Dealing with carbon dioxide at scale

Sackler Forum, October 2017

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DEALING WITH CARBON DIOXIDE AT SCALE

SACKLER FORUM, OCTOBER 2017

This summary of topics discussed at the Sackler Forum draws on the contributions made by participants at the meeting. It does not reflect a consensus of those present or the sponsoring organisations. However, the observations and vision as laid out here provide an overview of key issues and practical steps to take work in this area forward based on research at the forefront of the field.

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This report can be viewed online at
royalsociety.org/sackler-forum

Cover image © CHEN MIN CHUN.

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Preface

Image (top)
Venki Ramakrishnan, President of the Royal Society.

Image (bottom)
Marcia McNutt, President of the National Academy of Sciences.

Previous Sackler Forums have examined the worldwide food supply, neuroscience and the law, Earth modelling, climate change, cybersecurity and machine learning. This Forum looked in depth at two previously underexplored areas relating to the need to limit carbon dioxide in the Earth's atmosphere. The first of these was the potential to use carbon dioxide as a commodity in industry and manufacturing. Carbon dioxide might be of some value as a resource rather than just a costly and harmful waste. The second was to examine the role of agriculture and forestry in the sequestration of carbon dioxide and whether we could better harness the way plants, crops, trees and soils assimilate carbon dioxide.

The Co-Chairs, Professor Sir John Beddington and Professor Ellen Williams, brought together a distinguished group of speakers and participants including scientists at the forefront of their disciplines in chemistry, physics, biology, and plant and agricultural sciences. The Forum also drew in business leaders, engineers, economists and experts in evaluation to provide a reality check. This was designed to ensure that ideas were scrutinised not simply as an exercise in intellectual curiosity. The Co-Chairs wanted to know, from those on the ground, the potential for the ideas to work in practice – to be delivered at scale, to create business opportunities, and to be embraced by the public.

The Forum, *Dealing with Carbon Dioxide at Scale*, took place on 17 – 19 October 2017 at the Kavli Royal Society International Centre in Buckinghamshire, UK. It highlighted a tantalising and diverse range of technologies and approaches that could make a real difference to dealing with carbon dioxide at scale. The report concludes with the Chairs' vision as to how these scientific possibilities can be seized as opportunities in the real world.

The Raymond and Beverly Sackler USA–UK Scientific Forums have, since their inception in 2008, acted as a fulcrum for the exchange of ideas between thought leaders from the United States and United Kingdom on topics of worldwide scientific concern. In the modern world, science and technology have become engines that drive not only economic growth but also social and environmental change. By establishing the endowment, the Sackler Foundation has made it possible to examine forces that are creating our collective future and shaping the planet on which we live.

The National Academy of Sciences and the Royal Society share a mission to promote the use of science to benefit society and inform important policy debates. As Presidents of the Royal Society and the National Academy of Sciences, we are pleased to introduce the latest piece of work supported through the inspired generosity of the Sackler Foundation.

Overview from the Co-Chairs

Nature of the problem

Earth's climate is changing more rapidly than ever experienced in human history. The main cause of this is the accumulation of carbon dioxide in the atmosphere from burning fossil fuels. Scientists have predicted that a doubling of carbon dioxide in Earth's atmosphere from preindustrial levels would warm the Earth's surface by an average of between 1.5°C and 4.5°C.

The risks that arise from this include rising sea level, more severe and longer lasting droughts and heat waves, more destructive storms, increasing precipitation intensity, and associated disruption of terrestrial and aquatic ecosystems. Natural processes currently remove about half of the carbon dioxide emitted by human activities from the atmosphere each year. It will take thousands of years once emissions cease before those processes eventually return Earth to carbon dioxide concentrations close to preindustrial levels[1] with corresponding reversals of temperature increases. This is because of the long lifetime of carbon dioxide in the atmosphere, the release back into the atmosphere of carbon dioxide previously absorbed into the oceans (which act as a vast storehouse), and heat radiation from the surface of the ocean which may create a lag in the temperature response to reductions in carbon dioxide.

Options available

There are three main choices if society is not to suffer the consequences of climate change. The first of those is mitigation; reducing and eventually eliminating human-caused emissions of carbon dioxide and other greenhouse gases. The second is to adapt by reducing the vulnerability and increasing the resilience of human and natural systems. The third is to intervene by taking actions designed to produce a targeted change in some aspect of the climate system. The most benign such change can be brought about by capturing carbon dioxide at emission sources or by taking it out of the atmosphere and, where possible, using it for beneficial purposes.

The approaches of climate mitigation, adaptation and intervention are closely interrelated. All three require strategic and determined human action. Intervention that captures and repurposes carbon dioxide from the atmosphere for practical use can also be part of mitigation or adaptation approaches.

The potential costs and effectiveness of adaptation remain actively debated, especially with many different types of impact that may arise from climate change. Equally, the extent to which adaptation measures can succeed varies considerably in different regions of the globe.

Consequently, mitigation on a global scale through the decarbonisation of the world economy remains, rightly, the top priority. Yet most projections indicate that it may not be sufficient in itself to stop global mean temperature rising by more than 2°C. To achieve this, by mid-century we need to have intervened through taking steps to capture emissions at their source. In addition, many assessments indicate that we also need to remove carbon dioxide from the atmosphere at a scale of around 5 gigatonnes of carbon dioxide (GT CO_2) annually[2]. Accomplishing these goals requires expanding the existing portfolio of mitigation approaches with additional ideas capable of rapid and sustained implementation.

Image (top)
Professor Sir John Beddington.

Image (bottom)
Professor Ellen Williams.

Three step approach

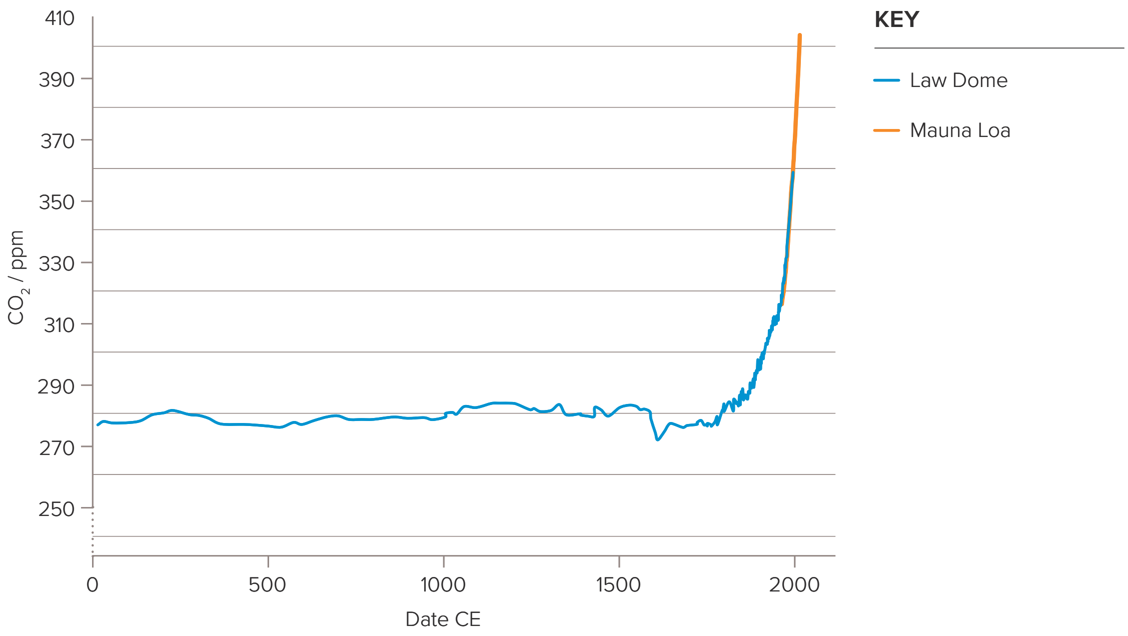
Step 1: Putting the problem in perspective

Human impact on climate change results from industrial, agricultural and other societal emissions of carbon dioxide and other greenhouse gases into the atmosphere. In 2016, these atmospheric emissions globally from fossil fuel and industry alone totalled an estimated 36 Gt CO_2 annually[3].

The global atmospheric carbon dioxide concentration has now passed 400 parts per million (see Figure 1), a level that last occurred about 3 million years ago. At that time, global average temperature and sea level were significantly higher than today. The observed increase in atmospheric carbon dioxide over the past 15 – 20 years has paralleled increases in anthropogenic emissions[4]. According to the World Meteorological Organization, the rate of increase of atmospheric carbon dioxide over the past 70 years is nearly 100 times larger than that at the end of the last ice age[5].

FIGURE 1

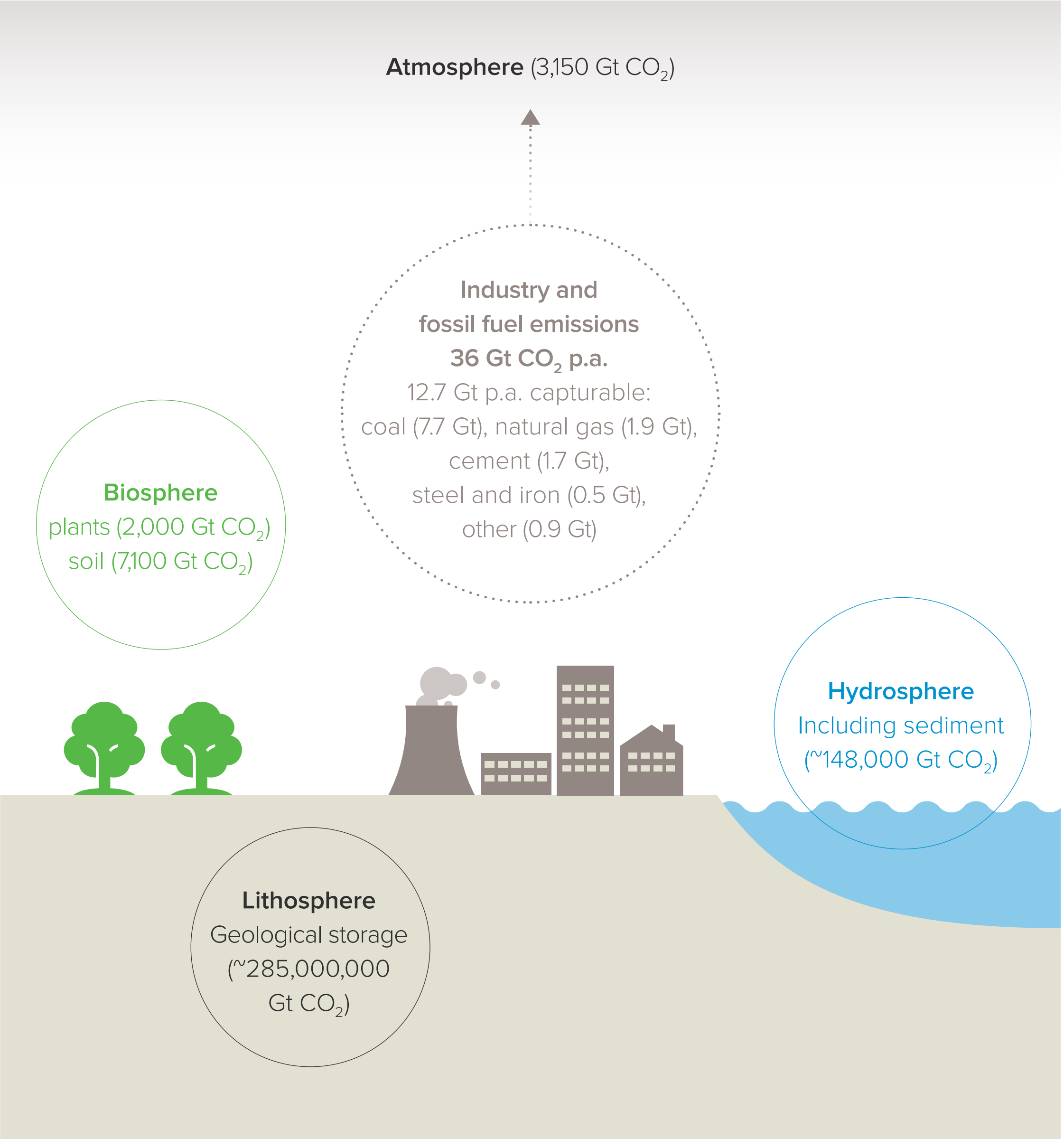
Historic atmospheric carbon dioxide levels.



Historic atmospheric carbon dioxide levels determined from ice core measurements from Law Dome, East Antarctic and direct measurements at the Mauna Loa Observatory, Hawaii. Data courtesy of NOAA.

FIGURE 2

Global stocks of carbon dioxide and capturable emissions



Dealing with carbon dioxide at scale requires a sustained and systematic approach.

For all this, there are many options for human action on the carbon dioxide problem. Annual anthropogenic carbon dioxide emissions represent a relatively small fraction (~1%) of total carbon dioxide in the atmosphere (~ 3,150 Gt CO_2), although the cumulative impact of these emissions is now about 25% of all the carbon dioxide in the atmosphere. Figure 2 depicts how atmospheric carbon dioxide interacts dynamically with the carbon dioxide stock in plants (~2,000 Gt CO_2), in soils (~7,100 GT CO_2), in sea water and sediment (hydrosphere – ~148,000 Gt CO_2) but interacts very slowly with the vast stock in minerals and rocks (lithosphere – ~285,000,000 Gt CO_2)[6].

Notwithstanding the absolute quantities, carbon dioxide remains a trace gas in the atmosphere. Consequently, other than capture at point emission sources, carbon dioxide is difficult to grapple with at scale. Its relatively low concentrations in the atmosphere (in parts per million) and stable, low-reactive characteristics make it challenging to capture and transform. The large amounts of carbon that must be removed to have a climate impact make it challenging to scale any approach. Accordingly, a wide range of innovative interventions are needed at a local, regional and global level and across business and agricultural sectors.

Step 2: Industrial and agricultural approaches

Potential solutions to supplement existing pathways in mitigation, including carbon capture and storage, fall in two broad areas:

Industry

Emissions of carbon dioxide have risen primarily as a consequence of the industrial revolution. This resulted in direct emissions from manufacturing, heavy industry, commercial and residential buildings and transport. It also led to a huge increase in the need for power, the great majority supplied from the burning of fossil fuels. Aspirationally, those very industries that have historically been a cause of emissions may be able to use carbon dioxide as an economic commodity in their processes and products. This includes chemicals, building materials and liquid fuels. To make a difference to the outlook for climate change will require a radical reversal of historical trends. Rather than being a primary source of emissions, industrial processes will need to contribute significantly to the reduction in atmospheric carbon dioxide levels.

Agriculture

In the course of Earth's history, the role of the land (forests, fields, soils) has been critical to regulating carbon dioxide levels in the atmosphere. It is possible to work with the grain of natural processes to improve assimilation of carbon dioxide by the environment. At the micro-level, this includes the way that farm and pasture management, crop characteristics and forest husbandry can affect carbon dioxide uptake. It also extends to deploying more far-reaching ecosystem management approaches such as applying carbon-dioxide-absorbing minerals to croplands and adapting plants for enhanced carbon storage.

Step 3: Evaluation and assessment

Candidate technologies must be assessed and evaluated from three key perspectives:

Environmental

Whether a particular approach will actually achieve the goal of reducing carbon dioxide without other undesirable environmental impacts. This involves looking at all stages of a product's life (raw materials, production, distribution, use and disposal).

Technical and economic

The prospects of deploying a technology at scale, the technical hurdles to be overcome, and the bottom line – that is, if the approach can become economically sustainable.

Social

This includes a wide range of behavioural and cultural issues that will determine whether a technological approach will be adopted by business and embraced by consumers and society.

A vision for dealing with carbon dioxide at scale

Various of the technological solutions considered in this report have the potential to deliver mitigation or atmospheric carbon dioxide reduction, but at different timescales and of varying magnitudes. The majority of these solutions will not, in the near term at least, be economically sustainable in the marketplace without policy or regulatory measures to support their early establishment. Realizing the practical potential of using carbon dioxide industrially or increasing its uptake into soils, requires identification of existing solutions near or at technical readiness and with potential for commercial viability. As these move into early deployment, the technology learning curve will improve products and drive down costs. Simultaneously, a broad palate of solutions needs space to germinate at the research level, recognising that a large number of those ultimately will not become viable.

Dealing with carbon dioxide at scale requires a sustained and systematic approach. To make a real difference requires a lasting partnership among scientists, engineers, business and government, as well as the public at large. The enormity of the global challenges of climate change, and the potential of both industrial and agricultural technologies to address it, make it imperative that real urgency is given to forging that partnership.

Chapter one

Industry

Carbon dioxide as a resource

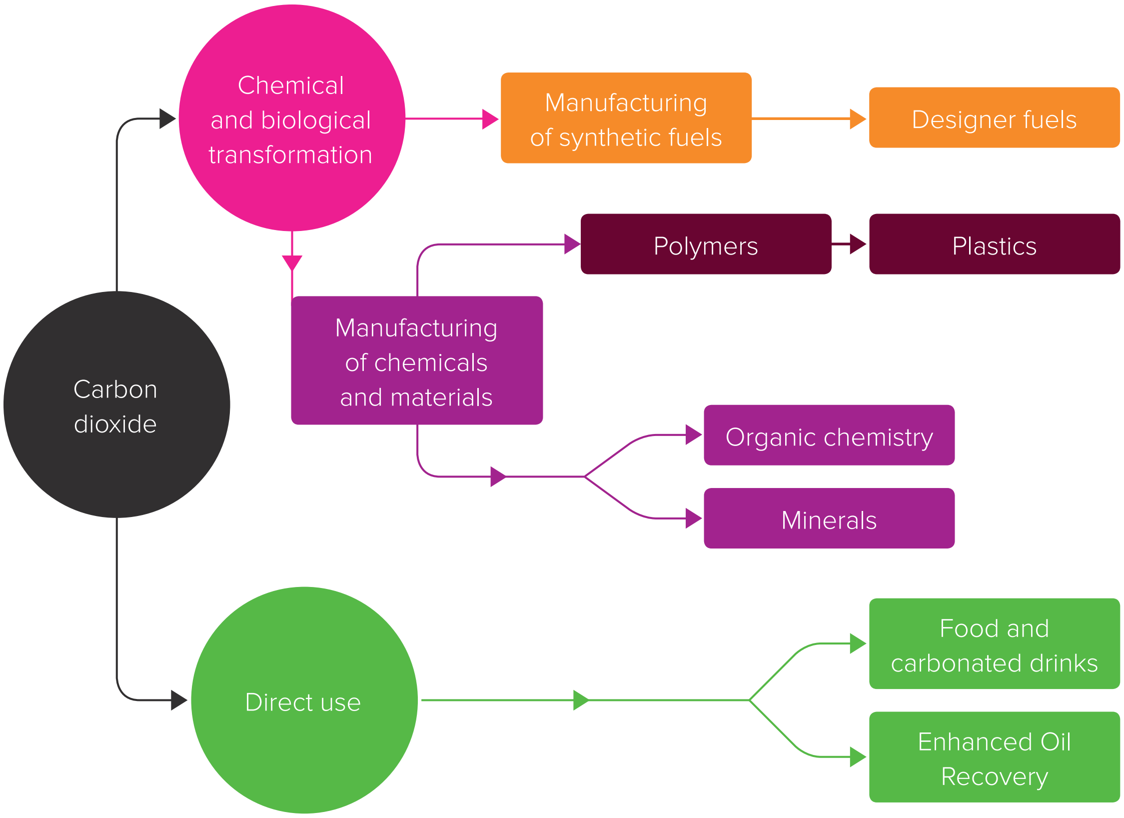
Carbon dioxide is already used by industry. Most notably, it is used in food and beverages in making carbonated drinks and also as an extractant to make flavourings. It is similarly used in areas as diverse as fire suppression, refrigeration, hydraulics and welding.

Increasingly, as seen in Figure 3, the further use of carbon dioxide as a starting material in chemicals, fuels and building materials is becoming possible. Carbon dioxide used in this way will not be released into the atmosphere, either permanently or at least in the medium or short term. However, the principal drivers for innovation are more likely to be the associated economic benefits. These would result from increased cost-efficiency in production or higher grade, more environmentally sensitive or aesthetically desirable products than those made by conventional means.

Advances in materials technology, such as new types of catalysts, and the way that modelling can help in our understanding of materials are making possible wholly new approaches. The discussion below illustrates some of the opportunities and the barriers to carbon dioxide utilisation in chemicals, fuels, and building materials. There are also critical feedstock and energy requirements that are dealt with at the end of this chapter.

FIGURE 3

Uses of carbon dioxide.



Source: Royal Society *The potential and limitations of using carbon dioxide* (2017).

Chemicals

About 8.5% of crude oil produced is used for products other than fuels[7]. A portion of these products, especially those used in plastics and polymers, are relatively high value commodities. Replacing fossil-sourced precursors for these products with carbon-dioxide-sourced precursors would create a small but high-value market to support the development of carbon dioxide capture and distribution infrastructure.

There are significant technical challenges in creating processes by which carbon dioxide can be chemically converted into the chemical precursors for polymers and plastics. One area of opportunity is improved catalysis, which is essential to facilitate the carbon dioxide uptake. An important area of ongoing research is to source catalysts that can generate high activity, operate at low pressure and are both abundant and inexpensive to manufacture. Potential future developments include more sustainable, recyclable polymer products based on carbon dioxide.

Electroreduction (the conversion of carbon dioxide using electrical energy and catalysis) is actively being developed to replace current fossil fuel based production of commodity chemicals with carbon dioxide as the feedstock. Research and early commercial development is currently seeking to achieve this in chemicals such as ethylene, methanol, acetate and ethanol, all falling within the world's top 50 produced chemicals[8]. Many of these processes rely on chemical pathways in which carbon monoxide is an intermediate product that can be used for the production of chemicals like acetic acid and formic acid as well as synthetic transportation fuels.

The commercialisation of such processes is critically dependent on the development of high performance, energy efficient and durable catalysts, membranes and electrodes. The availability of low-cost green hydrogen, as will be discussed below in the section on feedstocks, is also an important factor in development.

Fuels

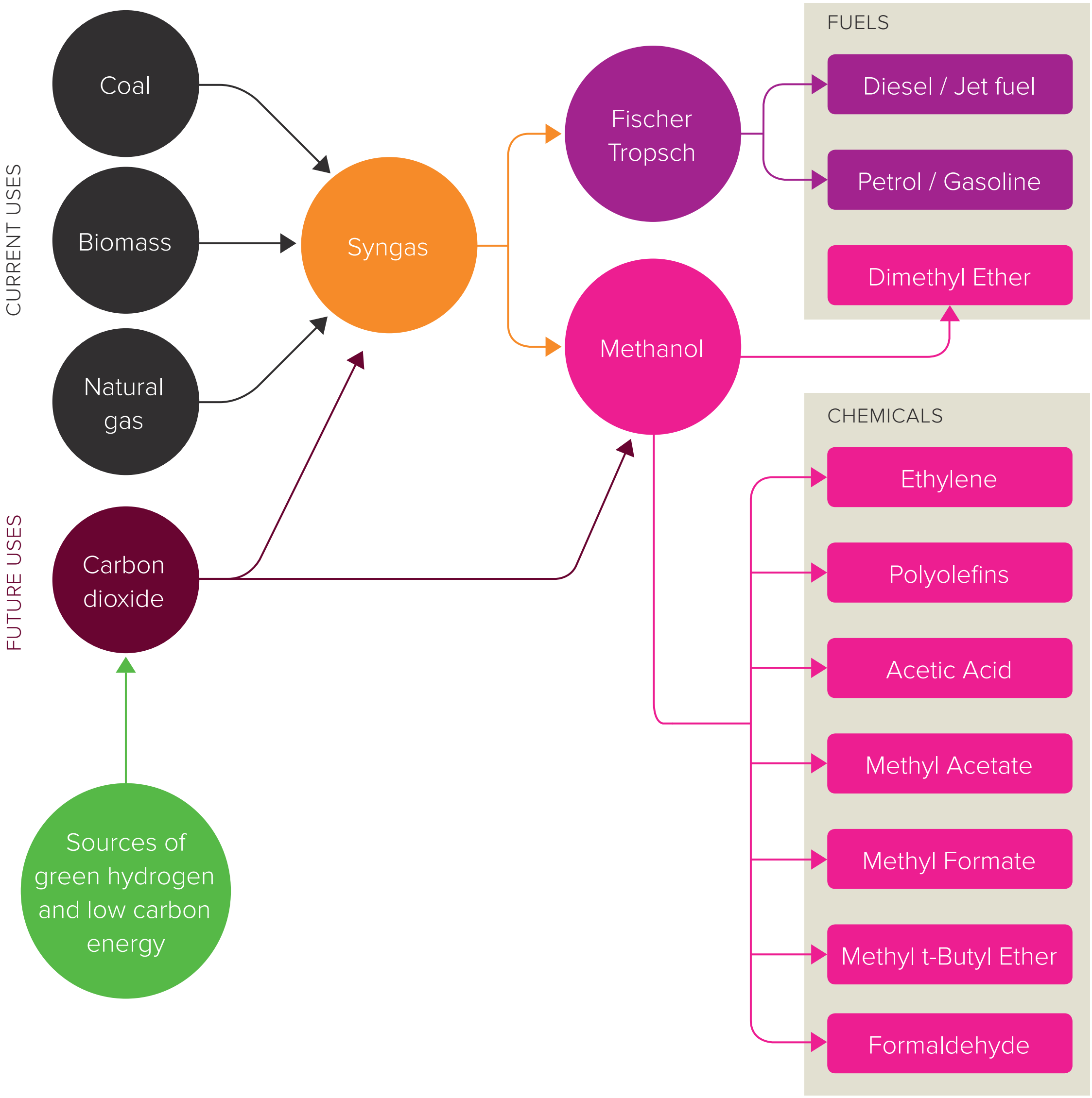
Energy stored in hydrocarbons, such as crude oil, is released when the fuel is burned. At the same time, carbon dioxide is released in to the earth's atmosphere. A cyclical relationship (low- or zero-carbon fuels) can be established by capturing that carbon dioxide (or sourcing carbon dioxide from elsewhere) and using it in the manufacture of further fuel products. For instance, water or hydrogen can be combined with carbon dioxide to produce methanol, a low-quality fuel, which however could serve as a fuel precursor that can be transformed readily to drop-in transportation fuels (see Figure 4). New catalysts will be needed to achieve this as the catalysts which are now used to make methanol do not perform well with carbon dioxide.

In the longer-term, further possibilities exist to use carbon dioxide in making fuels. These include biological transformation, photo-electrocatalysis to produce a variety of fuel products and the photo thermochemical production of syngas from carbon dioxide that could be directly used in the chemical and fuels industry.

> One area of opportunity is improved catalysis, which is essential to facilitate the carbon dioxide uptake.

FIGURE 4

Converting CO_2 into methanol – current and future use.



Source: Royal Society *The potential and limitations of using carbon dioxide* (2017).

Image
Oval Building Construction St Moritz Chesa Futura. CC0 1.0 Universal. creativecommons.org/publicdomain/zero/1.0

Substantial engineering challenges are faced in enabling fuel production at scale using carbon dioxide as a feedstock. These are similar to the challenges of chemical production, but compounded by the lower price points for fuels. One example of new opportunities under development involves platform technologies to convert carbon dioxide using electrolyzers deploying metal nanoparticle catalysts and novel polymer materials. Such technologies may considerably reduce the problems and risks of scale up by reducing the costs of upfront capital expenditure. Other approaches – such as thermochemical and biological conversion – are also showing early commercial progress in selected markets.

The issue of hydrogen – either as a fuel in its own right, or as an enabling reactant in production of low-carbon fuels – is addressed in the section on feedstocks (see page 13).

Building materials

A variety of promising approaches can be taken to utilising carbon dioxide in building materials. These include mineralising carbon dioxide in aggregates and using carbon dioxide in the curing of concrete. In the longer term, new carbon dioxide based polymers could also play a role in providing new building materials. These techniques involve substantial industrial processes and result in building materials employed abundantly in construction today – aggregates and concrete.

A rather different solution is that of using wood. Carbon is already stored within the wood without the need for heat, pressure, and injection engineering. Wood has an array of practical uses in building – from windows, decking and fencing, and with new developments such as cross-lamination, to full structural applications in houses, office blocks and bridges. New wood products have greatly improved strength and can replace materials that have some of the highest cradle to grave

Hydrogen is an essential feedstock for the manufacturing of many fuels and chemicals using carbon dioxide.

carbon footprints, such as aluminium, steel and concrete. Heavy timber is well suited to fire resistance due to a char layer that forms to slow heat reaching the interior of the material. Yet considerable forestry and technical challenges remain to be tackled for large scale impact.

Firstly, there is the need to replace hardwood with softwood in manufacturing. Softwood planting can drive reforestation, rather than leading to deforestation of tropical forests. This requires increasing the performance (durability, stability and mechanical properties) of temperate wood. Research can source softwood species with inherently better properties. Chemical treatments to make wood more resistant to degradation, but which are non-toxic and without other detrimental environmental impacts, are also being developed.

Secondly, there are some very practical issues for forestry such as the most opportune moment, economically, to fell a tree. A tree cut too soon will lose the benefits of years of rapid growth; a tree felled too late will have endured a number of years of uneconomic slower growth. It is necessary to look at forestry cycles over a long period (perhaps, around 70 years) to determine the most effective wood management strategies to reduce atmospheric carbon dioxide. Here, the biological and agricultural sciences can contribute to the production demands of heavy industry and so the bottom line for business.

Feedstocks and energy

There are three critical material and energy requirements to maximise the potential for using carbon dioxide in industry. These are hydrogen; carbon free sources of power; and, most obviously, industrial scale quantities of carbon dioxide – available at low production and distribution costs. Each of these requirements is interconnected with wider science and engineering research to address climate change.

Hydrogen is an essential feedstock for the manufacturing of many fuels and chemicals using carbon dioxide. Today, almost all hydrogen production (96%) comes from fossil fuel sources (natural gas, oil and coal), with only 4% being produced by electrolysis[9]. The engineering technologies for fossil sources (such as gasification, steam gasification and steam reforming) all release carbon dioxide as a byproduct for hydrogen production. Standard electrolysis of water will produce clean hydrogen if the electricity source is low-carbon. However, the costs for electrolysis are now significantly higher than for fossil-sourced hydrogen. Some of the electrochemical research directions being used for chemicals and fuels may also benefit hydrogen production. In addition, research is exploring wholly new approaches to hydrogen production. These include using the ‘photocatalytic window’ (when the sun shines) to make hydrogen using photo-electro-catalysis.

A rather different approach to reducing atmospheric carbon dioxide whilst addressing the need for hydrogen, is to rethink how energy gases are used. The combustion of methane (which comprises 95% of natural gas) releases carbon dioxide and water. Rather than burn methane, energy can be added to it to decompose it into hydrogen, from which energy can be generated, and solid carbon materials instead of carbon dioxide emissions. Catalysts and new chemical processes are being explored to make such a process commercially viable by enabling energy positive hydrogen production alongside the generation of commercially useful solid carbon products.

Chemical processes using carbon dioxide as a feedstock are energy intensive. Thus, a key challenge to the creation of 'green' chemicals and fuels is the need for large sources of cheap, low-carbon energy. Carbon dioxide benefits for mitigation and carbon dioxide reduction can only be sustained by using clean power to drive the chemical processing. There are, however, opportunity costs of using clean power to convert carbon dioxide. Use of low-cost power for chemical conversion will compete with other uses, such as charging electric vehicles. The use of excess clean power on the grid (e.g. due to strong winds or sun during periods of low power usage) could also provide economic benefits, but this could require the conversion plants to be scaled to match the peaks in power availability. The goal of 100% clean-power capacity to ensure 24/7, 365 days a year operation requires modernized grid systems in which clean-power sources and power-intensive mitigation opportunities are integrated with demand-response and storage.

Finally, carbon dioxide utilisation processes are dependent on industrial scale quantities of carbon dioxide as a feedstock. Commercial viability will depend on the relative costs of the carbon dioxide to the value of the final product. The first approach to meeting the feedstock need will use point sources of carbon dioxide, such as ethanol refineries, cement or steel plants and fossil-based electric power plants. There is still a need to draw down the costs of capture and compression of carbon dioxide from these sources. Advances of technologies such as high specification membranes to capture carbon dioxide dilute sources are an active area of research for more economical capture of carbon dioxide.

Chapter two

Agriculture

Part of the problem or solution?

Agriculture contributes significantly to greenhouse gases (around 10 – 12% of global anthropogenic emissions)[10]. The main gases released are methane (from ruminant animals) and nitrous oxide (from fertilizers yielding nitrification and denitrification). Equally, however, large amounts of carbon are stored in soils, grasslands, forests and crops and, because there have been significant reductions of global soil carbon, there is now considerable scope to extend this storage.

Achieving carbon dioxide reductions through agriculture can be approached both:

- At the farm or local level – improving soil, crop and grazing management practices; and
- At regional or international scale – pursuing improved understanding and control of crop/soil interactions or geophysical approaches to management of the land.

To achieve greater sequestration of carbon dioxide through agriculture requires looking in the round at ecosystem processes. This needs to reflect that, alongside the opportunities, greenhouse gases are currently generated by land use systems. Equally, there are only certain elements of the wider ecosystem that are controllable (both temporally and spatially). In addition to carbon dioxide reduction, there are a number of socio-economic factors to consider. Societies and individuals must make hard choices: how food is grown, how people are housed, how those who own land are incentivised in their stewardship and husbandry. The social and behavioural sciences have a clear part to play to ensure that solutions are not only technically feasible but also deliverable, literally, on the ground.

Soil management

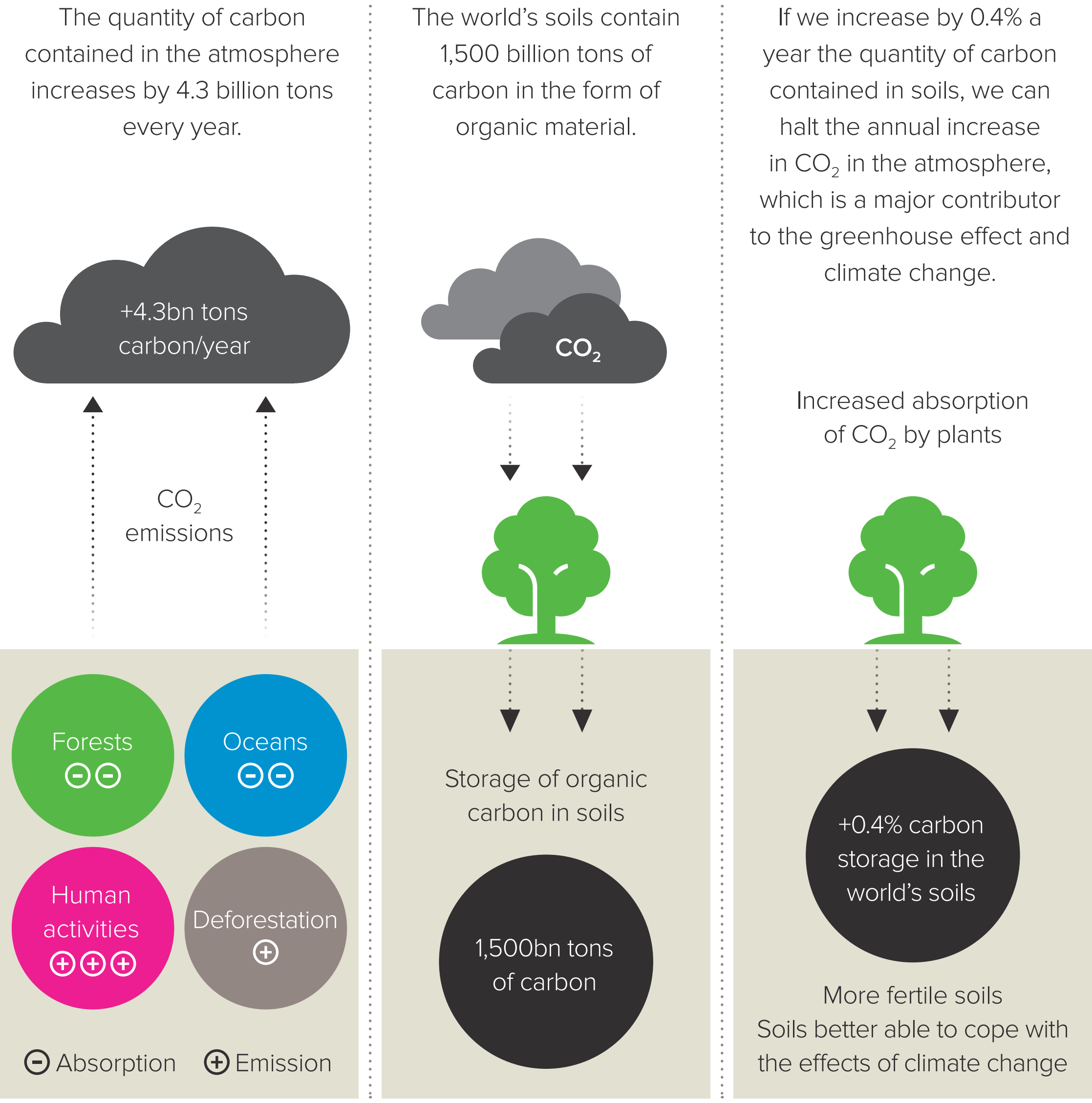
The potential for soil management to sequester significant volumes of carbon dioxide was underlined in the ‘4 per 1,000’ initiative (see Figure 5)[11]. This relies on two premises. Firstly, that the quantity of carbon contained in the atmosphere is increasing by 4.3 billion tonnes every year. Secondly, the world’s soils contain 1,500 billion tonnes of carbon in the form of organic material. Therefore, if the quantity of carbon contained in soils were increased by 0.4% a year, it would be possible to halt the annual increase in carbon dioxide in the atmosphere.

A central difficulty in achieving increased storage of carbon in soils is understanding the impact of agricultural practices and crop characteristics on carbon levels. The efficacy of measures such as reducing or intensifying grazing or crop tillage varies according to factors such as temperature and humidity. Proper assessment requires detailed soil inventories over large areas in the environment, nutrient cycling studies and repeated soil core analysis.

In principle, there are a wide range of interventions which are low cost in terms of climate change alleviation. They also offer co-benefits in terms of higher soil fertility and increased crop production. But there are corollary factors – carbon storage in soil can be reversed if good practices are not maintained. Also, ultimately soil will reach carbon saturation at a given rate of uptake. However, the uptake of carbon to that point would provide a significant decrease in the cumulative amount of carbon dioxide added to the atmosphere. Additionally, there will be trade-offs in terms of emissions due to fertilizer use. Improved soil carbon can reduce the need for fertilizer, but ensuring this would need to be part of the development and implementation process. Such issues tie into the non-economic barriers that result from the need to change behaviour at the farm level.

FIGURE 5

Carbon sequestration in soils for food security and the climate.



The quantity of carbon contained in the atmosphere increases by 4.3 billion tons every year.

The world's soils contain 1,500 billion tons of carbon in the form of organic material.

If we increase by 0.4% a year the quantity of carbon contained in soils, we can halt the annual increase in CO_2 in the atmosphere, which is a major contributor to the greenhouse effect and climate change.

Increased absorption of CO_2 by plants

More fertile soils
Soils better able to cope with the effects of climate change

Source: 4 per 1,000 initiative, Soils for food security and climate, Ministere de l'Agriculture, de l'Agroalimentaire et de la Foret, Republic Francaise. See https://www.4p1000.org/ (accessed 15 March 2018).

The regenerative grazing approach has shown a wide variety of benefits.

Grazing management

Linked to soil management is the management of grazing animals. Soil function is mediated by microbes, which depend on plants. The proper management of plants and, accordingly, the cattle that graze upon them, is critical.

One approach to grazing management of cattle that has been tried in rangeland environments is that of regenerative grazing. This involves a transition from heavy to light continuous grazing (known as adaptive multi-paddock grazing). Grazing is spread across a whole ranch by grazing one paddock at a time. Short grazing periods in each paddock are followed by adequate time for the grass to recover before allowing regrazing.

Alongside ground cover and soils, which create a stronger net carbon sink, the regenerative grazing approach has shown a wide variety of benefits. These include improved soil structure, improved nutrient access, extended root volume and depth, and high plant growth. As with other forms of soil management, evaluation of such grazing management is complex in different environments. Equally, widespread adoption of grazing management approaches relies on farmers being convinced that they are useful in the particular circumstance of their ranch.

Plant ecosystem adaptation

There are a number of places where carbon is stored in plant ecosystems:

- in soil (grasslands);
- in soil and above ground biomass (forests);
- in soil with above ground biomass harvested for production and revenue (crops).

The potential to enhance carbon storage through ecosystem adaptation in these different domains is an area of active research. This includes areas such as the photosynthetic efficiency of carbon dioxide sequestration and interactions in the rhizosphere (where the soil is directly affected by root structure and secretions).

Utilising the functional traits of plants to increase carbon storage is also being explored. Genotypic diversity for plant functional traits is being looked at through controlled experimental plant-atmosphere-soil systems. This will enable quantitative prediction of traits (biomass accumulation as well as soil carbon storage) and responses as a function of genomic and environmental variables (temperature, light and soil humidity). Developing advanced tools to characterize plant-soil interactions in situ will provide an important enabler of research in this area.

Enhanced weathering

It is also possible to conceive a strategy for capturing carbon dioxide through geophysical management of soil. This envisages harnessing reactions that have been stabilising climate for millions of years as a natural process (such as weathering). One example of this approach, known as ‘enhanced weathering’ is illustrated in Figure 6. This involves increasing the surface area of natural silicate rocks (such as basalt) by crushing and then spreading these rocks on croplands[12]. Carbon dioxide removal occurs through bicarbonate storage and, ultimately, very slow deposition on the ocean floor.

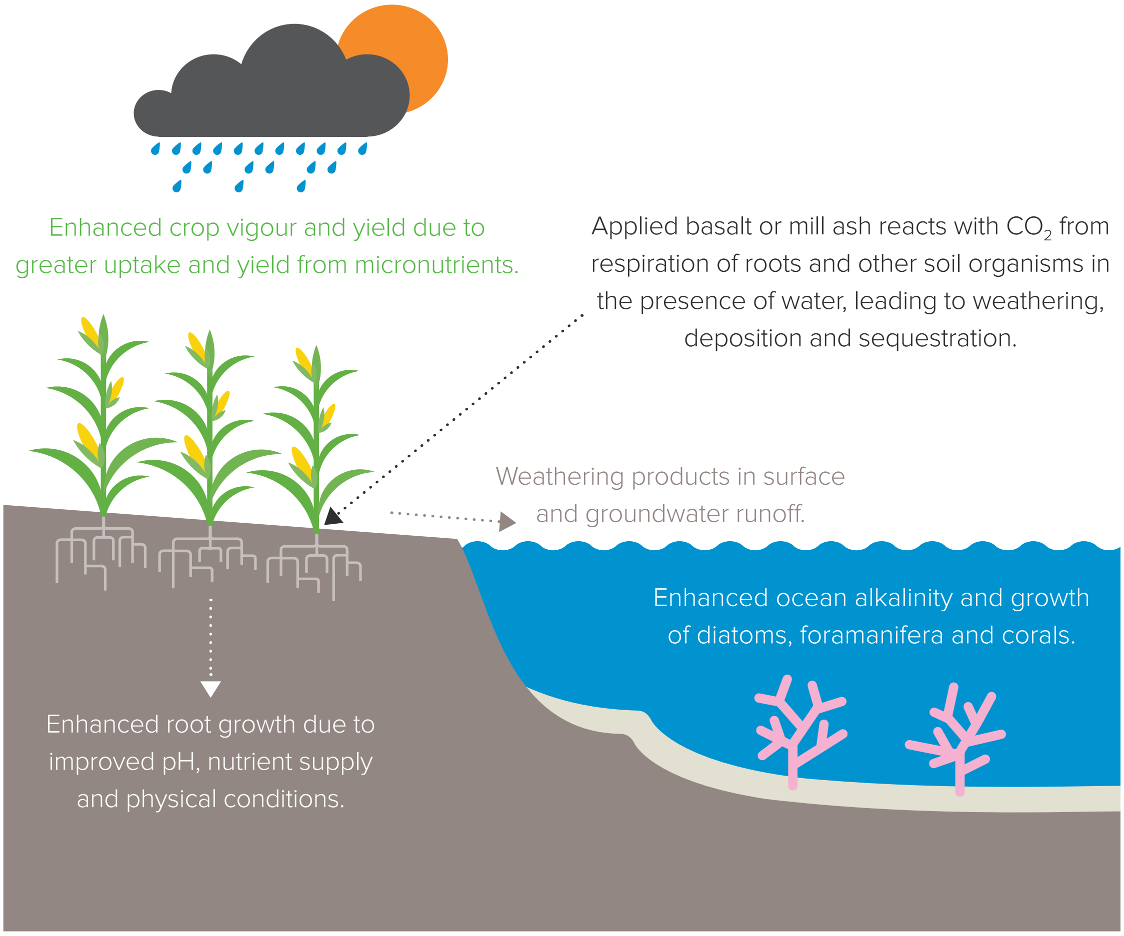
Enhanced weathering of this type is expected to contribute to crop production through increasing elemental nutrient uptake; increasing crop protection against pests and disease; reducing soil acidification; decreasing agrochemical usage; and restoring soil properties and quality. Carefully structured field-scale studies to assess its full potential are underway in the USA.

The costs and availability of silicate rock would depend on factors such as the extent to which it was possible to use silicate waste materials. Otherwise, the cost of mineral extraction, crushing and transport could make the approach uneconomical. As critical as the practical logistics would be the extent to which it was possible to achieve public acceptance of such a scheme and commitment to it from farmers.

FIGURE 6

Enhanced weathering in managed cropland soils – how does the concept work?

Application of natural silicate rocks to croplands harnesses reactions that have been stabilising climate for millions of years.



Source: David Beerling, University of Sheffield.

Chapter three

Evaluation and assessment

The moment is right to change the way we think about carbon dioxide.

Policy context – the scale of the task

The Paris Agreement[13] on climate change committed the signatory nations to: holding the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C; and to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century.

Even in idealised scenarios in which emissions of carbon dioxide are stopped immediately, atmospheric carbon dioxide levels will remain flat and not fall for hundreds of years.

One way of viewing the Paris Agreement is that net zero emissions globally need to be achieved by 2050, with 5 Gt of carbon dioxide being removed annually from the Earth's atmosphere[14]. The industrial and agricultural technologies to utilise and remove carbon dioxide considered in the Forum represent an opportunity to contribute to this goal in a significant fashion.

Business case

The moment is right to change the way we think about carbon dioxide; not as a waste, but as a potential feedstock. Converting carbon dioxide to products represents an opportunity to create early pathways to larger scale capture, utilisation and storage in the future. To seize that opportunity means taking a systematic and methodical approach:

- Fundamental science and engineering – having a deep technical understanding of the potential technologies and products;
- Economics – knowing the markets and driving capital towards carbon dioxide use and removal by demonstrating how investment returns might be achieved;
- Environmental and social – evaluating the risks and trade-offs and how they will be perceived by the public.

There are two critical components to the supply chain for carbon dioxide use and removal technologies. The first of these, most obviously, is carbon dioxide as the base feedstock. Currently, about 12 Gt CO_2 of emissions from point sources per annum is capturable (7.5 Gt from coal processes, 2 Gt from gas, 1.5 from cement, 0.5 from steel and 0.5 from other sources)[15]. That is a considerable resource. Yet, in the longer term, if negative emissions continue to be required, direct capture of carbon dioxide in air will be needed. Second, cheap, reliable, zero-carbon energy is essential to support many of the energy intensive processes that exploit the properties of carbon dioxide.

Framework for assessment

It is essential to lay down criteria on which to base decisions as to whether or not to pursue a particular carbon use or removal technology. The following factors are key:

- Climatological significance – will the technology make a real difference in terms of dealing with carbon dioxide at scale?
- Profitability – can the product be developed with economic sustainability? If it requires a carbon price, subsidy or regulatory framework, will these create significantly lower societal burdens than other options?
- Durability and permanence – does the approach provide long-term mitigation impacts, yield a significant offset in net emissions to the atmosphere over an extended time, or permanently remove carbon dioxide from the earth's atmosphere for a timescale that is meaningful?

The evaluation framework that follows helps to assess technologies against those criteria.

Life cycle analysis

This establishes the atmospheric carbon dioxide reduction potential of a technology. It requires rigorous input from academia and practical know how from industry. To carry out the analysis properly, it is essential to engage experts worldwide who are independent from the product or process and who bring different perspectives.

Currently, life cycle analysis can vary markedly, even for the same product derived by the same technical route. Scope for difference results from the way that systems boundaries are defined and how co-products and the supply of feedstocks (such as hydrogen and carbon dioxide) are treated. There is a need for greater standardisation of life cycle assessment toolkits (ideally led by a responsible international body), including more specific guidance on the value of carbon dioxide utilisation and on the basic assumptions of the analysis.

Techno-economic assessment

This determines the economic costs and benefits of a technology or product. It should be developed alongside the life cycle analysis. It needs to take into account a range of very practical factors that will determine ease of implementation. These include whether the process is scalable, regulatory and competitive barriers, the sustainability of the product and distribution channels. Critically, it needs to establish at what price point for carbon dioxide (whether on the basis solely of market forces or a laid down carbon price) the supply of the product will become economically viable. The assessment needs also to address co-benefits of the product (such as energy security, reduced air pollution) and downsides (such as dependence on fossil fuels to create carbon dioxide at scale). It would also be beneficial to create common comparators and terminology.

> There is a need for greater standardisation of life cycle assessment toolkits.

Cycling carbon dioxide from the atmosphere displaces the release of new carbon dioxide.

Durability and permanence

There are broadly three types of time domains to consider:

1. Mitigation, in which the impact is measured in reduction in the rate of carbon dioxide emissions to the atmosphere. Mitigation can be achieved in carbon dioxide utilisation by cycling carbon dioxide from the atmosphere. Such cycling is already accomplished through the use of biomass as a source of carbon from the atmosphere (e.g. wood chips in power generation), but may also be accomplished through the direct use of carbon dioxide to produce fuels or products that are burned or decay and re-release carbon dioxide. Cycling carbon dioxide from the atmosphere displaces the release of new carbon dioxide that would result from the use of fossil-fuel based processes or products. The time scales for product permanence may be days to years, or even decades for some plastics.
2. Steady-state storage, in which carbon dioxide is captured into a product, which later decays but then is replaced – requiring equivalent new uptake of carbon dioxide. Examples would be the use of wood as a long-term construction material, or storage of carbon dioxide into organic carbon in the soil. In this case, the cumulative storage over a number of years results in a permanent fixed decrease in the cumulative amount of carbon dioxide added to the atmosphere. The time scales for product permanence may be many decades to centuries.
3. One-time storage in which capture carbon dioxide is sequestered into permanent storage such as in a deep aquifer in which mineralization will occur. These time scales should be many millennia.

Achieving carbon dioxide reduction at any of these three timescales can help alleviate the problem, if only by buying humanity more time to address the issues.

Chapter four

Vision

Goals

To tackle climate change, the pressing need is to reduce carbon dioxide emissions into the atmosphere. Central to this is the transition to renewable energy sources, capturing carbon dioxide emissions from industry at source or through plants' (prairie, farm and forest) ability to capture carbon dioxide through photosynthesis. This vision aims to complement carbon dioxide emission reduction strategies through targeted intervention measures:

1. Technological

Making a difference at scale to the reduction of atmospheric carbon dioxide levels through carbon dioxide use and removal technologies;

2. Assessment

Having the tools and evaluation techniques to assess the contribution to atmospheric carbon dioxide reduction and viability of scientific and engineering solutions;

3. Partnerships

Establishing relationships and creating networks that will shape a global industry so carbon dioxide use and removal technologies move forward with pace.

1. Technological

A number of factors determine whether a technology will make a difference to atmospheric carbon dioxide reduction. These include scale, durability, permanence and economic viability. These factors decide the research and implementation priorities on page 25.

Scale

Disruptive technologies have the potential both to prevent or capture emissions and to remove gigatonnes of carbon emitted to the atmosphere each year. Within the power sector, this may be through either displacement of existing technologies or by local carbon dioxide capture and recycling or storage. Similarly, the long-term potential in areas such as agriculture, forestry and building materials may be on this very large scale. Other industrial sectors (such as chemicals) have diverse products, each of which may require specific technical development. Their contribution might better be measured in terms of the cumulative impact of many products each yielding fractions of gigatons of carbon dioxide utilisation per annum. Research in these sectors may lead to lower cost methods of utilising carbon dioxide for larger markets such as fuels, or create infrastructure with the potential to address chemical transformation at scale.

> Disruptive technologies have the potential both to prevent or capture emissions.

Using carbon dioxide to produce fuels and feedstocks can displace the use of fossil fuels.

Durability and permanence

As discussed above, the timescale over which technologies keep carbon dioxide from the Earth's atmosphere, or the time scale over which the technologies enhance displacement of fossil fuels, matters. Geological scale solutions (such as enhanced weathering and utilising carbon dioxide in cement building materials) may capture carbon dioxide for millennia. Timber building materials and soil assimilation have a cycling time of many decades or even a century for timber, but in steady state create a permanent offset to cumulative emissions. Fossil fuel displacement by chemicals has timescales of months to decades, whereas fossil fuel displacement by carbon-dioxide based fuel production provides continuous displacement of emissions for as long as there is no alternative (e.g. electric vehicles) to fuel use. The longevity of carbon capture provides opportunities to create a new steady state after a period in which cumulative emissions to the atmosphere are reduced. Using carbon dioxide to produce fuels and feedstocks can displace the use of fossil fuels, and thus prevent additional carbon dioxide emissions, and so offers a sustainable short-term route to sourcing energy materials on which society globally currently relies.

Economic viability

A technology that can be delivered commercially is easier to establish than one that requires long-term incentives or subsidies. However, policy or regulatory measures may be needed to establish market demand if the technology delivers a societal benefit (such as energy efficiency or reduction of harmful emissions) that serves customer needs indirectly. New technologies will, in any case, face tough competition from incumbent supply chains and cannot, therefore, be expected to compete immediately with existing industries. High upfront capital expenditure for engineering infrastructure can reap dividends as costs related to a product later reduce or new product features can drive demand uptake.

PRIORITIES

Research

As a strategy to avert risk, fundamental research funding is needed for a broad portfolio of carbon dioxide use and removal technologies at different technology readiness levels. This recognises that a large proportion of those technologies will not progress to implementation. A diverse range of technologies are, therefore, needed to tackle the carbon dioxide problem as a whole.

Specific identified research needs that can be addressed now include: catalysis and electrolysis in the chemicals industry; the manufacture of green hydrogen (which can unlock a number of pathways to carbon dioxide use); and pilots and systems for evaluating approaches in agriculture and forestry in well controlled conditions.

Research needs for carbon dioxide use and removal are intrinsically linked to broader clean energy research, such as renewable power, a modern power grid, cheap hydrogen, and direct capture of carbon dioxide in air. This is because the potential contribution at scale of many carbon dioxide use and removal technologies is inhibited in the long-term without parallel progress in these wider areas.

Implementation

Low hanging fruit: Early potential exists in approaches such as grazing, forestry and soil management, using new high-strength wood products more widely in building, and in construction materials such as concrete and aggregates. (Albeit, there are economic challenges to such uses, for instance the need to compete on price with the low costs of many building materials.) As these are deployed and technological learning curves take effect, these will serve as proof of concept that carbon dioxide use and removal approaches work in the real world and can be economically sustainable. Their adoption will also buy time for other technologies to come on stream.

Products with existing economic potential: There is likely commercial value in using carbon dioxide in specialty chemicals. Prioritising such products will allow technical capabilities to progress without long-term state intervention and enable the potential for addressing the larger market of fuels to be developed. Less mature technologies, such as those to use carbon dioxide in making carbon fibres and absorb it in microorganisms such as algae and yeast for biofuels, also merit development support.

Developing economic potential: There is already technical potential to manufacture products such as fuels from carbon dioxide. These are not, however, broadly cost competitive today with existing production technologies. However, the learning curves from development of high-value products may spill over to allow realization of the larger scale impacts of fuels.

Support for pilot plants and scale-up approaches is also needed to develop these technologies, especially with regards to quickly translating laboratory-scale experiments to demonstration systems.

> Techno-economic analysis should be used to understand market and business opportunities.

To bring all of these factors together requires wide ranging collaboration and a shared sense of purpose.

2. Assessment

Tools and evaluation techniques to assess carbon dioxide use and removal approaches should be made more robust in the following four areas:

Environment

There should be greater standardisation of life cycle assessments and definition of system boundaries, which nevertheless must be sufficiently flexible to deal with a diverse range of technologies. To provide transparency, open source toolkits should be developed. Uncertainties in such assessments can be reduced in relation to complex systems (such as agriculture) and by using technologies such as spectroscopy, satellites and drones to improve measurement and data.

Business

Techno-economic analysis should be used to understand market and business opportunities. There is also a need to prevent undue regulatory barriers to the adoption of new products by ensuring that compliance can be demonstrated in a reasonable timescale in areas like building materials, chemicals and sustainable management processes for woods. Professional standards bodies, such as ASTM International and ISO, and global rules bodies, such as the World Trade Organisation, should be engaged to ensure standards and tariffs support the development of the emerging industrial products.

Social

A wider range of social impact and indicator studies should be used. These can assist in understanding both public perceptions of new technologies and likely behavioural responses, for instance from the owners of agricultural land.

Scenario planning and matrix analysis

These should be used to look holistically at the impacts of a range of potentially disruptive technologies. These should be multidisciplinary processes which aim to understand impacts on a regional scale, interconnections between technologies and unforeseen consequences, both positive and negative, on areas such as land use, water and non-carbon dioxide emissions.

3. Partnerships

A global industry from carbon dioxide use and removal technologies requires:

Leadership

Senior scientific, engineering and business leaders collaborating to inspire and bring direction to all those working in this field. Such leadership can develop through informal networks. It is, however, more likely to arise where there is a central point of focus, such as an international centre of excellence or a global academic partnership.

Human element

Carbon dioxide use and removal technologies must respond to societal, business, and consumer needs. This involves a realistic and open dialogue about what is achievable in terms of atmospheric carbon dioxide reduction and the risks technologies give rise to. It also requires education and promotional strategies through universities, industry and in small business support.

Long and short-term goals

To bring all of these factors together requires wide ranging collaboration and a shared sense of purpose among stakeholders. That can be achieved through the development of roadmaps, which focus on the ultimate prize of a circular economy. Such roadmaps should balance technologies that both stop carbon dioxide emissions in the first place and those that serve to remove and reuse carbon dioxide where emissions are unavoidable. The roadmaps can align technological opportunities with short-term and long-term goals. They also provide a space to assess potential future developments and to coordinate the various activities and propose timescales. As importantly, developing roadmaps can engage all the partners, so making the relationships that will give the technologies the opportunity to succeed.

Annex

Members of Steering Committee

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Other members
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