2015).

LCA studies for CCU techniques

Subsequently, a comparison of the environmental impact of some CCU technologies studied based on LCA found in the literature, summarized in Table 8, will be made. LCA is a quantitative tool that allows collecting and evaluating the inputs and outputs of matter and energy and the potential impacts of a product, service, process or activity throughout the life of the product. Thus, in a complete LCA, all the environmental effects derived from the consumption of raw materials and energy necessary for production, emissions and waste generated during the productive activity as well as the environmental effects of its transportation, use, and consumption are attributed to the final product. The prerequisites that are generally important for a CCU technique to really reduce this environmental impact are the availability and use of clean energies as well as the use of raw materials that do not imply a negative environmental effect including CO_2 capture (Cuéllar-Franca and Azapagic 2015; Kressirer et al. 2013).

Conclusions and future prospect

This study confirms that a range of CCU technologies are available for use in several applications. From direct utilization of CO_2 as a solvent or for chemicals production, to obtain fuels or improve EOR techniques, with the potential for meaningful cuts in CO_2 emissions and associated benefits in the industry globally. Among the different alternatives studied, the processes of carboxylation have stood out, that is the synthesis of carbonates and carboxylates. The production of salicylic acid, DMC, and mineral carbonation are presented as the most likely applications of CO_2, at least in the short term. Along with the production of urea, the synthesis of salicylic acid and DMC has been carried out on an

Table 8. LCA studies for some CCU options.

REFERENCE	CCU OPTION	PROCESS	SCOPE	CO_2 CAPTURE METHOD	FUNCTIONAL UNIT (kg of CO_2 per item indicated)
EPA-7 2015	Carboxylation	Production of salicylic acid	LCA comparison of different methods of synthesis of salicylic acid from resorcinol by K-S reaction. LCA includes initial and processing processes, waste disposal, isolation and purification of the final product. Comparing different reaction media and heating methods for continuous and discontinuous process.	Post-combustion capture via MEA	Production of 1 kg of salicylic acid
Honda et al. 2014b	Acyclic carbonates	Production of dimethyl carbonate	LCA comparison of different methods for the synthesis of DMC from methanol. The environmental impact of the most widespread commercial methods (Eni and Ube) is compared with a process that involves the electrochemical reaction of methanol with CO_2 in potassium methoxide.	Post-combustion capture via MEA	Production of 1 kg of DMC
Khoo et al. 2011	Mineral carbonation	Serpentine mineral carbonation	LCA from a mineral carbonation plant in Singapore, comparing 4 scenarios. It is considered CO_2 capture, mineral carbonation, the exploitation and the transport of the serpentine. CO_2 is captured from a natural gas combined cycle power plant (NGCC), analyzing capture LCA with MEA or direct use of combustion gases. Two possible yields of carbonation are distinguished.	Post-combustion capture via MEA/Direct use of combustion gases	Production of 1 MWh of electricity in NGCC
Nduagu, Bergerson, and Zevenhoven (2012)	Mineral carbonation	$MgCO_3$ production from CO_2	LCA from a coal power plant located in Canada. This study includes coal and serpentine mining and transport, CO_2 capture, transport and mineralization.	Post-combustion capture via MEA	Sequestration of 1 tonne of CO_2
Wang et al. 2016b	Polymerization	Synthesis of polyols based on CO_2 for use in polyurethane	LCA comparison of polyols based on CO_2 with the conventional method for its synthesis, to use it for the production of polyurethane. The LCA includes all the energy supply for obtaining the raw materials, as well as the CO_2 capture of a lignite power plant.	Post-combustion capture via MEA	Production of 1 kg of polyols and 0.36 kWh of lignite power plant electricity
Elbashir et al. (2018)	CO_2 reforming of CH_4	CO_2 reforming of CH_4	LCA comparison of different synthesis gas production methods. Problem when comparing LCA since the ratio of synthesis gas produced by each method is very different.	Post-combustion capture via MEA	Production of 1 kg of synthesis gas
Campbell, Beer, and Batten (2011)	Biofuels from microalgae	Production of biodiesel	Comparative LCA of biodiesel production from microalgae between canola and ultra-low sulphur diesel.	Direct injection/Post-combustion capture via MEA	Tonne kilometer
Jaramillo, Michael Griffin, and McCoy 2009	Enhanced oil recovery	IGCC and EOR	LCA comparison among five IGCC plants including capture, compression, transport and use for EOR.	Pre-combustion capture via selexol	The total amount of electricity production during the project lifetime
Viebahn et al. (2007)	CO_2 pure for multiple uses	Could be applied to multiple processes	LCA comparison of CCS to obtain a pure CO_2 applied to PC, CCGT and IGCC power plants in Germany.	Pre-combustion via rectisol and oxy-fuel combustion	1 kWh of electricity

industrial scale with success. Although at the moment, mineral carbonation has been the technology whose analysis of life cycle has reflected the most positive result on global warming prevention by reducing the net emission of CO_2 into the atmosphere. As it is gathered in this paper, technological advances in this field are being a slow but constant process. The number of studies on CCU continues to increase, achieving satisfactory results and, in some cases, better than expected.

Future work should be aimed at the economic improvement of the processes mentioned above, which could allow its implementation on an industrial scale, as well as at technological improvement in the development of processes to achieve a greater added value such as, for example, the synthesis of methanol, the use of CO_2 consuming microalgae for the generation of ethanol and the use of electrochemical reactions that are showing initial results of great interest. The main objective will be to improve the processes already studied, increasing the activity of the catalysts and the performance of the final products.

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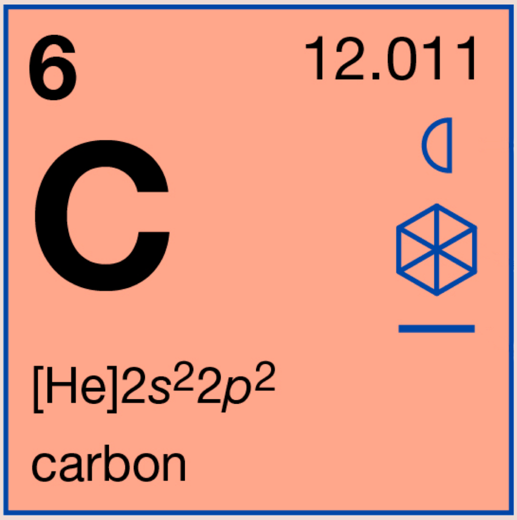

Suess, S. (2019) Distributed Resistance, Streamlined Silk. Synoptique.ca, https://synoptique.ca/wp-content/uploads/2019/03/8.1-Suess-1.pdf

This essay by Solveig Suess talks about globalised flows of materials, including carbon, particularly concerned with logistics and the tracing of this materiality. Suess deals as well with the conceptual tools of new materialism that focus on the mechanics which extract both logistics and industry for capital, and their impacts on environments.

Distributed Resistance, Streamlined Silk

Solveig Suess

Fig. 1 The train tracking system at the rail yard on the Chinese border in Dostyk is a remnant of the Soviet era, photography by James Hill for the New York Times, 2013. (Accessed from www.nytimes.com/newsgraphics/2013/07/21/silk-road, 06/02/17)

In 2012, Hewlett Packard had negotiated the construction of an alternate rail route between their manufacturing facilities in China and their consumers in Europe which, in their words, was "defined not only according to business logic, but also with certain strategic calculation" (Zelenin, Center for Strategic Assessment and Forecasts, 2017). Faster than slow-ocean, cheaper than airfreight, this calculation led the rail route to travel from Chongqing through the Xinjiang Province into Kazakhstan, Russia, Belarus, and Poland, before reaching its destination in Germany, 11,179 kilometres later (Asia Perspective, 2017). Translated as "the flowing of goods," "物流" (wuliu or logistics) expresses the naturalized desire of unhinged flow. Here, streamlined circulation is permitted through the displacement of sovereign borders, installing a new framework of transnational regulation, labour management, and security measures along with standardized units across various platforms. Later known to be part of the New Silk Road, distributive and docking spaces become key nodal events, where time and territory along its routes are converted for maximum value efficiency. But as the rail-route speeds through the growing deserts in its regions, the shifting lands attests to ongoing exploitation and resistance. With an optimization of commodity movements, the counter-efforts of slowing the desert have become increasingly pressing as Asian dust storms frequently ride the air currents, sometimes as far as California, blind to jurisdictions.

The storm moves through a series of chemical transformations where during their long-range transport, its particles collide with bacteria, gases, and coagulate solid particles. "The dust aerosol [mixes] with pollution aerosol, such as industrial soot, toxic materials, and acidic gases" (Yele Sun et al, 2005) as it travels over China's heavily industrialized zones. Particulate matter is then scattered, congealed into a whole new series of constellations, embroiled with manufactured and chemical residue: "What emerges, then, is a contest between the tenacity of corporeal memory and the corrosive power, over time and space, of corporate amnesia emboldened by a neoliberal regime of deregulation." (Nixon 2009, 449) They collect the corporate afterlives of the unevenly distributed ravages remnant of high-carbon industrial practices, bringing a sense of an environmental uncanniness when modernity is materially readdressed with the unintentional consequences of its own grand designs.

In light of such movements, the formations of these studies on logistical innovations towards economic growth must be understood alongside managing weather behaviours and methods of containment. John Durham Peters describes what he calls "logistical media" to "establish the zero points where the x and y axes converge." (Peters 2016, 37) Ned Rossiter includes various logistical media ranging from calendars and clocks, to addresses, maps, indexes, and logs, to extend inquiry on logistical media's "[coordination] and control [of] the movement of labour, people, and things situated along and within global supply chains." (Rossiter 2015, 139). Both Peters and Rossiter engage with media as ordering devices, providing a closer attentiveness to the protocols structuring the parameters in which movement occurs. With growing scholarly attention on the role of logistics in shaping the conditions of contemporary political, economic, and social life, this article seeks to bring in a more ecologically informed understanding of logistical media. Within the literature on logistics, a select number of authors take as their main focus the linkages between capitalism, modernity and imperialism (see, for example Chua, 2017; Cowen, 2010; Moten and Harney & Moten, 2013; Sekula, 2002 [1995]). However, these prior inquiries scarcely frame these histories as a longer project, where calculating material conditions such as weather acted as foundational to global forms of capitalism.

Drawing on a range of reportage and theory, I utilize the conceptual tools of new materialism to highlight how the specific mechanisms that shape the industry of logistics to the goal of profitability for capital have long colluded with spatial and environmental conditions. I use these theories to foreground the role of environmental agency where, as Karen Barad explains, agency "is about the possibilities for changing the configurations of spacetimematter relations… [and] power is rethought in terms of its overall materialising potential." (Barad 2007, 230) Barad's idea of "intra-action" argues for a more performative and discursive practice of understanding, or, as she writes, "thingification—the turning of relations into 'things,' 'entities,' 'relata'—[which] infects much of the way we understand the world and our relationship to it."(Barad 2007, 812) To trace practices of calculating and predicting weather also entails tracing epistemological shifts which "intra-act" in ways to further the expansion of empire during the 18th and 19th century. The project of optics and of observation came to shape later practices of fluid-dynamics and logistics in formations which powered commerce, measurement, and forecasting. The global economy, as a result, was very much influenced by ambitions of what anthropologist Anna Tsing calls "scalability," where scientific reason and pre-emptive calculations, remnants from the Enlightenment, brought forth a certain assemblage of governmentality over geographies of distribution and production. (Tsing, 2012, 505) In this article I will place Paul Virillo's notion of speed into productive tension with Anna Tsing's terminologies of friction and scalability when speaking of geographies across the supply chain. I also aim to evoke Amitav Ghosh, Denise Ferreira da Silva, and Rob Nixon urgent calls to bring together postcolonial and environmental theories. Here I consider the intrinsically colonial past of logistics against the currently unsettled desert of Xinjiang, China.

The method of argumentation in this article goes in order of three scales: from a general investigation into the relationships between weather-natural phenomena and logistics, the management of sand and wind across western Chinese territories, to the closer lens of Hewlett Packard's involvement in the New Silk Road as case-study. I begin with the extended histories of intermediary infrastructures and their roles in co-constructing global-scale production networks, as a way to stress its importance towards understanding contemporary conditions along the New Silk Road project. To this end, I refer to the railroads from the early Central Asian cotton and oil industry, as extensions to topologies of technoscientific practices and observations. They bled into ideal designs for smoothness and efficiency, translated from weather to the organizations of forms and movements. In the late 1950s, the Vietnam War served as a testing ground for logistics and provided a key example of how differences were reproduced and felt along the chain. Finally, the digitalization and abstraction of pre-emptive network organization acted as a continuance of economic hierarchies between the Global North and South that we see in today's supply chains, with Hewlett Packard taking origins from the U.S. military industrial complex. The global race to the bottom naturalizes deeply engrained inequalities, alienation, and violence. It is particularly urgent to relink these histories as we see an increase of logistical practices used as tools to remake and rescale territories.

The argument of the article continues to the management of sand and increasing desertification issues in western China, largely as a result of large scale social agricultural experiments. Environmental factors, such as sandstorms, interrupt the production of a smooth inter-Asian space as imagined by corporations and the state. Taking a closer look into the corporate beginnings of the Silk Road economic belt, global tech conglomerate Hewlett Packard exemplifies a historically relevant agent in the development of supply chains with their most current involvement with Chinese state elites revealing how logistics is premised on a form of control, where the centralization of capital power in monopolistic companies rely on the state‘s cooperation in aspects of development. Hewlett Packard scaled up their operations to include monopolizing the entirety of their supply chain, where their moves contributed to the state‘s overall large-scale efforts to move industries towards the western, most arid parts of China. These networks form as a hybrid grown from China‘s reform-era politics, where the economy is controlled through state-led efforts. As the Chinese economy slows, technologies of zoning and logistical strategies become increasingly important. Infrastructural expansion rearranges cartographic space into nodes and events catering to strategies of controlled circulation and containment. These activities often lie paradoxical to the efforts of slowing the increasing environmental problems in the area. Distinctly intertwined with the securitizing and direct targeting of Xinjiang's Uyghur minorities, the increasing ecological unpredictability and societal ills from broken lands forms a different reality on the ground to that of so-called "liquid modernity" (Bauman 2000).

Sedimented Elsewheres

Fig. 2 A chart of the Gulf Stream, Benjamin Franklin, 1785. (Accessed from www.raremaps.com/gallery/detail/34528/A_Chart_of_the_Gulf_Stream_with_Remarks_Upon_the_Navigation_from/American, 15/04/17)

The trade-winds were originally labelled to mean "steadily in one direction," with the term "trade" borrowed from the German language during the 14th century. While historically the word simply meant a way of life, a habitual course of action, it was during the 18th and 19th centuries that it took on the more familiar resonances—of business, a frequent practice of bartering (Online Etymology Dictionary, 2017). It was the trade winds which were truly responsible for the commencement of the global circulation of goods in the 18th century. The logic was that one had to understand weather in order to be able to extract its use value: "The oceans and the atmosphere form a nonlinear dynamic system that contains ten times more solar energy than plants capture through photosynthesis" (Delanda 2014, 53).

Benjamin Franklin's maritime observations in 1785 drew the first maps that sought to encapsulate the relationship between turbulent waters and patterns within the currents of the Atlantic Ocean. He drew them while being Deputy Postmaster General of the Colonies, after hearing a complaint from the Board of Customs in Boston. Mail packets from England took two weeks longer to make the westward crossing than the Rhode Island merchant ships. Perplexed at this difference in time, he later found that the captains who were able to move faster were familiar with the Gulf Stream and were thus able to avoid it while traveling the westward crossing. The English captains, however, were not, and instead were being trapped in its currents while en-route (Carson 2014, 101). Like in Franklin's maps, boundaries were drawn to involve calculations of the wind, its currents and directions in which would later be technically engineered in favour of the transatlantic slave trade. After-all, "the winds are the trade winds first and foremost." (Leslie 2016, 12)

Here mobility, and control over mobility, reflect and feed back into reinforcing power. Imperialism, through its ability to observe atmospheric conditions, used wind and currents as force multipliers of trade, engineering it alongside managerial strategies of the supply chain. They were able to use these conditions to allow for cheaper modes of production and extraction elsewhere, while speeding up nationalist, transnationalist, and corporate interests within their imperial centres. The "intra-action" in the trade winds, between the atmosphere, its windy circulations, the ships, its captains, and their maps, colluded in what accelerated the uneven formations of a whole series of relations across vast bodies of water. These formations can be interpreted as what Barad writes of in *Agential Realism*, the reciprocated and active formation of objects and agencies of observation within phenomena; here, "individuals emerge through and as part of their entangled intra-relating" (Barad 2007, ix). These dynamic relations continuously brought into being many elements of our current modern political geography (Ahmed 2017).

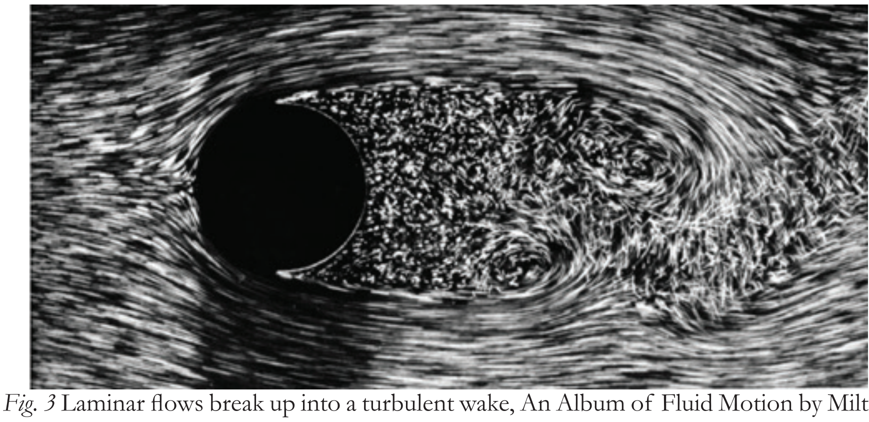

Fig. 3 Laminar flows break up into a turbulent wake, An Album of Fluid Motion by Milton Van Dyke, Department of Mechanical Engineering. Stanford University. (Accessed from courses.washington.edu/mengr543/handouts/Album-Fluid-Motion-Van-Dyke.pdf)

The beginning of the 19th century marked a rupture in epistemology. With the rise of thermodynamics, theories from physics and mathematics popularized metaphors of flow or blockages of energy through thermodynamic systems, along with hydraulic metaphors of reservoirs and damming, as these concepts became essential in thought (Frow 2005, 120). With Newton's invention of calculus, being able to predict nature and its behaviours through clean calculations gave humanity an apparently objective viewpoint (Barad 2007, 233). Grounding the modern subject, many such instances of methodological and ontological thinking featured linear temporality and spatial separation. Theorist Denise Ferreira da Silva writes that separability is the perspective that all things of the world are able to be rationally understood through quantity, quality, relation, and modality, when gathered through space and time. Knowledge can be extracted through the understanding of its ability to be outlined, formalized, and made useful—allowing for truth claims to be deducted (da Silva 2017, 61). Symptomatic of a Cartesian split which privileged binaries, it produced hierarchies such as the mind over the body, where Western reason was defined by its clean boundaries. Claims of ownership and sovereignty over land to be exploited were the very foundations of modern state and law, with lines drawn separating human individuals and nature. This began what da Silva calls "a trajectory that would extend beyond the confines of knowledge to become the ruler of modern economic, juridical, ethical, and aesthetic scenes" (da Silva 2017). Along with the seemingly objective practice of science, the Enlightenment project of modernity fueled notions of mastery and possession through reason and intellect (Serres 2011, 32).

As da Silva articulates, "The emergence of modern science can be described as a shift from a concern with forms of nature, which prevailed in scholastic thought, to an inquiry into the *efficient* causes of changes in the things of nature" (da Silva 2017). Efficiency revolutionises operations on matter, through high temperatures, the calculus of thresholds, and of the transformations of phases allowing for new heights of energy to be accessed. It was during this era when the telegraph, steam-powered vessels, administrative reforms, manufacturing industries, and railway construction collectively amplified one another (Ghosh 2017, 102). With the arrival of carbon-fuelled technologies, flows do not have to rely on winds, as landlocked settlements almost as accessible as those by water (DeLanda 2014, 81). For example, the Imperial cotton and oil industry in Russian Turkestan was co-constructed along with the building of a Central Asian railroad network in the 1890s. The whole region became part of a single economy geared towards cotton production on a massive scale. This followed a distinct mode of upscaling, including immense projects on land irrigation, across long-distance networks, expanding the ambit of Russian imperial power and dynamics (Uryadova 2012, 5). Campaigns for modernization under later Soviet rule continued such large-scale plantations that in turn exhausted the region's land and water networks, leading to devastating ecological effects (Kreutzmann 2016, 113). Western powers determined the shape of the global carbon economy through military and political presence in much of Asia and Africa, when steam technology was in its beginnings.

In the 1970s, firms in the Industrialized Global North were experiencing a downturn in profits due to the rising costs of production and wages, and sought cheaper production costs elsewhere. The answer was to return to older colonial modes of production, where seeking extraction and cheap labour sources internationally allows for profit value reaped in the north while offshoring production to the global south. Logistics originates as a military term, hegemonic on a global scale when the first shipping container was designed as a way for the US army to supply materials and arms in the Vietnam War (Charmaine Chua, Skype interview with author. May 05, 2017).

Fig. 4 Saigon, Republic of Vietnam, Douglas Kiser of the Vietnamese Welfare office arranges the loading into Sealand container trucks for shipping throughout the Republic of Vietnam under project HandClasp, National Archives D.C., 1972. (Accessed from Wesley Attewell, 15/08/17)

Together, these threads of inquiry demonstrate how environments have long been instrumentalized towards extracting value in ways which are historically contextualized. The managerial sciences of colonialism continued into logics that were later adopted by the Industrialized Global North, albeit construed through various ongoing geopolitical events. One event crucially being the U.S. involvement in the Vietnam War. During the burgeoning of the "military industrial complex" in the 1960s, new surges in state funding funnelled into developments relevant for military applications. Fluid mechanics emerged as a discipline extending from mechanical engineering that was dedicated to research for the designs of faster trains, jet engines, and re-entry physics for spacecraft and ballistic missiles. Eighty percent of graduates from these departments found employment in the defence industry (Wisnioski 2016, 103). It was at this time that nonlinear dynamics became popular amongst various fields of mathematics, physics and engineering. Spilling across disciplines, its equations of the Chirikov criterion or the Butterfly Effect became relevant from industrial design to meteorology (Holmes 2007). It was also during this period that the military science of logistics was developed and digitized. Designs of containers, along with IBM's involvement in the development of a centralized network, helped usher in a transpacific militarization (Wesley Attewell, Skype interview with author, August 9, 2017). The supply chain management in Saigon was the first to be automated, streamlining decision-making processes which made the distribution of commodities extremely efficient. IBM-applied computer technology and calculations were supplied through cooperation with RAND (Wesley Attewell, Skype interview with author, August 9, 2017).

Here, the tracking and designing of flows expanded and contracted, moving between scales. Non-linear dynamics of climates scale into strategies of movement on ground, streamlines, and fluid dynamics into the efficient management of objects. "Scalability is, indeed, a triumph of precision design, not just in computers but in business, development, the 'conquest' of nature, and, more generally, world-making. It is a form of design that has a long history of dividing winners and losers." (Tsing 2012, 505) The art of logistics was in the method deployed through dividing and supplying various forms of life (Wesley Attewell, Skype interview with author, August 9, 2017). From 1965 onwards, the Vietnam War's military backlog allowed for faster mobilization, which transported commodities into Vietnam, mitigating bottlenecks (Wesley Attewell, Skype interview with author, August 9, 2017). But as these systems ran through experience, when implemented, scalable data along with its differences are reproduced. Hierarchies amongst racialized labour became more pronounced, along with the ability to mobilise certain U.S. power relations in South-east Asia. It was also claimed that the experiments in management led to the sudden boom of Asian economies, nicknamed the Four Asian Tigers (Wesley Attewell, Skype interview by author. August 9, 2017). Along with the Cold War and all its uncertainties, the time period nurtured a desire for U.S.-led technological advancement, to aim for "crystalline definiteness" of algorithms that could "cope with a world on the brink." (Amoore 2018, 9). The increase of transnational mobility and geographical dispersal went together with resources for managing and servicing that network of movement. Calculations for the least amount of resistance across spaces—from a missile or the shape of the train—translates forms into quantifiable nodes and allows for these designs to further perpetrate global modes of production foundational to power dynamics today.

With the current global infrastructural project of the New Silk Road, the ordering of things are led by alliances between transnational corporations and the Chinese State. These alliances simultaneously produce frictions from their designs. While acknowledging that imperialism had crucially designed itself in relation to planetary currents such as wind, the contemporary state of imperialism is no doubt different. The New Silk Road traverses terrains which are amongst the most affected by climate change, with its long-distance infrastructures needing to be designed in ways to withstand increasingly erratic weather events.

Uneasy States

Fig. 5 Sand management methods along the Chongqing Xinjiang Europe rail-route, Solveig Suess, 2017

A grain of sand is found, amongst many others, covering patches of the Chongqing Xinjiang Europe rail-route. Sand can find its entrance anywhere, potent with the ability to irritate and agitate things as solid as infrastructure. Despite algorithmic oversight, a relentless material disruption frequents the New Silk Road. Every grain carries the potential for interfering into the machinic workings of infrastructure on various temporal levels. The intense sand-carrying wind requires trains to be cleaned every three days, or it would have the power to corrode the surface of trains and fade its paint. Sand becomes an oxide after reacting with moisture on the ground, where it does not forget the industrial chemicals which meld into its chemical composition, nor the salt from its original bed (Chuanjiao and Chang 2015; Rahn 2007). Over a longer duration, it gradually wears down the tracks and train wheels (Windblown Sand Modelling and Mitigation Research Group 2016). Its material disturbances are happenings, enfolding into and (re) configuring the infrastructural framework.

Sand becomes an agent which troubles the totalising ambitions of the New Silk Road. Encountering sand and its erratic movements provoke a feeling of the "environmental uncanny"—striking a chord of familiarity with something we had once known, but cannot seem to remember how we turned away from. Eerie moments of sudden confrontation with strange weather remind us of "the presence and proximity of nonhuman interlocutors" (Ghosh 2017, 32). The landscape is a sentient entity, one without subjectivity, but nonetheless an entity, not a background. Our recently announced current geological epoch, the Anthropocene, describes shifts in the earth's own physical processes as human activities have become the world-determining forces of change. But we should add that it is not just any human that produces change on this scale, but particular humans, perhaps of a specific mode of production and consumption, or a set of relations, maybe an assemblage of industrial and post-industrial high-carbon lifestyles (Choy and Zee 2015, 210).

In 2007, the press covered a hurricane-force sandstorm which derailed a train in the Xinjiang area. Some cars were knocked off the rails, others were left with cracked windows (The Associated Press, 2007). Each following year trailed with reports of similar severities, necessitating design modifications along its routes costing up to $US 23 billion (Shepard 2017). All along the New Silk Road economic belt, the infrastructure rushes through vast landscapes which clearly suffer from high degrees of aridity. Its landscapes are criss-crossed with various methods designed to keep dust and sand grounded, to prevent particulate matter from being mobilized by the winds, from transitioning its phase into suspension. Netted materials are pinned to the ground, both in grids and as vertical walls. Grids made out of stones create similar effects of catching sand. Many artificially planted trees dot the regions as their roots hug the ground. Train tracks undulate on and above ground, the heights determined by the intensities of the landscape‘s sand composition. 463 kilometers of windproof walls were built along the Gobi Desert stretch of the line, as well as the 3600 meter-high Qilianshan tunnel in Gansu Province (Shepard 2017). Delaying its future, governmental efforts have been organized to predict and slow the terrain‘s relentless movements eastwards, against the current of the Western economic tide. As each train carries around $US6 million-worth of goods when heading towards Europe, strong winds remain a major threat to the rail-line, particularly around the Xinjiang-Lanzhou-Urumqi 710 kilometre stretch. The faster the trains, the more of a threat they become (Jia, 2013).

The sands are close reminders of the expanding deserts from the nation state’s peripheries, Xinjiang and Inner Mongolia. The low pressures in the atmosphere over the Taklamakan and Gobi deserts create windy conditions in the area during late winter and early spring. Loose top soils are picked up by westerly winds, pulling these sands into an increasingly intense Asian dust storm (Phys.org, 2017). Freezing all activity in its path, such storms have become an annual occurrence, compared to half a century ago when each phenomenon struck only once every seven or eight years. The deserts are expanding roughly 1,300 square miles a year, with movements both fast and slow. Each grain of sand carries the potential to be thrown across thousands of miles with the storm (Mullany, 2017).

Over the past few decades, utopian social-agricultural experiments of high Maoist socialism have completely drained groundwater and many lakes across Xinjiang and Inner Mongolia. The Uyghur ethnic minorities of Xinjiang had previously used an extensive network of *karez*, a localized technique which had irrigated arid areas for millennia. These infrastructures were then replaced by large-scaled agricultural production used towards cotton plantations which resulted in its quickly receding water tables (Vanderklippe, 2017). Lop Nur, a lake that disappeared forty years ago, is now one of the four sources of sandstorms in China. Twenty percent of the country currently exists as desert, whereas in 1975 desert lands were 21,000 square miles smaller (Haner et. al., 2016). Anthropologist Jerry Zee writes that the mobile dunes of the deserts are “sites and material forms where we can trace emergent alignments of politics to the inorganic afterlives of the broken land” (Zee 2017, 218). The state-led ecological construction slogan in these areas speak of “blocking wind, holding sand” (fangfeng gusha), where it is through the control of sand‘s conditions, specifically in managing its transition between on-ground to in-air, which influences local environmental politics (Zee 2017, 232).

In a turbulent flow of agency, sandstorms irritate the calculated journey of the train. Rail-routes have been known to be riskier due to overland possibilities of local ‘terrorist’ insurgencies and extreme weather events, especially those which traverse deserts. They cannot be easily governed due to shifting lands. With China‘s rail-network spanning across a wide range of climatic zones, sandstorms frequently disturb routes like ones which cross the desert-ified areas of Xinjiang (UIC eNews 2017).

Trains crossing the Eurasian steppes are armed with guards stationed aboard, with a high-speed rail monitoring system actively sensing and monitoring for possible risks of a transition into turbulence—wind speeds, anti-intrusion, vibration, and geological disasters (Szyliowicz et. al., 2016, 154). Maintaining an all-encompassing algorithmic oversight while traversing westwards towards Europe, the route has become one of the most monitored areas within China. Algorithmic oversight of the rail-line operates by feeding data through numerous types of radio systems, inventory histories, and the internet of things, which in turn translate back into risk assessments and security protocols informing management procedures. As business advisory manager Wing Chu explains, “Today, most logistics operators are capable of monitoring the cargo during the whole process and provide the consignor with clearance on arrival at the railway terminus, warehousing, and trans-shipment to the desired destination” (Chu 2016). Just-in-time, precision management, and forms of regulation seek to calibrate the supply chain precisely towards predictive models for the destination of goods. Virilio writes, “modernity is a world in motion, expressed in translations of strategic space into logistical time, and back again” (Virilio 1986, 7). The political landscape is governed by various and collaborating surveillance, mobilization, and fortification technologies, building a nervous attentiveness when movement and time are governed so tightly (Virilio 1986, 7).

Wind and its movements have not always been seen as a hindrance to production. Rather, one could say that in the inception of modernity was the ability to calculate and efficiently use all weather conditions towards capitalistic means. As outlined in the previous section, observing weather laid the groundwork for future techniques of predictive analytics. The project of optics and of observation came to shape the world in a particular formation which powered commerce, measurement, and forecasting, producing differences which matter. Taking cues from Karen Barad, carefully reading for such differences demonstrates how they are not predicated on conditions which are external to them but rather in entanglement, with effects produced as concrete in mattering and in material conditions. Without such an understanding and instrumentalization of weather, there would be no global capitalism as we know it. But increasing ecological disturbances signal an urgent need to shift our common-sense understandings and contemporary culture in ways which are both imaginary and epistemological. Climate change is amplified through dramatic environmental systems, resulting from the build-up of certain human practices, now acting as an agent of disruption feeding back onto those same practices. The replacement of the *karez* with state-led social agricultural experiments engineered the area of Xinjiang towards short-term benefits, with its lands now suffering from increasingly strange and unpredictable weather. Sand and its movements interfere, interrupt, and deviate the fluxes of logistics across contemporary Xinjiang province while simultaneously refining algorithmic calculations towards further control and efficiencies. Such technologies which fixate themselves on control and the absorption of contingencies, fold into larger societal shifts and formations of communities.

Turbulent Drag

Fig. 6 Still taken from a Russian logistics company, AvtoGSM, employee surveillance camera, 24/03/15. (Accessed through www.youtube.com/watch?v=pt2lGOQnj_s, 03/02/17)

In the wake of slowing economies, geographies of supply and demand currently spread themselves across vast spaces in mutable forms. Capable of absorbing peripheral communities at the edges of markets, logistical networks assist the drive of states and corporate conglomerates to continuously seek the extraction of capital in places otherwise untouched by its capture. As Virilio notes, layers of people and things move faster, driven by the "competitive advantage of speed" (Virilio 1986, 9). Speed fuels economic production towards distribution, and maintains a level of metabolic intensification in central nodes or global cities (Virilio 1986, 14).

Used now as a tool to stave off slowing economies by "bringing the outside in," 由外至内 (youwai zhinei), a catchphrase amongst planners of the New Silk Road economic belt, reinforces the logistical and infrastructural as a new method of governance (Eyler, 2015). When recasting geographies of law and violence through the arranging of the inside and outside of state space, actions like land grabs, military actions, and dispossessions are all part of its territorial reconfiguration (Cowen 2014, 102). Deregulated environmental and labour laws offer legal independence from the domestic laws of the host country through the creation of zones: "The zone typically provides premium utilities and a set of incentives—tax exemptions, foreign ownership of property, streamlined customs, cheap labour, and deregulation of labour or environmental laws—to entice business" (Easterling 2015, 10). Within the Chinese Communist state system, zoning technologies are devised as a distinctive way to re-territorialise national socialist space whilst generating a controlled development of capitalism (Ong 2004, 72).

In the case of the New Silk Road, the transnational company Hewlett Packard initiated the inter-governmental negotiations for saving two weeks-worth of transportation time (Shepard, 2017). It was seen to be an alternative to the Pacific Ocean route, which was filled with chokepoints and perils. This followed a move made by the company, as well as others including Foxconn and Volkswagen, to shift their factories towards China's western border (Abe, 2014). As part of the "Go West" program, state-led encouragement was offered to develop these western regions. The western regions are also the location of large amounts of energy and mineral resources, including coal and iron ores from the politically troubled Xinjiang Uygur autonomous region. With more speed and less cost of transporting Chinese-made goods to western markets, large incentives allowed transnational corporations like Hewlett Packard to leverage geo-politics in their favour (Frankopan, 2015). The Hewlett Packard-initiated rail-route later became part of the Chinese state's centralised framework of the New Silk Road Economic Belt initiative in 2015, ironing out any potential issues with bottlenecking (Yin-nor 2015, 112).

There is a particular characteristic of scalability which remains faithful to the universalist notion whereby a singular, global conquest of a certain knowledge moves objects and peoples. This unified ideal sways and naturalizes the idea of expansion. Scalability appears across various forms throughout the supply-chain, where to be "scalable" is to be expandable without needing to rethink basic elements (Tsing 2012, 505). A common tactic of neoliberal global capitalism, or large transnational corporations, scalability describes what Rob Nixon calls "geographies of concealment in a neoliberal age" (Nixon 2009, 444). By its design, difference is disguised in homogeneity, occluding troubled relations within transnational spaces with a sheer glaze of shared modern ambitions of efficiency.

From scalabilities, Hewlett Packard was also the first western company to incorporate Japan's pioneering industrial methods of supply chain management. Hewlett Packard influenced the U.S. military industrial complex to embed their standards within America's domestic policies (Weiss and Schoenberger 2015, 69). In post-war Japan, Toyota pioneered supply-chain management by moving production outside their sovereign borders, coordinating space and time through a more cost-beneficial manner. As a flexible production technique, just-in-time (J.I.T) management aimed to shave off expenses and optimize, where possible, through various methods of tweaking. This technique standardized a rhythm of labour throughout the production line, with working hours described by Stefano Harney as a "killing rhythm of labour" (Wesley Attewell, Skype interview with author, August 9, 2017). It globalizes an acceptance of working the body at a rate which physically and mentally destroys it over time (Wesley Attewell, Skype interview with author, August 9, 2017). As an *Economist* article reports, "One study found that American firms that introduced J.I.T gained over the following five years (on average) a 70% reduction in inventory, a 50% reduction in labour costs and an 80% reduction in space requirements" (Tim Hindle, *The Economist*, 2009). Such expansion of micromanagement practices tracks and traces, finding points of drags in time and space which then inform overall operational decisions. J.I.T management pioneered a rationalization which seeks calibration of work throughout the whole body of the supply chain (Cowen 2014, 196).

Efficiency is implemented through different scales within strata of inventory lists to political economic agreements along the New Silk Road railway. Thousands of laptop computers and accessories are piled neatly in these sealed shipping containers to travel across the New Silk Road three times a week. Borders have also shifted, with the train route's security checks displaced. Fulfilling ambitions of free-trade, a two-day wait for a ten percent physical container inspection has been eliminated because of the Eurasian Customs Union Agreement, allowing for goods to instead travel freely through Russia, Kazakhstan, and Belarus. Time is shaved through a shortened transit duration; inventory lists are reduced, leaving less room for complications. Objects placed in inventories are effectively tracked, allowing for quick calculations to channel profits and organize the commodity chain. In these digital spreadsheets and inventory lists, labour and environmental conditions where theft or violence are also part of the production process are siphoned off as excess. Neoliberalism is an agent of general equivalence.

Hewlett Packard negotiated with the Chinese government to implement their own border customs software for processing documents, permitting its containers to instead stay locked and un-inspected at border crossings *en route*. This allows for the inclusion of cargo inspection, quarantine, and customs clearance to occur in one stop (Chu, 2016). One does not have to look far to see that the flow of goods and capital means the arrest of movement for others. In 2016, the Uighur ethnic minorities of Xinjiang were told to hand in their passports to local authorities for "examination and management"; the area had been heavily policed for forms of separatist activity. Police checkpoints dot the area, targeting local inhabitants during the duration of the developmental works (Al Jazeera 2016). Since the development of the New Silk Road economic belt, the faster trade through these overland lines means more restrictions and containment for the Uyghur minorities in the area. The area is filled with checkpoints interrupting movement every few kilometres, providing only the surface of the extremities of the police occupation and colonization in the province as big as France and Germany combined. Deborah Cowen writes that the neoliberal management of life and death and its anti-political calculations, cost-benefit analysis, and market-driven logics embed themselves in the most minute of measures. Time and space are designed with technologies of efficiency and standardization, eliminating resistances including possibilities for political claims or ruptures. The management and security of the life of the whole supply chain is crucial, not just the population it serves (Cowen 2014, 231). Ethnic-specific targeting occurs on various levels as part of the close watch of the state. This includes anything from identity and mobile phone screenings, WiFi sniffers, cars with compulsory tracking devices, to one meter of resolution available through satellite imagery. Xinjiang is currently the test-zone for the entire country's artificial intelligence operations.

The fantasy of logistics, and where it accumulates its power, appears as the all-encompassing smooth operator, adept at hiding the fact that it needs friction in order to stay in business. Friction, in Anna Tsing's view, is the awkward, unequal, and unstable force which "refuses the lie that the global operates as a well-oiled machine" (Tsing 2015, 6). Understanding these global points of friction is exactly what allows Hewlett Packard to maintain its market dominance, where what is at stake for them involves finding logistical solutions towards keeping costs low. Speed, then, is engineered across frictions traversing between the body and continents. Hewlett Packard's innovations for the New Silk Road aligned with the national interests of the Chinese state in that these joint plans assisted the westward movement of industries. This is an increasingly serious collaboration, as the mitigation of risks involves both the violent arresting of the Uyghur population along with the increased deterioration of the lands. The implications of these logistical calculations are disturbing ecologies as well as societies. It is with this urgency that these processes need to be seen together as two sides of the same coin.

(Re)configuring Flows

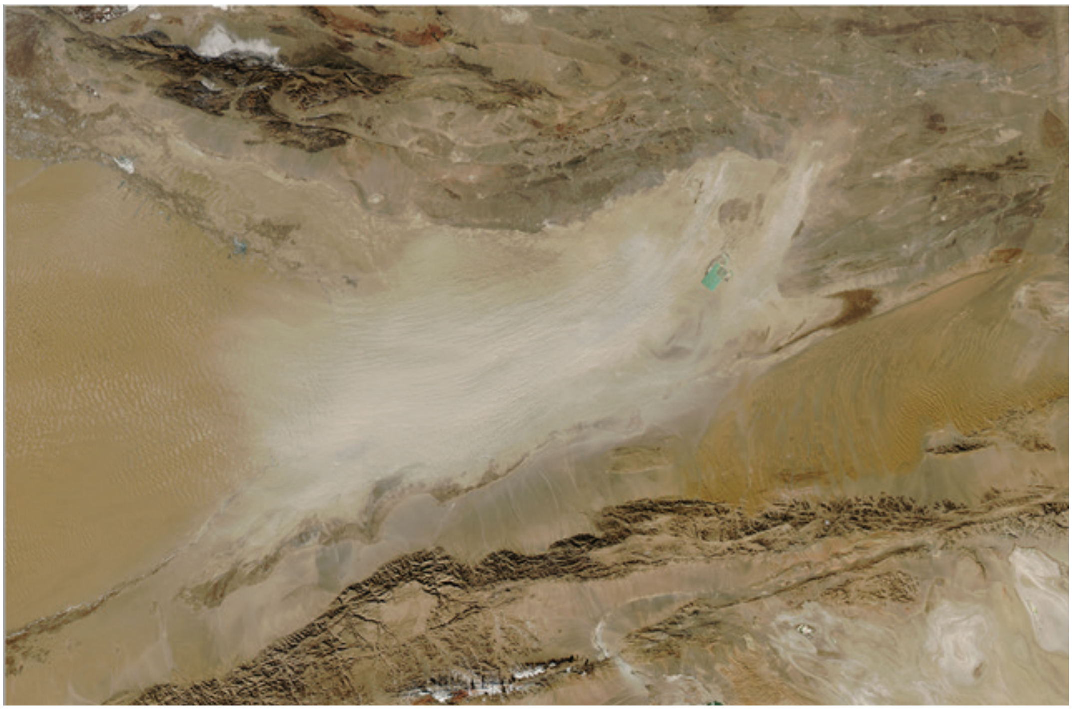

Fig. 7 NASA's Aqua satellite took a photo of a dust storm blowing over the Taklimakan Desert in China, 01/02/14. (Accessed from https://earthobservatory.nasa.gov/NaturalHazards/view.php?id=51705, 02/07/17)

This paper has mapped logistical media through its intra-actions with weather across various scales. Backgrounding with the epistemological shifts that came with different forms of forecasting and measurement, particularly of thermodynamics, the notion of efficiency has led to specific geographic modes of production, distribution, consumption, and dispossession. Long-distance networks of transportation, initially wind-dependent, later connected scalable operations of production through networks of steamships and railways, expanding the ambit of what is possible for global logistical capitalism. With the development of the military industrial complex during the Cold War underwriting a lot of how current transnational configurations are forged, notions of efficiency continue to reproduce violent Cartesian separations between human individuals and nature across its spatial and temporal orderings. Together, they demand we interrogate fundamental logics to how we make sense of increasingly strange weather—knowing that these storms do not merely trouble global scale ambitions, but that they are as much part of it.

Here, sandstorms obscure the military, scientific, corporate, and state alliance matrix with their agencies. The various temporal disturbances in which sand affects the railway and its supporting infrastructures bring forth unscalable relationships that actively reconfigure these global flows of capital and goods. As sandstorms assert themselves as an undeniable threat to the infrastructure of the New Silk Road, it folds and reorganizes corporate and material histories and futures, generating their own sets of desires, contradictions, and political and economic logics. Particulate matter finds its way of creating friction within ideal states of smoothness, influencing new programs focused on the management of risk geared towards protecting the corpus of the supply chain. The turbulent nature of sands and winds are able to interrupt the continuous fluxes of logistics but also, at the same time, increase and refine their algorithmic overview towards a more efficient control.

Referring to Hewlett Packard's history of supply chain logistics, their current collaboration with Chinese state elites is crucial in understanding newer forms of logistics today. Hewlett Packard based its innovations on points of friction for keeping its industry dominance. As the New Silk Road is currently one of the most ambitious ongoing infrastructural projects in the world, it is important to observe such points of friction as they feed back and reinforce the supply chain as a whole. The corporation's involvement with infrastructural and material conditions includes repercussions which are both environmentally and socially devastating. The calculations for speed and the least amount of resistance exceeds into biopolitical control of the local Uygher population and increasingly strange weather in Xinjiang Province. Studying tech firms like Hewlett Packard through the lens of logistical media enables increased attentiveness to the logics of organization that bear such spatial and temporal implications. With the engineering of immediate time and space, the long-term, delayed effects of industry and capital form what Rob Nixon would call a temporal disjuncture—an out-of-sync (Zee 2017, 218). These sandstorms force-multiply cruel differences inherited through an amalgamation of global-scale industrial, modern, and capitalist practices.

The increasing nervous attentiveness to weather prediction within these regions coincide with the province as a testbed for algorithmic governance. While western colonial projects functioned differently to Chinese state-led experiments, both fundamentally imply a dismissal of other forms of logistical organization. This can be seen through the denial of older methods of irrigation, such as the Uygher *karez* technique, in parallel with systemic destruction and colonial dispossession by the Chinese state. The sheer scale of control which Chinese state-elites have over various territorial decisions places is further evidence of the current urgency to examine these trans-corporate and state infrastructural collaborations. Decisions made by these collaborations shape broader hegemonic parameters coordinating a wide range of material settings, such as ports, warehouses, transport, and even university and military operations. Efforts to recognize interconnections between more-than-human scales of logistical media are crucial to finding commonalities among struggles to unite along the supply chain.

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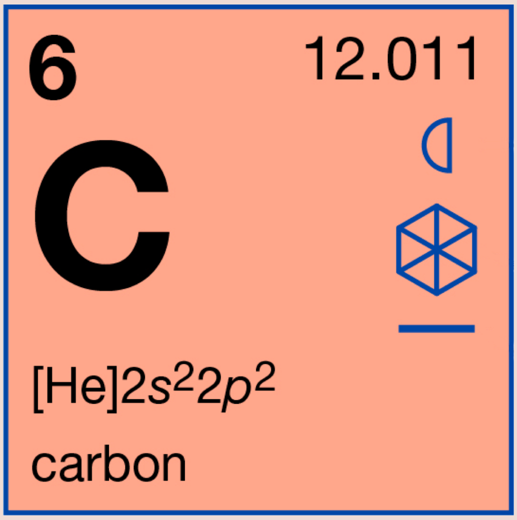

MacKenzie, D. (2009). Making things the same: Gases, emission rights and the politics of carbon markets. Accounting, organizations and society, 34(3-4), 440-455.

A paper on the ways that markets level things out and create means of exchange for incommensurate elements, materials and value. MacKenzie's work analyses carbon markets specifically, how these markets were created, and how something as ephemeral as atmospheric gases have come to be measured and analyzed through the "politics of market design."

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Making things the same: Gases, emission rights and the politics of carbon markets

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Abstract

This paper analyses the development of carbon markets: markets in permits to emit greenhouse gases or in credits earned by not emitting them. It describes briefly how such markets have come into being, and discusses in more detail two aspects of the efforts to 'make things the same' in carbon markets: how different gases are made commensurable, and how accountants have struggled to find a standard treatment of 'emission rights'. The paper concludes by discussing the attitude that should be taken to carbon markets (for example by environmentalists) and the possibility of developing a 'politics of market design' oriented to making such markets more effective tools of abatement.

Introduction

Around the world, markets in permits to emit greenhouse gases or in credits earned by not emitting them are emerging. Some already exist; others are in construction.[1] This article describes briefly the route – at the level of 'policy' – that has led to their emergence. It then delves a little deeper into the conditions of possibility of these markets, by examining two examples of what it takes to make the entities traded in these markets 'the same'. The examples are how the destruction of one gas in one place is made commensurate with emissions of a different gas in a different place, and how accountants have sought (so far with only limited success) to make 'emission rights' equivalent. Finally, the article discusses the issue of politics: the question of the attitude that should to be taken to carbon markets (for example by environmentalists, especially those who conceive of themselves as opponents of 'capitalism'), and the tightly-related issue of the process of market design viewed, as it has to be, as politics.

Although the article draws upon the 'finitist' perspective sketched briefly below (see Barnes, Bloor, & Henry, 1996; Hatherly, Leung, & MacKenzie, submitted for publication), its approach is prompted by the view of economic life suggested by the 'actor-network' theory of Michel Callon and Bruno Latour (for which see, for example, Latour, 2005). In Callon's and Latour's view, the characteristics of an 'actor' – a term which, follow-

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ing semiotics (especially Greimas, 1987), they view as encompassing more than just human beings – are not intrinsic, but are the result of the networks of which the actor is made up and forms part. What we call 'capitalism', for example, is not an entity with fixed characteristics. 'Que faire contre le capitalisme?', they write: 'D'abord évidemment *ne pas y croire*' (Callon & Latour, 1997, p. 67). What is to be done against capitalism? First of all, of course do not believe in it.

In Callon's and Latour's view, economic life is 'performed' – framed and formatted – by 'economics at large', a term that encompasses not just the academic discipline but also economic practices such as accounting and marketing (Callon, 1998, 2007). The characteristics of economic actors and of markets arise from, amongst other things, the 'dispositifs de calcul' (Callon & Muniesa, 2003) – the calculative mechanisms – of which they are made up.

If the characteristics of 'capitalism' are not inherent, they can be changed by changing the calculative mechanisms that constitute it. The markets in greenhouse-gas emissions that are being constructed globally are a set of experiments (Muniesa & Callon, 2007) in the validity of this prediction. Hitherto, greenhouse-gas emissions have been, in economists' familiar terminology, an 'externality': from the viewpoint of the emitter, they bore no cost, and so did not figure in emitters' economic calculations. The goal of a carbon market is to bring emissions within the frame of economic calculation by giving them a price. In such a market, emissions bear a cost: either a direct cost (because allowances to emit greenhouses gases need to be purchased), or an opportunity cost (because allowances that are not used to cover emissions can be sold, or because credits can be earned if emissions are reduced below 'business as usual'). A carbon market is thus an attempt to change the construction of capitalism's central economic metric: profit and loss, the 'bottom line'.

The experiments in carbon-market construction have scarcely begun, so the validity of the prediction that capitalism can be 'civilized' (Latour, forthcoming) by changing calculative mechanisms remains undecided. We do not yet know whether the bottom line will be changed to any substantial extent, in particular to an extent sufficient to keep global warming below the threshold (uncertain and fiercely contested, but often taken to be 2 °C) beyond which the risk of severe impacts rises sharply (Schellnhuber, 2006).

In consequence, this paper is necessarily preliminary. The empirical material on which I am drawing is limited. It consists primarily of a set of 24 interviews conducted with people involved with carbon markets (particularly with the European Union Emissions Trading Scheme) as market designers, as carbon traders and brokers, or as members of NGOs seeking to influence the evolution of carbon markets. This interview material is supplemented by analysis of relevant documents such as monitoring reports and contributions to the debate in accountancy touched on below.

The article's main aim is simply to help broaden social-science research on carbon markets, both in terms of its disciplinary base (though their origins lie in economics, carbon markets cannot be understood by the conventional tools of that discipline alone) and in terms of its empirical focus. In that latter respect, I hope to show that it is productive to investigate not just overall questions such as the reasons why policy-makers might choose carbon markets rather than other tools to combat global warming, but also the specifics of how carbon markets are constructed. Whether or not carbon markets are environmentally and economically effective depends on such specifics, and the issues involved are various and demand inter-disciplinary treatment. One of the two topics examined below – how different gases are made commensurable – is a natural question for the social studies of science and technology; the other – how to find a standard treatment of 'emissions rights' – is a question obviously suitable for researchers in accounting. Although for reasons of space I do not discuss them here, questions for other disciplines can also easily be identified: for example, vastly more needs known about how emission reduction projects in developing countries actually work in practice, a question that raises issues ranging from how verification is conducted to the impact of projects on local communities and local environments. Investigating such issues in genuine depth requires the skills of, amongst others, anthropologists and other area specialists.

Because the specifics of market design matter, I make no apology for the fact that this article touches upon matters of apparent detail. The commensurability of gases and the accounting treatment of emission rights are inevitably 'technical' questions, and those technicalities cannot altogether be

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avoided: they matter to overall outcomes. The commensurability of gases, for example, is crucial to how the world's two main existing carbon markets – the European Union Emissions Trading Scheme and the Kyoto Protocol Clean Development Mechanism – interrelate, while there is at least tentative evidence that the accounting treatment of emissions rights affects firms' behaviour in carbon markets. It is precisely issues of this detailed kind that an effective, inter-disciplinary analysis of carbon markets will need to address.

Carbon markets

Carbon markets come in two main species: 'cap and trade' and 'project-based'.[2] Let me begin with the former. It involves a government or other authority setting a 'cap' – a maximum allowable aggregate total quantity of emissions – and selling or giving the corresponding number of allowances to emitters. The authority then monitors emissions and fines anyone who emits without the requisite allowances. If the monitoring and penalties are stringent enough, aggregate emissions are thus kept down to the level of the cap. The 'trade' aspect of cap and trade arises because those for whom reductions are expensive will want to buy allowances rather than incurring disproportionate costs. The requisite supply of allowances is created by the financial incentive thereby provided to those who can make big cuts in emissions relatively cheaply. They can save money by not having to buy allowances, or (if allowances are distributed free) can earn money by selling allowances they do not need. So, as already noted, emissions, which previously had no monetary cost, now have one.

The origins of the idea of controlling emissions via a cap and trade scheme can be traced to the work of Nobel Laureate Ronald Coase (1960), but a more proximate source is the University of Toronto economist Dales (1968a, 1968b), who first put forward the idea in something like full-fledged form.[3] Emissions markets were implemented in relatively minor and sometimes ham-fisted ways in the 1970s and 1980s, mainly in the United States (see, e.g., Hahn, 1989). It was only in the 1990s that the idea became mainstream.

The crucial development was the start of sulphur-dioxide trading in the US in 1995 (for which see, especially, Ellerman, Schmalensee, Bailey, Joskow, & Montero, 2000; Burtraw, Evans, Krupnick, Palmer, & Toth, 2005). It had been known for twenty years or more that damage to the environment and to human health was being caused by sulphur-dioxide emissions, notably from coal-fired power stations, which react in the atmosphere to produce 'acid rain' and other acid depositions. Numerous bills were presented to Congress in the 1980s to address the problem, but all failed in the face of opposition from the Reagan administration and from Democrats who represented states that might suffer economically from controls on sulphur-dioxide, such as the areas of Appalachia and the mid west in which coal deposits are high in sulphur.

Sulphur trading broke the impasse. It combined a simple, clear goal that environmentalists could embrace (reducing annual sulphur-dioxide emissions from power stations in the US by 10 million tonnes from their 1980 level, a cut of around a half) with a market mechanism attractive to at least some Republicans. The cut was achieved in practice far more cheaply than almost anyone had imagined. Industry lobbyists had claimed it would cost $10 billion a year, while the actual cost was around $1 billion. Allowance prices of $400 a tonne were predicted, but in fact prices averaged around $150 or less in the early years of the scheme. The flexibility that trading gave to utilities helped to reduce costs (by around a half compared to having to meet a standard that imposed a uniform maximum emission rate: see Burtraw et al., 2005; Ellerman et al., 2000) but other factors were equally important. 'Scrubbers' to remove sulphur from smokestacks turned out to be cheaper to install and to run than had been anticipated, and rail-freight deregulation sharply reduced the cost of transportation from Wyoming's Powder River Basin, the main source of low-sulphur coal in the United States (Ellerman et al., 2000).

That the sulphur-dioxide market was, broadly, a success shaped how the Clinton Administration approached the negotiations that led to the 1997 Kyoto Protocol. In the Protocol, the industrialized nations undertook that by Kyoto's 2008–2012 'commitment period' they would have limited their greenhouse-gas emissions to agreed proportions of

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[2] This article concentrates on regulatory markets, largely setting aside the 'voluntary' market, in which, for example, firms choose to 'offset' their emissions, even though they are under no compulsion to do so: see, for example, Bumpus and Liverman (forthcoming).

[3] The history of emissions trading will be treated in more detail in MacKenzie (submitted for publication). The brief account given here draws upon that in MacKenzie (2007).

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their 1990 levels: 93% for the US, 92% for the European Community overall (with varying levels for its member states), and so on.

At the insistence of the US, Kyoto gave its signatories sulphur-like flexibility in how to meet their commitments. The Protocol contains provision for a cap and trade market between nation-states. States with caps they will exceed can pay others that in the commitment period are emitting less than their caps for their unneeded 'Kyoto units' (quantities of carbon dioxide or their equivalents in other gases: see below). Just how much trading of such units between nation-states there will be remains to be seen: it is possible it will be quite limited. More significant so far have been two other Kyoto mechanisms – 'Joint Implementation' and, especially, the 'Clean Development Mechanism' (CDM) – which are project-based schemes, not cap and trade.

Let me concentrate on the CDM (for which see, for example, Lecocq & Ambrosi, 2007), which is the more important of the two. It is a crucial – perhaps *the* crucial – aspect of the Kyoto Protocol (Grubb, 1999), crystallizing the political compromise at the Protocol's heart, between the refusal of developing countries to take on emissions caps and the Clinton Administration's conviction that global emissions could be restrained far more cheaply if the developing world were part of the Kyoto regime. The CDM allows the creation of Kyoto units from projects in developing countries approved by the Executive Board of the CDM (a body established under the United Nations Framework Convention on Climate Change).

To gain approval, it must be shown that a project is 'additional' (that it would not take place without CDM funding) and that it will reduce emissions below the 'baseline' level they would have been at without the project. A developing world entity, or industrialized-world government, corporation, bank or hedge fund can then earn the difference between emissions with and without the project in the form of a specific type of Kyoto units: 'Certified Emission Reductions' (CERs). A CER is a credit, not a permit or allowance: it does not *directly* convey any right to emit. However, some governments are purchasing CERs as a way of meeting their Kyoto caps, and crucially CERs also have monetary value because the European Union permits its member states to issue allowances in the most important cap and trade market, the European Union Emissions Trading Scheme (ETS), in exchange for the surrender of CERs (European Parliament, Council, 2004). A credit earned in, for example, China or India can thus be transformed into a permit to emit in Europe.

As with the CDM, the ETS, launched in January 2005, was shaped by political exigencies.[4] What pushed Europe towards trading rather than its initial preference, harmonized carbon taxes, was in good part an idiosyncratic feature of the political procedures of the European Union. Tax measures require unanimity: a single dissenting country can block them. Emissions trading, in contrast, counts as an environmental, not a tax matter. That takes it into the terrain of 'qualified majority voting'. No single country can stop such a scheme: doing so takes a coalition of countries sufficiently populous (since voting weights roughly follow population) to form a 'blocking minority'. A plan for a Europe-wide carbon tax had foundered in the early 1990s in the face of vehement opposition from industry and from particular member states (notably the UK), and its advocates knew that if they tried to revive it the unanimity rule meant they were unlikely to succeed. 'We learned our lesson', one of them told me in interview. Hence the shift in allegiance to trading.

In terms of volume of transactions, the ETS is the largest greenhouse-gas market. The scheme has had its difficulties – the over-allocation, violent price fluctuations and 'windfall profits' discussed below – but it saw trades worth $24 billion in 2006 (World Bank, 2007, p. 3). The prospect of 'monetizing' CERs via the ETS is the main driver of investment in Clean Development Mechanism projects, which generated CERs worth $5 billion in 2006 (World Bank, 2007, p. 3). Between them, the ETS and CDM form the core of the world's carbon markets, and it is on them that this paper focuses.

Making things the same: Gases

The political decision to create a carbon market such as the CDM or ETS is not the same as constructing such a market. A new commodity – an emission allowance or emission credit – needs brought into being: defined legally and technically, allocated to market participants, made transferable and tradable, and so on. To give a flavour of what is involved, let me concentrate on one issue: the heterogeneity of the means by which the 'sameness' – the fungibility of allowances and credits – necessary for

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[4] On the emergence of the ETS, see, e.g., Zapfel and Vainio (2002), Christiansen and Wettestad (2003), Damro and Méndez (2003), Wettestad (2005) and Cass (2005).

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Fig. 1. The interface of the gas corrector meter in the input pipe to Edinburgh University's central area combined heat and power plant. Photograph courtesy David Somervell, Estates and Buildings, University of Edinburgh.

a carbon market is brought into being.[5] Consider, for example, two very different sites: the central-area combined heat and power plant of Edinburgh University, situated a couple of hundred meters from my office there, and the refrigerant plant operated by Zhejiang Juhua Co., 6.5 km south of Quzhou City in China's Zhejiang province. How is the activity at one made commensurable with that at the other, so that both can form part of the same market, and CERs at Zhejiang Juhua's plant can be equivalent to the ETS allowances that a European emitter such as Edinburgh University needs?

As its name indicates, the combined heat and power plant in Edinburgh generates electricity (by burning natural gas in a device that resembles a giant car engine), and uses what would otherwise be waste heat to warm up nearby buildings. Because its thermal input capacity is slightly greater than the 20 MW threshold of the European Union Emissions Trading Scheme, this plant became part of the ETS in January 2008. (Most such installations have been part of the scheme since its launch in 2005, but Edinburgh University was exempted from the first phase because of its involvement in an earlier, voluntary UK emissions trading scheme.) CO_2 emissions from the combined heat and power plant are measured using a gas corrector meter (the interface of which is shown in Fig. 1) on the large pipe that takes gas from the national gas grid into the plant. It is called a 'corrector meter' because it samples temperature and pressure, and can thus convert volumes into masses of gas input, which are in turn converted to estimates of CO_2 output using standard multiplication factors.

Zhejiang Juhua Co. is involved in something quite different, the manufacture of HCFC-22 (chlorodiflouromethane), which is used mainly as a refrigerant (especially in air conditioners), though also as a foam blower and as a chemical feedstock. The standard process used to produce chlorodiflouromethane involves combining hydrogen fluoride and chloroform, using antimony pentachloride as a catalyst, and even when optimized the process leads to a degree of 'overfluoridation': trifluoromethane, HFC-23, is produced as well.[6] HFC-23 is, unfortunately, long-lived in the atmosphere and an efficient absorber of infrared radiation; the combination makes it a very potent greenhouse gas.

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[5] On commensuration in the SO_2 market, see Levin and Espeland (2002).

[6] 'HFC-23' and 'HCFC-22' are not standard chemical formulae, but instances of a code, widely used in the refrigerant business, for identifying haloalkanes. The standard formula for trifluoromethane is CHF_3, but 'HFC-23' is how it is referred to in carbon markets.

Until recently, the HFC-23 was discharged into the atmosphere. Now, the Zhejiang Juhua plant's waste gases are fed into a specialised incineration furnace imported from Japan, in which they are mixed with hydrogen, compressed air and steam, burned at 1200 °C using a high-intensity vortex burner, and thus converted to hydrogen fluoride, carbon dioxide and hydrogen chloride. These products pass through a quencher (in which they are cooled rapidly to minimize the formation of dioxins), and the resultant acid solution is either sold or disposed of via a facility for treating fluoric waste (CDM Executive Board, 2007).

As already noted, to gain approval it must be shown that a Clean Development Mechanism project reduces emissions below the 'baseline' level they would have had in the absence of the project, which in many cases is a tricky exercise in establishing a credible counterfactual (Lohmann, 2005): for an introduction to the issues involved, see Michaelowa (2005). In the case of HFC-23 decomposition, however, a straightforward argument has sufficed: without the decomposition process, the HFC-23 would, as already noted, simply have been discharged into the atmosphere (CDM Executive Board, 2007). The amount actually decomposed then needs measured, but in such a way that a connection is kept to the baseline of the HFC-23 that would have been emitted in the absence of the decomposition incinerator. (The quantity of HFC-23 generated is affected by the precise parameters of the HCFC-22 production process, and hence there is a need to reduce the incentive to operate the process in an unoptimized way and generate unnecessary HFC-23 in order to earn credits by destroying it.) So to standard equipment such as flow meters and a gas chromatograph is added a regulation: for each tonne of HCFC-22 produced, there is a maximum mass of HFC-23 whose decomposition can earn credits.[7]

Crucially, the allowable mass of HFC-23 that the measurement devices reveal has been decomposed is then multiplied by 11,700.[8] By decomposing a tonne of HFC-23 in China, one can – via the link between the CDM and ETS – earn allowances to emit 11,700 tonnes of CO_2 in Europe. Certified Emission Reductions are now a major income stream for China's refrigerant plants, and for the Chinese government (which imposes a 65% tax on them, hypothecated for environmental purposes). Indeed, HFC-23 decomposition is the biggest single sector of the Clean Development Mechanism, accounting for 67% of the CERs generated in 2005 and 34% of those generated in 2006 (World Bank, 2007, p. 27). Since the price of CERs is likely to be a chief determinant of the European carbon price – and thus, for example, a major input into electricity prices – the effects of the commensuration are considerable.

The crucial figure, 11,700, is the product of a calculation of the 'global warming potential' (GWP) of HFC-23 published by the Intergovernmental Panel on Climate Change. Set up in 1988 by the World Meteorological Organization and United Nations Environmental Programme, the IPCC has as its remit the establishment of authoritative scientific knowledge about climate change (see Agrawala, 1998a, 1998b). As the IPCC put it in 1990, GWP is '[a]n index... which allows the climate effects of the *emissions* of greenhouse gases to be compared. The GWP depends on the position and strength of the absorption bands of the gas, its lifetime in the atmosphere, its molecular weight and the time period over which the climate effects are of concern' (Houghton, Jenkins, & Ephraums, 1990, p. 45). Although very similar notions are to be found in the scientific literature of the time (see, e.g., Lashof & Ahuja, 1990), it was the IPCC itself that gave 'global warming potential' its canonical definition

$$\mathrm{GWP} = \frac{\int_O^{\mathrm{TP}} a_x[x(t)]\mathrm{d}t}{\int_O^{\mathrm{TP}} a_r[r(t)]\mathrm{d}t}$$

x designates the gas in question (e.g., HFC-23). a_x is an estimate of the effect on the radiation balance at the tropopause (the boundary of the upper and lower atmosphere) of an increase in the amount of gas in the atmosphere, an effect measured in watts per square meter per kilogram. $x(t)$ is the mass of the

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[7] The mass of HCFC-22 produced (which is determined by weighing shipping containers and storage tanks) determines the 'eligible quantity' of HFC-23: the quantity for the incineration of which credits can be earned. For each tonne of HCFC-22 produced by the standard antimony pentachloride process, the eligible quantity of HFC-23 is 0.0137 tonnes, corresponding to the lowest recorded emission level from a process optimized to minimize HFC-23 production (see McCulloch, 2005, p. 11). The mass of gas fed into the incinerator is determined from the readings of a flow meter, and the concentration of HFC-23 in it is determined by gas chromatography of periodic samples. (A correction for leakage is also applied.) The product of mass of gas (in tonnes) and HFC-23 concentration, up to the maximum given by the eligible quantity, is, as noted in the text, then multiplied by 11,700 to give the quantity of Certified Emission Reductions earned (SGS United Kingdom Ltd., 2007).

[8] I am grateful to Thomas Grammig and to members of the audience of a talk I gave at the University of Oxford for sparking my interest in how gas equivalents are brought into being.

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gas that will remain in the atmosphere at time t from 1 kg released at time zero. TP is the overall time period in question: in the calculation in the HFC-23 commensuration, it is 100 years. The denominator is the equivalent integral for the reference gas, CO_2.

The expressions in this equation inscribe complex processes. $r(t)$, for example, is not (and obviously could not be) determined by releasing a kilogram of carbon dioxide and measuring what happens over a century: it is a mathematical function generated from a standard model (the Bern model: see, e.g., Siegenthaler & Joos, 1992) of the exchange of carbon between the atmosphere, the oceans and the terrestrial biosphere. a_x and a_r, likewise, are in part the products of sophisticated spectroscopic studies, recorded largely in a database managed by the Harvard–Smithsonian Center for Astrophysics. (The database was originally a military project, designed to enhance understanding of absorption of infrared radiation with a view to improving the detection of heat sources: see Taubes, 2004.) But a_x and a_r also assume a scenario that is believed to be helpful in predicting the climatic impact of a gas. In this scenario, temperatures in the stratosphere, which are understood as adjusting relatively quickly to such perturbations, have done so, while temperatures in the lower atmosphere and at the earth's surface (which adjust only slowly) have not.[9] Again, the scenario cannot be observed empirically, so modelling as well as spectroscopy is involved in the determination of a_x and a_r.

In 1990, the IPCC felt able to offer estimates of the GWPs of only 19 gases, not including HFC-23, and it labelled the figures 'preliminary only' (Houghton et al., 1990, p. 59 & Table 2.8, p. 60). By 1995–1996, the list had expanded to 26, and included HFC-23, the GWP of which was estimated as 11,700 (Houghton et al., 1996, table 2.9, p. 121). Both the notion of 'global warming potential' and the IPCC's mid-1990s estimates of GWPs were then inscribed into the Kyoto Protocol, which laid down that they should be used to translate emissions of other greenhouse gases into their equivalents in CO_2 and that the IPCC's mid-1990s estimates should be used until the end of the 2008–2012 commitment period.[10]

The 'exchange rate' of 11,700 used to translate HFC-23 into CO_2 is thus an example of 'black-boxing' in the sense of Callon and Latour (1981) and MacKenzie (1990, p. 26). GWPs could be contested in at least two senses. First, whether GWPs really give the best estimates of the climatic effects of different gases could be and has been challenged (see Shackley & Wynne, 1997, and also Shine, Fuglestvedt, Hailemariam, & Stuber, 2005, and the literature cited in the latter): for example, the choice of a 100-year time period is in a sense arbitrary, and very different GWPs can be generated if, for example, 25, 50 or 500 years is used.[11] Second, GWP estimates were acknowledged to be subject to significant uncertainties, of the order of ±35% (Houghton et al., 1996, p. 73, 119). By 2007, for example, the consensus estimate of the global warming potential of HFC-23 had increased from 11,700 to 14,800 (Intergovernmental Panel on Climate Change, 2007, p. 212). Neither of these two forms of challenge, however, has spilled over into the carbon market. GWPs, with their apparent simplicity and the black-box 'possibility of use by policy-makers with little further input from scientists' (Shine et al., 2005, p. 297) remain the way in which different gases are made commensurable, and the inscription of the mid-1990s' estimates of GWPs into the Kyoto Protocol means that uncertainties and the changing estimates of GWPs remain inside the black-box: a matter for technical specialists, not carbon traders.

This black-boxing is crucial to allowing carbon markets to encompass greenhouse gases other than CO_2: liquidity in such markets would be greatly reduced if the relevant 'exchange rate' between gases had to be negotiated *ad hoc* for each

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[9] 'The long-term forcing is…more accurately represented by that acting after the stratosphere has returned to a state of global-mean radiative equilibrium. Studies with simple models show that the climate response, that is, the surface temperature change, is proportional to the radiative forcing when the radiative forcing is defined in this way… Importantly, the proportionality constant is found to be the same for a wide range of forcing mechanisms' (Pinnock, Hurley, Shine, Wallington, & Smyth, 1995, p. 23227).

[10] See article 5, paragraph 3 of the Kyoto Protocol, the text of which is available at http://unfccc.int/resource/docs/convkp/kpeng.html. Accessed 24.03.06.

[11] Amongst other criticisms is 'the fact that, despite its name, the global *warming* potential does not purport to represent the impact of gas emissions on temperature. The GWP uses the time-integrated radiative forcing and this does not give a unique indication of the effect of pulse emissions on temperature, because of large differences in the time constants of the various greenhouse gases. Although a strong greenhouse gas with a short lifetime could have the same GWP as a weaker greenhouse gas with a longer lifetime, identical (in mass terms) pulse emissions of the two gases could cause a different temperature change at a given time. Economists have also criticised the GWP concept for not being based on an analysis of damages caused by the emissions' (Shine et al., 2005, p. 282).

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transaction. Note that the black-boxing rests upon a 'social' factor: the authority of the Intergovernmental Panel on Climate Change. Although that authority has been challenged by climate change 'sceptics' and 'deniers', public controversy has focused on the reality, extent of and evidence for anthropogenic climate change, not on matters of 'detail' such as GWPs, debate over which has taken place only in much more limited circles. The IPCC's authority in such detailed matters is thus an essential part of 'making things the same' in carbon markets, by keeping the 'exchange rates' between gases inside the black-box and separate from political and economic disputes.

It is perfectly possible, however, that this black-boxing may become harder in the future. At the time of the Kyoto Protocol, it is unlikely that anyone imagined that the figure of 11,700 for the global warming potential of HFC-23 would determine a flow of funds of the order of $3.5 billion (the likely total value of credits from HFC-23 decomposition up to 2012: see Wara, 2007). As negotiations begin over a successor to Kyoto, however, the financial consequences of such figures can now be seen. It is possible that GWPs will remain in practice unchallenged – it would be very hard, given the diversity of economic interests involved, to get agreement on a measure other than GWPs, or on anything other than the IPCC's estimates of them (which are a 'focal point' in game-theoretic terms), so no party to the negotiations may attempt to do so – but it is not a foregone conclusion.

Making things the same: 'Emission rights'

Gases are thus made the same by a combination of measurement devices, complex natural science, and the capacity (at least so far) of the Intergovernmental Panel on Climate Change to keep the estimation of global warming potentials bracketed off from carbon-market politics. But practices of many other kinds are also needed to make 'carbon' fungible, and amongst these accounting is of particular importance.[12] The European allowances that Edinburgh University needs to emit carbon dioxide and the CERs generated by Zhejiang Juhua Co. are items that Europe's (or indeed China's) accountants have not previously encountered. What kind of items are they? What accounting treatment should they receive? These questions are significant for the operation of carbon markets, since accounting makes economic items visible, and whether and how it does so is consequential.[13]

Hatherly et al. (submitted for publication) argue that a 'finitist' perspective is useful for the analysis of accounting, especially of accounting classification, and it is particularly appropriate here. In this perspective, how to classify an item (not just an accounting item, but an item of any kind) is always implicitly a choice. Past classifications – which are always finite in number, hence 'finitism' – influence present classifications by analogy ('this item is like previous items we classified as X, so this should be classified as an X'), but do not determine them.

Of course, classification often does not *feel* like a choice. Classifiers – bookkeepers, accountants, ornithologists, botanists, and so on – often, probably normally, come across items that seem familiar and simply 'see' them as an X ('this *is* an X', not 'I am classifying this as an X'). Items that seem to classifiers to be unfamiliar are thus of particular analytical interest, because they make implicit choice explicit. Instead of relying on habit and routine, those involved have consciously and explicitly to decide what classification is appropriate, and the debate that is often sparked can reveal the contingencies that affect classification.

In the run-up to the launch of the European Union Emissions Trading Scheme, the International Financial Reporting Interpretations Committee (IFRIC), a subsidiary body of the International Accounting Standards Board, discussed how to apply accounting standards to the new items, which it called 'emission rights', which were about to come into being. What kind of items were they? For example, were they indeed 'rights'? The IFRIC concluded that they were not: 'an allowance itself does

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[12] I am deeply grateful to Allan Cook, who served as Coordinator for the International Financial Reporting Interpretations Committee at the end of the period in question for his help in the research underpinning this section. Cook (forthcoming) is his own account of these events. For broader legal debate over the nature of carbon credits and allowances, see, Wemaere and Streck (2005).

[13] The issue of devising appropriate frameworks for making carbon emissions 'visible', for example in corporate accounts, has received considerable attention: see, for example, the work of Fred Wellington and his colleagues at the World Resources Institute (such as Lash & Wellington, 2007) and The Prince's Charities (2007). How to account for emissions allowances, however, has received much less attention: see Cook (forthcoming) and Casamento (2005).

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not confer a right to emit. Rather it is the instrument that must be delivered in order to settle the obligation that arises from emissions' (IFRIC, 2004, p. 19).[14]

An allowance was, however, in the IFRIC's view clearly an asset. But what was its nature? Was it an 'intangible asset' – 'An identifiable non-monetary asset without physical substance' (IASB, 2005, p. 2227) – and thus within the scope of International Accounting Standard (IAS) 38? Or was it a 'financial instrument' – a 'contract that gives rise to both a financial asset of one entity and a financial liability or equity instrument of another entity' (IASB, 2005, p. 2219) – and thus within the scope of the standard governing such instruments, IAS 39? Some of those who commented on the IFRIC's initial draft argued that an allowance was indeed a financial instrument, but the IFRIC disagreed: though allowances 'have some features that are more commonly found in financial assets than in intangible assets' – such as being 'traded in a ready market' – they were not financial instruments (IFRIC, 2004, p. 21).

An allowance was thus, in the IFRIC's view, an intangible asset, and therefore governed by IAS 38. If governments issued allowances at less than their market value (most have issued them free-of-charge) the difference was, IFRIC decided, a 'government grant', and its accounting treatment should therefore follow the relevant standard, IAS 20. Emissions themselves – as noted, previously outside an economic or accounting frame – now had to come within it. The emissions of those governed by cap-and-trade schemes should, said the IFRIC, be treated as giving rise to liabilities that were 'provisions' whose treatment should follow IAS 37 (IFRIC, 2004, p. 7).

The IFRIC's conclusions – crystallised in *IFRIC Interpretation 3: Emission Rights*, issued in December 2004, on the eve of the start of the European Union Emissions Trading Scheme – thus made 'emission rights' the same by laying down a homogeneous approach to accounting for them, in which, for example, an allowance received free by an industrial company or bought by an investment bank were both treated in the same way as intangible assets. However, IFRIC 3 encountered strong opposition, with critics arguing that the relationship of IFRIC 3 to the three relevant standards – IAS 20, 37 and 38 – would create accounting mismatches, especially in the light of anticipated changes to IAS 20, which if made will mean that non-repayable government grants have to be recognized when they are received (see Cook, forthcoming). For example, the fair value of the allowances that a company received free would have to be recognized immediately as income, while the costs of the corresponding emissions would be recognized only gradually as they accumulated.

Reflecting the criticism of IFRIC 3, the European Financial Reporting Advisory Group told the European Commission in June 2005 that the interpretation 'will not always result in economic reality being reflected', and recommended that the Commission not endorse it.[15] The following month, the International Accounting Standards Board, while defending IFRIC 3 as 'an appropriate interpretation' of existing accounting standards, acknowledged that it 'creates unsatisfactory measurement and reporting mismatches' and withdrew it.[16]

There was, of course, a 'bottom line' issue underpinning the controversy surrounding IFRIC 3. Corporations generally fear earnings volatility: there is a widespread conviction that investors prefer earnings that rise smoothly to those that fluctuate, even around the same underlying trend. IFRIC 3 threatened to produce volatility that, in its critics' eyes, would be artificial. For example, the advantage, for corporations, of classifying an 'emission right'

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[14] 'It therefore follows that a participant in a cap and trade scheme does not consume the economic benefits of an allowance as a result of its emissions. Rather a participant realises the benefits of that allowance by surrendering it to settle the obligation that arises from producing emissions (or by selling it to another entity). Therefore, the IFRIC observed that amortisation, which is the systematic allocation of the cost of an asset to reflect the consumption of the economic benefits of that asset over its useful life, is incompatible with the way the benefits of the allowances are realised. Although the IFRIC agreed that this observation pointed to precluding amortisation, it agreed with those respondents who highlighted that in some cases such a requirement could be inconsistent with the requirements of IAS [International Accounting Standard] 38. The IFRIC therefore decided not to proceed with its proposal... that allowances should not be amortised. Nonetheless, for most allowances traded in an active market, no amortisation will be required, because the residual value will be the same as cost and hence the depreciable amount will be zero.' (IFRIC, 2004, pp. 22–23).

[15] Letter from Stig Enevoldsen to Alexander Schaub, 6 May 2005. Available from http://www.iasplus.com/interps/ifric003.htm. Accessed 11.07.07.

[16] International Accounting Standards Board, 'IASB withdraws IFRIC Interpretation on Emission Rights', available from http://www.iasplus.com/interps/ifric003.htm. Accessed 11.07.07.

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as a financial instrument would have been that it would make available the 'hedge accounting' treatment permitted under IAS 39. If allowances could 'be treated as the hedging instrument of a forecast transaction (ie future emissions)' (IFRIC, 2004, p. 20), then allowances and the corresponding emissions would offset each other. If a company received *N* free allowances, forecast emissions of *N* tonnes of carbon dioxide, and emitted *N* tonnes, then its earnings would at no point be affected. 'Carbon' would thus remain invisible.

The withdrawal of IFRIC 3 means that it remains permissible to treat carbon in this way: as inside an economic frame, but in a sense invisibly so, since no accounting recognition is needed if the above conditions are met. A survey by Deloitte (2007) found that some market participants were doing just that. Others were in effect following IFRIC 3, while others again were doing so partially, treating the provision for the liability created by emissions in a different way.[17] The attempt to make 'emission rights' the same has, in this sense, so far failed.

The partial invisibility of carbon also means that the incorporation of the carbon price into the market's 'calculative mechanisms' (Callon & Muniesa, 2003) is only partial. Although it is impossible to be certain, there is tentative evidence from my interview data of effects of both the accounting visibility of carbon in some firms and its invisibility in others. Consider, for example, the effect of the European Union Emissions Trading Scheme on electricity prices. If allowances are distributed free, one might naïvely think that they should have no effect on the price of electricity. If a generator is given enough allowances to cover its emissions (most generators have actually had to buy some allowances, but let me set that aside), what it charges customers surely shouldn't change? An economist will quickly tell you what's wrong with that argument. As already noted, there's an opportunity cost involved. In a 'perfect market', a profit-maximizing firm will produce electricity only if the price it receives is greater than what it can earn by not generating electricity and selling its stocks of the required inputs: its coal, its gas, and now its carbon allowances (Point Carbon, 2007, pp. 24–25). If its allowances can command a non-zero price, the price of electricity must rise correspondingly.

According to an interviewee in the electricity market, however, it has required accountants to give force to this economists' reasoning. The 'naïve' view prevailed in the industry until explicit valuations of allowances started to be made. The price effect 'should' have been manifest in forward contracts covering supply from January 2005 (the start of the ETS) onwards, but apparently it initially was not.[18] The effect began in the UK only once January 2005 was reached, and analysis by the consultancy Point Carbon (2007) suggests it was even slower to appear on the Continent. (Once the effect began, the result in the UK was, for example, an increase in domestic electricity prices in 2005 of around 7%[19] – for example, about £20 on a £300 annual bill – and it is increases of this kind that are the source of the much-criticized 'windfall profits' that electricity generators have made from the Emissions Trading Scheme.)

Carbon has thus been 'visible' for some time in the electricity sector. When, in contrast, carbon is kept invisible in accounting terms effects of three

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[17] Deloitte (2007) does not estimate the relative prevalence of the three forms of accounting treatment. Those in the third category 'recognise a provision on the following bases: To the extent that the entity holds a sufficient number of allowances, the provision should be recognized based on the carrying value of those allowances (i.e., the cost to the entity of extinguishing their obligation). To the extent that the entity does not hold a sufficient number of allowances, the provision should be recognized based on the market value of emission rights required to cover the shortfall; and the penalty that the entity will incur if it is unable to obtain allowances to meet their obligations under the scheme, and it is anticipated that the penalty will be incurred (note that the obligation to deliver allowances must still be fulfilled).' (Deloitte, 2007, p. 3)

[18] This is an interviewee's assertion. Unfortunately, I do not have access to the price data needed to test it quantitatively.

[19] Calculation by Karsten Neuhoff, quoted on BBC Radio 4, 'File on Four', 5 June 2007. Controversy is growing across Europe about these 'windfall profits'. In the UK, for example, the energy regulator Ofgem has called for the windfall profits of the UK's electricity generators in the 2008–2012 phase of the Emissions Trading Scheme – which Ofgem estimates at £9 billion – to be used to help customers in fuel poverty (Crooks, 2007). In Germany, the Bundeskartellamt (Federal cartel office) charged electricity generator RWE with behaving illegally by incorporating in the price it charged industrial consumers the market value of permits it had received free. The case was settled out of court in September 2007, with RWE continuing to defend its pricing but agreeing that in 2009–2012 it would hold annual auctions of quantities of power almost equivalent to its annual sales to German industry (46,000 GWh in total over the 4 years) and transfer to the purchasers, free of charge, the corresponding carbon allowances if it had received these at no cost (RWE AG, 2007).

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kinds can be anticipated. The first, which is hypothetical (I have no direct evidence on the point), would be to undermine a major desired effect of a carbon market: incentivizing even those companies which have 'enough' allowances to cut their emissions so as to generate income by selling allowances. For this effect to be realized, allowances need to be seen as assets with potential monetary value, not simply as means of complying with regulatory requirements. The second, related effect (of which there is some tentative evidence) is to delay the sale of allowances by those who, even without abatement, have more allowances than they need. The sale of allowances – and also lending allowances for short sale – means that they can no longer be kept invisible. They must be recognized in accounting terms, and, for example, a tax liability may be crystallized. This disincentive may reinforce other reasons for not selling, such as the fact that emission levels will in general be known in advance only approximately and the lack of a culture of proprietary, risk-taking trading in many industrial companies (in contrast to electricity suppliers, which are active traders) that would permit the sale of allowances that probably – but not certainly – will not be needed.

Source: Point Carbon

Fig. 2. Price history of allowances, phase I of European Union Emissions Trading Scheme. Courtesy Point Carbon.

My interview data do not permit me to judge the relative importance of the various reasons for postponing the sale of allowances that are likely to be surplus to requirements, but those interviewees with whom I explored the topic all believed delayed sale to be a real phenomenon. It has been consequential because the complex process of setting national allocations for the first phase (January 2005–December 2007) of the European scheme led to over-allocation of allowances. The extent of over-allocation was, however, not clear initially, and the failure of those who were 'long' allowances to bring them to market led to a constriction of supply, which helped market prices to rise to €31/tonne (see Fig. 2). Curiously, when the extent of over-allocation became clear in the spring of 2006, prices – though plunging dramatically – did not initially fully reflect the fact that allowances no longer had any significant economic value. It took several months for the market price of a phase-one European allowance to fall close to zero (only in 2007 did prices become in effect zero, with allowances towards the end of the year costing less than €0.10/tonne). Interviewees suggested that delayed sale by those who were 'long' allowances accounts for this paradoxical behaviour of the carbon price. Even though it was clear that allowances were intrinsically close to worthless (because, in aggregate, there were more of them than would be needed), they still commanded a price of several euros, because not enough were brought to market.[20]

The third – again hypothetical – effect of the accounting invisibility of carbon may be to strengthen the hand of managers whose interests lie in protecting market share by not passing on to customers the opportunity cost of allowances that have been allocated free, even when passing on the cost is profit-maximizing for their firms. The extent to which firms pass on the opportunity cost is crucial to the environmental effects of a cap-and-trade market – if they pass it on, there is likely to be carbon 'leakage' from the scheme, as imports from outside its boundaries become more attractive – and there is fierce controversy over likely behaviour in this respect. Economists tend to predict profit-maximization, cost pass-through and thus leakage, while firms themselves tend to argue that market share will be protected and costs will not be passed through, at least in full. Unfortunately, empirical analysis of the Emissions Trading Scheme so far is too limited to be confident how firms outside the electricity sector have behaved in this respect: see Carbon Trust (2008).

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[20] One interviewee, at a hedge fund, reported making a considerable amount of money by taking a short position in allowances in this period.

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The politics of carbon markets

One could go deeper into the issue of fungibility, of making things the same. A trade, for example, is a legal transaction requiring documentation, and with three bodies (the International Swaps and Derivatives Association, the European Federation of Energy Traders, and the International Emissions Trading Association) competing in this sphere, interviewees reported that it has taken orchestrated action to reduce the differences to a level at which a trade documented in one format can be regarded as similar enough to one documented in another, for example for one to be used to hedge the other. There has also, for instance, been sharp criticism from competitors of the efforts by Barclays Capital, a leading player in the carbon market, to standardise CERs via its SCERFA (Standard CER Forward Agreement). The competitors regard a SCERFA as specific to Barclays, not as a 'standard' entity.

Instead, however, let me consider the question of the attitude to be taken to carbon markets. There is a great deal of suspicion of them, ranging from rightwing distaste for emissions caps to leftwing hostility to an extension of market relations. The efforts at market construction so far have led to some environmental benefits – for example, because of HFC-23's potency, curbing emissions of it is very valuable – but also significant problems. There has, for example, been only modest abatement by Europe's electricity producers (the sharp rise in gas prices in 2005–2006 swamped any carbon-price incentive to switch from coal to gas), while the mechanism discussed above led them, as noted, to make substantial windfall profits.

Similarly, the large sums that can be earned by decomposing HFC-23 also create substantial profits, because the costs of decomposition are modest. A specialized incinerator of the kind needed costs around $4–5 million to install and $20,000 a month to run (McCulloch, 2005, p. 12). Even with China's 65% tax, a large HCFC-22 plant can recoup the installation cost in a few months and go on to earn revenues of well over a million dollars a month. There is debate over just how much the subsidy increases HCFC-22 production: McCulloch (2005) argues that because the cost of HCFC-22 is only a small proportion of the costs of the products in which it is used,[21] a reduction in the price of HCFC-22 will not expand the market for it very much. However, the *de facto* subsidy may slow the replacement of HCFC-22 by more environmentally friendly refrigerants. (HCFC-22 is an ozone depleter, the use of which as a refrigerant will eventually be phased out under the Montreal Protocol governing such substances, and it is also a greenhouse agent, though not as potent as HFC-23.) Because of fears of this kind, 'new' HCFC-22 production (i.e., over and above 2000–2004 levels) is currently not eligible for CDM credits, but the consequence is that there is no economic incentive not simply to discharge HFC-23 from such new production into the atmosphere rather than decomposing it.

In the light of issues such as these, it is tempting to conclude that carbon markets are inherently flawed means of achieving abatement. As Callon (1998) points out, constructing a market requires an enormous degree of 'cooling': of knowledge, of metrologies, of actors, of identities, of interests. In a perceptive article, Lohmann (2005, pp. 211 and 229) applies Callon's analysis to the carbon market and essentially concludes that market construction will indeed fail: 'conditions are not cool enough for the spadework for commercial relations', and 'an unstoppable fount of complexity' has been uncorked.

Indeed, much of what I have described is consistent with a bleak, essentialized view of capitalism, as inherently irresponsible and environmentally damaging, rather than Callon and Latour's more optimistic perspective. Yet the conclusion that carbon markets are inherently flawed carries a risk. Abandonment of such markets might well mean no serious international abatement efforts, rather than abatement by other means. If the Emissions Trading Scheme were abandoned, could the European Union find a viable alternative, and how long would it take? The political viability of a harmonized carbon tax, the obvious other route, remains questionable, because of the unanimity required.

Similarly, political constraints mean that if international agreement on a replacement for the Kyoto Protocol can be reached, it is likely to include something similar to the Clean Development Mechanism. The CDM is, as noted, a result of the need to secure developing-country participation in abatement efforts in a context in which the developing world was and is unwilling to take on caps: even caps postponed to a later date, given the risk that by then many of the cheaper opportunities for abatement might be exhausted. The reluctance is understand-

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[21] An air conditioning unit retailing at $500–1000 needs less than a kilogram of HCFC-22, which costs around $1–$2 (McCulloch, 2005, p. 7).

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able, given the desire not to allow a problem caused by the industrialized countries to serve as a brake upon development, and it is likely to persist – even in a context in which China, in particular, no longer fits the traditional template of a developing country. Abatement efforts in the developing world are thus likely to continue to require funding from the developed world. Of course, such funding could be achieved by direct government aid – Wara (2007) points out that HFC-23 decomposition could have been achieved far more cheaply via this route than via the CDM – but that again raises the question of whether governments would in practice make the requisite large transfers of resources.[22]

To conclude that carbon markets must fail may also be unduly pessimistic, in that it would miss the extent to which carbon markets hitherto have been experimental, in the case of phase 1 of the European Union Emissions Trading Scheme, quite explicitly so: interviewees involved in establishing it reported the many compromises that had to be made to get it up and running, such as the fact that it was possible to challenge only the most egregiously over-generous national allocations of allowances. While existing carbon markets unquestionably have major flaws, those flaws are increasingly becoming manifest, and ways of remedying them are available. Thus, windfall profits within the European scheme could be eliminated by moving from free allocation to full auctioning (Dales's original proposal), and there is now a real possibility that this will happen from 2013 on, at least in the electricity sector.

If carbon markets are here to stay, can they be improved? One example of a successful intervention is of particular interest from the viewpoint of this paper, because it involves making things *not* the same. NGOs, especially the World Wildlife Fund, have sought to create a separate category of 'gold standard' CERs, covering only renewable energy and energy conservation projects, and excluding industrial gas projects such as HFC-23 decomposition.[23] The gold standard is a form of cooling in Callon's sense (as with the CDM as a whole, there is a formal methodology, automated tools, a role for auditors, and so on), and there are 'bottom-line' effects. Although from the viewpoint of the Kyoto Protocol or of monetizability via the European Emissions Trading Scheme, an ordinary and a gold standard CER are identical, my interviewees reported that the market price of the latter is now around 10–20% higher. (They suggest that the cause of the higher price is that those who are buying CERs not just for compliance but to achieve 'carbon neutrality' or other forms of offsetting fear reputational risk if it is discovered that 'neutrality' is being achieved via industrial gas projects such as HFC-23.) 'Multiple monies' have emerged in the carbon market, as a result of intervention by activists.

The intervention by the World Wildlife Fund and other NGOs was informal: it did not alter the formal procedures of the CDM. However, NGOs are also seeking to practise a politics of market design in a more formal sense, seeking to alter rules and procedures. That, indeed, is precisely the course of action that Callon and Latour's perspective implies. If markets are plural – Callon's best-known work is titled *The Laws of the Markets* (Callon, 1998) – and 'capitalism' has no unalterable essence, then this may indeed be productive.

Such efforts are too recent and too limited to know whether they will be successful. However, it is worth noting that changes in market design of a kind that seem potentially achievable could be consequential. Take the underlying issue of a carbon market versus a carbon tax. Many environmental activists prefer the latter, as do some economists such as Nordhaus (2007). Nordhaus argues that the classic analysis by Weitzman (1974) of the conditions that influence the relative efficiency of 'quantity-based' instruments (such as a cap-and-trade scheme) and 'price-based' instruments (such as a carbon tax) suggests, given the specific cost-benefit features of combating global warming, the superior efficiency of a carbon tax.

Yet carbon markets seem politically feasible, even in the US; carbon taxes may not be, even in Europe. Intriguingly, however, a cap-and-trade market, with full auctioning rather than free allocation, can be equivalent to an optimally set tax. In both, polluters pay, either by having to buy permits or by paying the carbon tax. Indeed, under admittedly 'idealized conditions' (Hepburn, 2006, p. 229) they pay the same amounts, and the environmental outcomes are the same. Thus, if the relationship between emission levels and the carbon price is known with certainty, either a cap-and-trade market

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[22] For an intriguing suggestion of a means of achieving north–south transfers at a sufficient level to make a significant impact on developing countries' needs to adapt to climate change, see Müller and Hepburn (2006).

[23] See http://www.cdmgoldstandard.org. Accessed 17.01.08.

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or a correctly set tax can achieve a required level of abatement, and the necessary tax rate will be the same as the allowance price. Of course, the relationship between emission levels and the carbon price is not known with certainty, and for that and other reasons the full equivalence between tradable permits and a tax does not pertain in the real world. However, economists' analyses suggest ways of designing a carbon market that might make it and a tax more closely equivalent in practice. These include rules facilitating the 'banking' of permits for future use and the 'borrowing' of permits from future years, regulated perhaps by an adjustable requirement for firms to hold a certain amount of permits in reserve, analogous to the adjustable reserves that banks are required to hold (Newell, Pizer, & Zhang, 2005).

Precisely because of the similarity of auctioning to a carbon tax, emissions markets seem almost always initially to involve free allocation, because this reduces lobbying against them and political opposition. However, once markets are well-established, as the European Union Emissions Trading Scheme now is, shifting to auctioning may become easier (especially now the 'economic experiment' of Phase I of the ETS has made publicly visible the problems that free allocation leads to). For example, in October 2007 Sweden announced that it was ending free allocation of allowances to its electricity and heat sectors.[24] Indeed, as noted above, it seems increasingly likely that in the third phase of the ETS, from 2013 onwards, auctioning may be much more heavily employed, at least for sectors such as electricity that cannot in practice easily move production outside of the European Union.

The effort to shift the ETS to auctioning is 'politics' of a classic, recognizable kind, involving governments, the policy-makers of a supranational body, nation-state representatives, fierce industry lobbying against auctioning, and so on. Not all the politics of carbon markets, however, fits that recognizable template. Neither the IPCC nor the International Accounting Standards Board see themselves as political bodies, and indeed it is of particular importance that the former not be seen as political, despite the efforts of its critics to paint it as such. Yet they are arguably locales of 'subpolitics' in Beck's sense: politics 'outside and beyond the representative institutions of the political system of nation-states' (Beck, 1996, p. 18; see Holzer & Sørensen, 2003). For example, the IFRIC and now the International Accounting Standards Board (which is turning its attention to emission rights) have to contend with pressure that has had the effect of blocking efforts to 'make things the same' in carbon markets. In the case of the IPCC, the key 'subpolitical' matter is, paradoxically, preserving the boundary between 'science' and 'politics', since that boundary is precisely what is needed to facilitate political action, because it matters that action can be seen as based upon 'sound science'.

The subpolitics of carbon markets may seem esoteric, and it is certainly not simple, but it is important. Clearly, such markets are only one tool for combating global warming, and other tools are also important: direct regulation, carbon taxes (where these are feasible), greatly increased public expenditure on research and development and on necessary infrastructure (for example, the electricity grid changes needed to make increased renewables production more attractive economically), the removal of the many subsidies for fossil-fuel extraction and use, and so on (see, for example, Lohmann, 2006; Prins & Rayner, 2007). Nevertheless, making carbon markets more effective is crucial, and the esoteric nature of their subpolitics means that researchers have a particularly salient role to play in bringing to light matters of apparent detail that in fact play critical roles in this respect.

It is this author's hope that this paper will encourage the work of this kind that is so badly needed. The existing and planned experiments in changing capitalism's bottom line are heterogeneous, widely diffused worldwide, and involve many aspects – scientific, technological, political, accounting, sociological, anthropological, geographical – beyond economics as narrowly conceived. The experiments need 'witnesses' (Shapin & Schaffer, 1985), and those witnesses must be multiple: lay as well as professional, from many countries, and if they are academics from many disciplines.[25] Carbon markets need to become part of a process of 'social learning' (qv Williams, Stewart, & Slack, 2005), in which institutions to mitigate climate change are

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[24] Announcement of Environment Minister Anders Calgren, reported by news service Point Carbon (www.pointcarbon.com). 11.10.2007.

[25] I owe this way of formulating the matter to Andrew Barry.

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created, evaluated and reshaped.[26] Such multiple witnessing and social learning needs to concern not just the overall features of carbon markets, but the crucial 'nuts and bolts' of their construction, questions such as how different carbon sources and sinks are commensurated, how allowances are treated in accounting terms, and many other such matters that I have been unable to discuss for space reasons. If this modest paper recruits others to take part in this multiple witnessing and social learning, then it will have achieved its goal.

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[26] There is of course a trade-off between the need to evaluate and improve a market's design and the need for rules that are stable over reasonably long time periods. The European Union's trade-off seems reasonable – an explicitly experimental three-year initial phase, then a five-year second phase, followed by a third phase that is likely to last eight years (2013-20).

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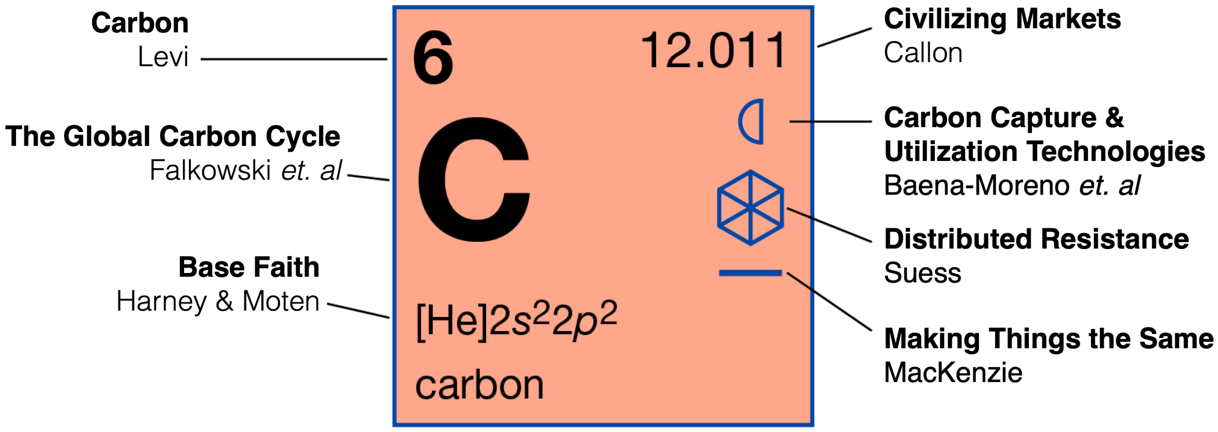

Carbon
Levi

The Global Carbon Cycle
Falkowski *et. al*

Base Faith
Harney & Moten

Civilizing Markets
Callon

Carbon Capture & Utilization Technologies
Baena-Moreno *et. al*

Distributed Resistance
Suess

Making Things the Same
MacKenzie

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