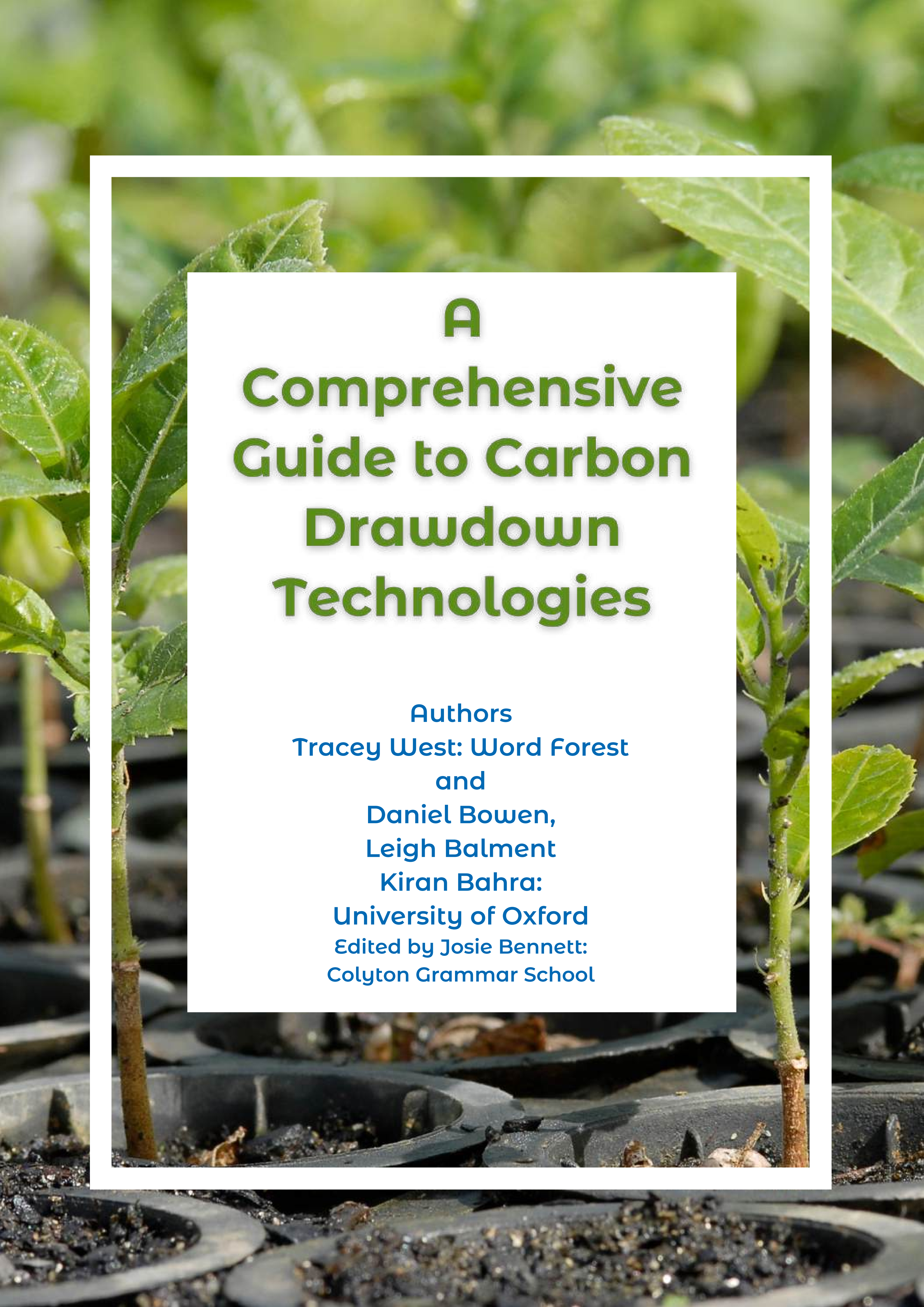

A Comprehensive Guide to Carbon Drawdown Technologies

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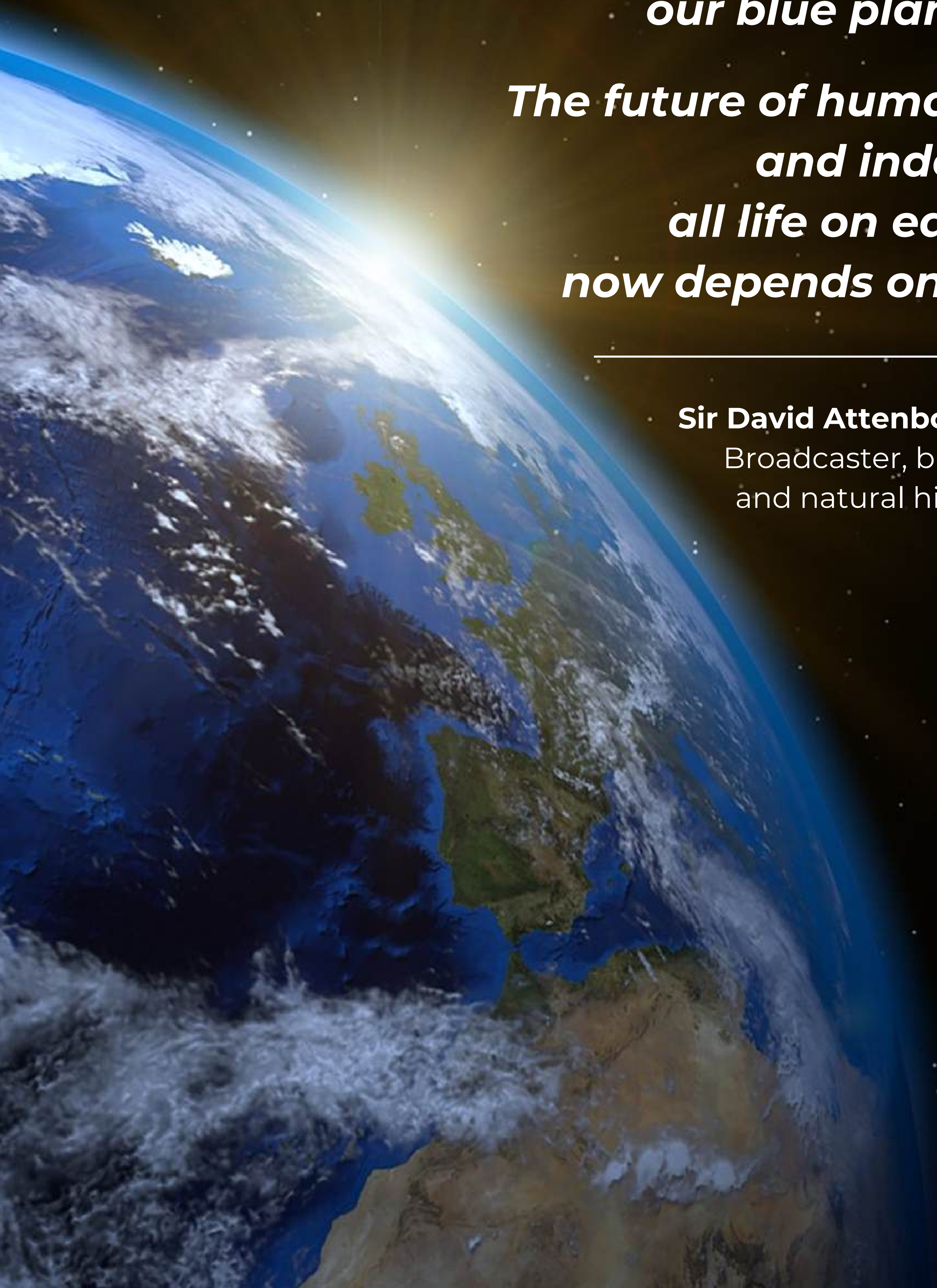
"Surely we all have a responsibility to care for our blue planet.

The future of humanity and indeed, all life on earth, now depends on us."

Sir David Attenborough
Broadcaster, biologist and natural historian



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Inspired by National Geographic Magazine

Clare Nasir
Met Office Meteorologist
and Patron of Word Forest

INTRODUCTION

The issues that surround the topic of carbon offsetting remain as contentious as they were back in the 1980's when the marketplace first revealed itself. Projects that remove CO_2 and slow down global heating are essential for our planet's future. Urgency is paramount. Every day that passes exacerbates the challenges we face to survive this crisis. We need to act swiftly and decisively.

Yet carbon offsetting is still offered up in many guises. Take reforestation as an example. Recent exposés of a handful of schemes via accredited bodies have blown the subject wide open; we consider that a good thing. Far greater clarity and transparency are needed if business leaders are expected to plot a course to a world where decarbonisation is more than a buzz word and our planet is meteorologically more stable and sustainable.

Over the past 40 years, a lot of deep thinking has occurred and innovation has come a long way, thanks to an inspired set of mission-driven people. Startling technological advancements have been made and some purport to be the silver bullet required to solve our climate emergency. Despite their efforts, the sum of these parts has completely fallen short of the whole - a well balanced Earth. The silver bullet remains elusive and the climate emergency trajectory continues to spiral.

Where are we with carbon offsetting right now? It is almost 30 years since COP1 in Berlin and a decade since the celebrated Paris Agreement where Article 6 created a framework for countries to cooperate on carbon offsetting projects. It is worth noting that, upon closer inspection, some of the solutions we've investigated for this report are relatively embryonic options. Some have substantial implementational issues which could inhibit the rapid progress we need.

They may render some of these credible technological solutions contributorily useful but fatally handicapped in terms of efficacy and expeditiousness. That said, they undoubtedly have a collective role to play in the multi-disciplined, urgent solutions the Earth desperately needs. With varying degrees of speed and success, I suspect they will all help decarbonise the atmosphere to some degree. However, what's needed immediately is a viable, affordable and swiftly executable plan.

Read our report and ask yourself: which of these CO_2 reduction methods are able to provide the rapid, consistent, reliable assistance our planet requires today? Our report examines well-understood, traditional solutions, along with newer, more complex alternatives for CO_2 removal from the Earth's atmosphere. The methods we have explored have the capability to draw down and lock in this shockingly abundant greenhouse gas which sits at the root of our climate crisis.

One of the strongest conclusions of the report is that the most affordable and easily implementable solution is planting trees in Kenya, whilst providing a multi-faceted level of care to the amazing people who plant and tend them. Trees in Kenya, like other tropical regions around the world, grow at an astonishing rate. In some cases, up to 10 times faster than in temperate and tundra latitudes. They have the ability to lock in ¼ of a tonne of CO_2 in 5-7 years, which is astonishing.

Consider the additional benefits to Kenyans from the production of fruit, nuts, food, medicine and other commodities. One is easily able to grasp the dent they could make in hunger, malnutrition and poverty: what a phenomenal bonus.

The UN Secretary General, Antonio Guterres, frequently advocates for immediate climate action. He refers to our precarious situation as: '*The era of global boiling*', which rather renders the 1970's term '*global warming*' obsolete.

Until transparency across the entire value chain of the carbon offset marketplace has been addressed and clarified, the credibility of all schemes will continue to be threatened by issues surrounding their efficacy. It is highly likely it will take time to resolve and in truth, our planet simply doesn't have the time to waste.

Whilst technological solutions continue to establish their rightful positions in the pecking order, may I be so bold as to suggest you employ Occam's razor and boost Word Forest's remarkable endeavours to reforest Kenya?

Traffic Light System

Throughout the guide, we have used a system of traffic lights to show the capabilities and limitations of each of the applications.

We used three different assessment criteria: cost of implementation, complexity of implementation, and potential capacity of CO_2 absorption.

An explanation of our traffic light system is depicted below.

High cost, great complexity and low capacity of sequestration

Medium cost, medium complexity and medium capacity of sequestration

Low cost, low complexity and high capacity of sequestration


CO_2
CO_2
CO_2

Direct Air Capture

Direct Air Capture (DAC) technologies extract carbon directly from the atmosphere in any location, allowing it to be mineralised or utilised. While DAC can be implemented anywhere, carbon capture at the source of emissions is much easier, cheaper and more efficient than atmospheric removal due to the level of CO_2 concentration.

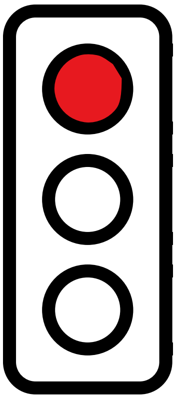
Today's solutions use liquid solvents or solid sorbents consisting of common chemicals which are already in use in other applications. These solvents/sorbents combine with the CO_2 to extract it from the air, so it can then be transformed into pure CO_2 and stored underground. This allows the solvent/sorbent to be reused.

If the carbon is used for other purposes, this can often defeat the purpose of the carbon capture, as many of these purposes will just release the CO_2 back into the atmosphere. Therefore, for maximum climate gain, the carbon must solely be put into storage, though this will drive costs higher than they already are.

Many companies and governments are investing heavily into DAC. The most notable example is the US Government giving up to $35-50 per tonne of CO_2 captured as tax credits to the companies investing in DAC, as well as spending millions of dollars on research and development into these technologies. Major companies including Stripe and Microsoft have also invested in DAC.

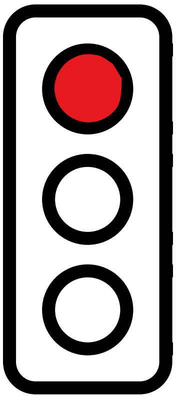
However, could this money be better spent elsewhere? DAC is one of the most expensive forms of carbon removal; had this money been spent earlier on reforestation, there would now be billions more trees in the ground - billions more carbon capture stores which would be both highly beneficial and cheaper in the long-run.

Cost of Implementation



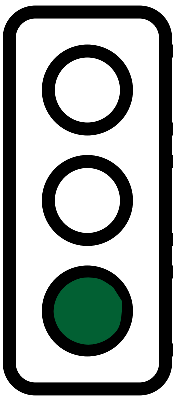
DAC is one of the most expensive ways of removing carbon, as costs can range anywhere from $200-$1000 + per tonne of CO_2. Costs are cheaper when removing carbon in high concentrations, such as from power plant emissions, yet remain particularly high when removing carbon from the general atmosphere due its low concentration.

Complexity of Implementation



Without investment into green fuels, DAC emits more carbon than it captures and fully electric operation is not currently technologically feasible. With a lack of ecological co-benefits and valuable by-products, as well as requirements of huge amounts of capital and energy, DAC is seen as one of the most difficult carbon reduction schemes available.

Capacity



As DAC has the potential to treat the entirety of the Earth's atmosphere, the potential is endless; DAC would be able to return the global CO_2 levels to pre-industrial standards. However, if we only focus on carbon capture from concentrated sources, then we can only capture future carbon emissions. It cannot reduce the amount of carbon currently in the atmosphere.

Example

Carbon Engineering is one company pioneering DAC from the atmosphere and not just from concentrated sources of CO_2. Their technology is designed to capture CO_2 from atmospheric air and extract it as a gas.

The first step in the process is to draw in air using a large fan. This air is then passed through a potassium hydroxide solution which binds with CO_2 molecules to be converted into pure CO_2 gas by a series of chemical processes consisting of trapping the it in the solution that then travels through the DAC system and is used for storage. This means that the air it came from returns outside with much lower levels of CO_2.

Carbon Engineering's design has been created so that replicating a plant will be fairly simple, meaning the technology can be reused and capacity can be increased fairly quickly. It also assumes that 10 identical plants will be built in the same location to maximise cost efficiency.


Direct Ocean Capture and Electrifying Seas

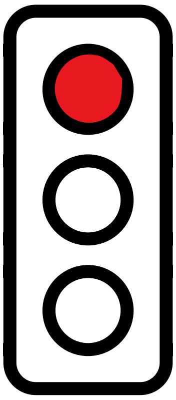
Similar to DAC, Direct Ocean Capture (DOC) takes a large quantity of seawater into a processing plant and then return it to the ocean with most of its carbon or acidity removed, making the returning alkaline water better at absorbing carbon from the air. Since seawater has a concentration of CO_2 150 times higher than air, a lot more CO_2 can be removed when taking in seawater. Many of these methods involve the use of an electric current, which is commonly referred to as electrifying the sea.

The most direct way of removing carbon from seawater uses 4 inputs: seawater, air, rock and renewable energy. Initially, an electric current is passed through the seawater in a process called electrolysis, then atmospheric air is passed through this electrolysed water. These steps trap CO_2 in solid minerals or as dissolved substances that will last in the oceans for thousands of years. Finally, rock is used to neutralise the processed seawater to preserve the oceans chemistry.

Another benefit of this process is its production of carbon-negative hydrogen (a reaction where hydrogen is produced and removes CO2 from the atmosphere simultaneously). This is a resource in high demand and currently produced in very carbon-intensive reactions. A large increase in carbon-negative hydrogen would mean fewer carbon emissions while still obtaining hydrogen.

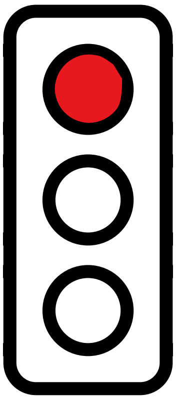
Other methods of DOC involve using sodium compounds, such as sodium carbonate microcapsules, which absorb the CO_2 from seawater through chemical reactions as the water is passed through. This technology is only just undergoing research, so it will be many years before anything similar can be deployed for vast use in real-world applications.

Cost of Implementation



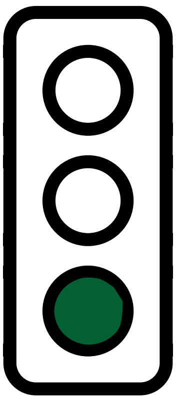
This technology is still going to need a lot of upfront investment before it can get up and running. Since it is so new, the current costs of removing a tonne of CO_2 are extremely high. While scaling up will reduce this cost, it is not known currently how much costs can be driven down, but estimates place DOC as one of the most expensive forms of carbon capture.

Complexity of Implementation



Currently, this technology is still used on a very small scale and there are several limiting factors to increasing capacity. One of the main issues is increasing the electrolyzer manufacturing capability. Saltwater electrolysis is still fairly new, so creating the necessary equipment for this is not currently achievable on a large scale. Furthermore, companies must ensure that removing the carbon (and potentially changing the alkalinity of the water) will not harmfully impact ecosystems.

Capacity



One of the best parts of this technology is its potential capacity. The ocean is a vast resource that has the potential to store almost unlimited amounts of carbon. Therefore, once the suitable technology has been developed, the potential capacity of such systems is endless.

Example

The main company currently working on DOC is Equatic, a US-based firm that has opened a plant off the coast of Los Angeles in California. They're also building another larger plant in Singapore that will remove 10 tonnes of CO_2 from the ocean per day by the second quarter of 2025.

Currently, their process consumes less than 1.4 megawatt-hours of energy per tonne of removed CO_2, although some of this cost is offset by the hydrogen produced from the process.

The new project preparing to launch in 2025 is called Equatic-1. One of its key features is its modular design, meaning that individual units can be easily replicated and added to the existing buildings in order to rapidly increase capacity. They have also committed to building their first commercial-scale deployment as early as 2026, with carbon credits already being sold to companies such as Boeing.


Mineralising Carbon

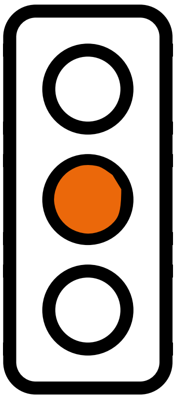
Mineralising carbon involves accelerating the natural processes in which atmospheric CO_2 undergoes chemical reactions to be converted into minerals and soluble ions. The minerals needed for these reactions exist within the Earth, but accessing these minerals is a tricky and environmentally degrading task.

Studies have shown that the Earth already absorbs around 100 billion tonnes of carbon per year through natural mineralisation processes, which is equivalent to around 350 billion tonnes of CO_2 - approximately 10 times the amount that humanity emits per year. However, despite humanity's output seeming less significant, it is disrupting a delicate balance between natural emission and absorption levels, resulting in atmospheric CO_2 levels increasing at an unsustainable rate.

The key rocks involved in the mineralisation process are mafic and ultramafic rocks, and these are often found deep underground. One method of mineralisation, known as subsurface mineralisation, involves pumping water with a high CO_2 concentration through wells into these rocks, which will then react with the CO_2 to form minerals.

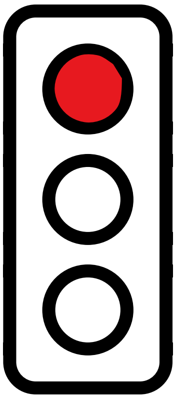
The other method is surface mineralisation, where crushed alkaline feedstock (such as mined rocks or industrial waste) is reacted with ambient or concentrated CO_2. This can be done on carbon capture sites, which have access to highly concentrated sources of carbon. Another method is enhanced rock weathering, where the mafic and ultramafic rocks are made into powder and sprinkled along coastlines or fields, which react with the ambient CO_2 and form minerals.

Cost of Implementation



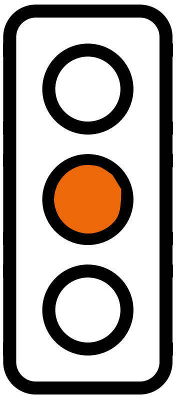
The key part of most carbon mineralisation is accessing mafic and ultramafic rocks, or other substances that can be used to react with CO_2. While this is a fairly challenging process, it is manageable. This technology also still requires a lot of costly research before it can be fully implemented.

Complexity of Implementation



Implementing carbon mineralisation will be very challenging. Even when researchers can carry out this method on a large scale, there are plenty of negative consequences that will need to be overcome. For example, the negative effects of obtaining the materials that the carbon will react with, or processes which release toxic materials such as nickel or chromium, must be responsibly addressed.

Capacity



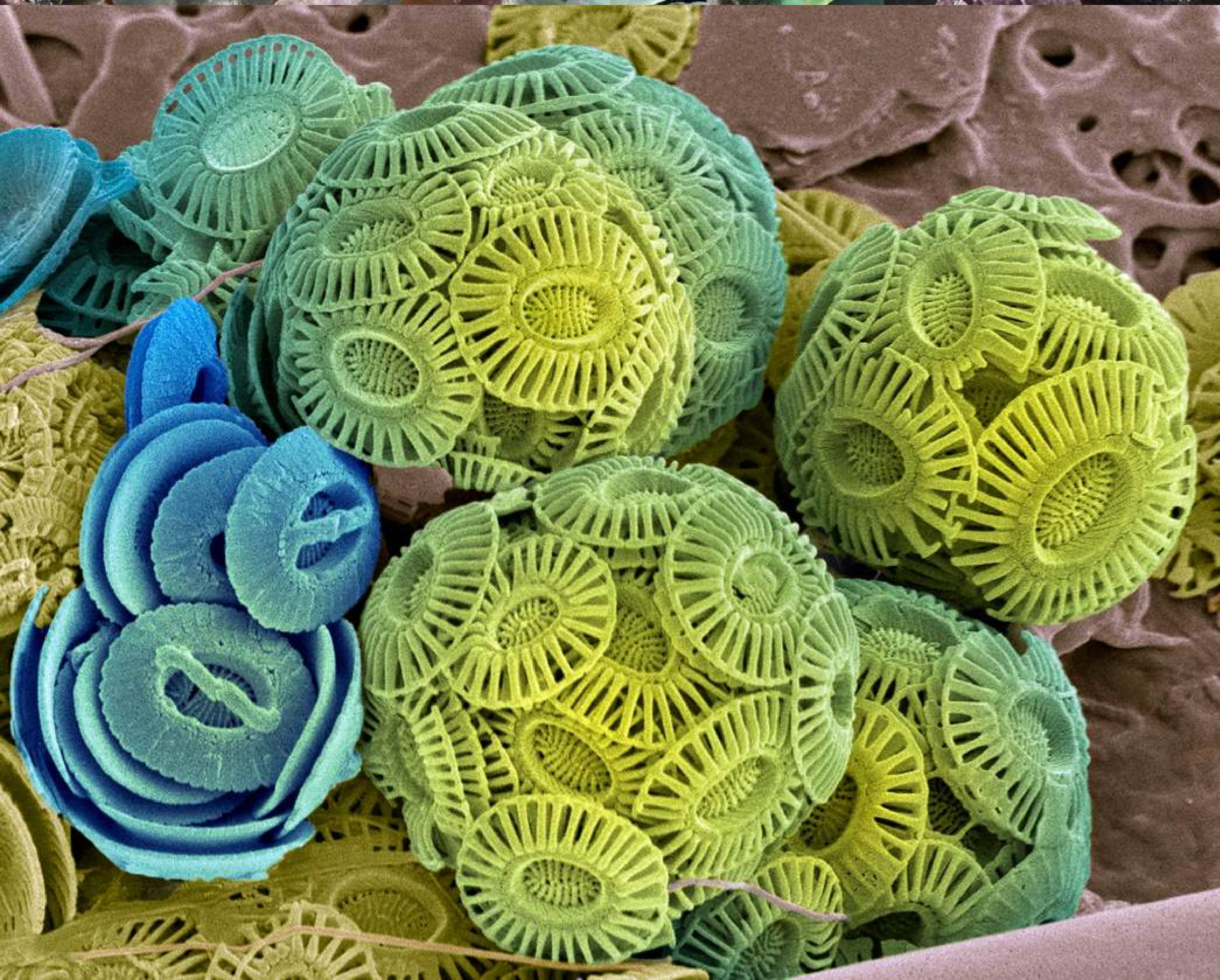
Carbon mineralisation is mainly limited by access to the resources that are needed to carry out the chemical reactions, as these are in limited supply and often hard to access. Scientists estimate that up to 1 gigaton of CO_2 per year could be removed by 2035, which, when compared to the current global emissions of 40 gigatons per year, clearly shows that while this solution can remove a significant proportion of CO_2, it does not have enough capacity to solve the emission on its own.

Example

In Iceland, a pilot project called the CarbFix Project, funded by the European Union, commenced in 2012. It involved 230 tonnes of pure CO_2 and a CO_2/hydrogen sulphide mixture from the local Hellisheiði geothermal power plant being fully dissolved in groundwater and then injected into basaltic rocks at a depth of 500 metres.

This method requires 25 tonnes of water per tonne of CO_2 to fully dissolve the CO_2, which at scale, would be a huge water requirement. The carbon-heavy water is denser than the normal water, meaning it sinks and accelerates metal release from the bedrock, speeding up the formation of carbonate minerals.

A second trial began in 2014, which scaled the project up to great success. Currently, over 50% of the injected carbon is fixed as carbonate materials within months of injection. The project captures 33% of the CO_2 emissions from the power plant, with aims to increase that to 90% by 2030.



Mineralising Oceans

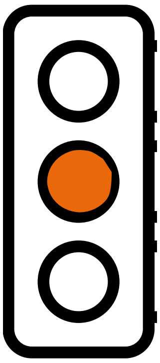
Mineralisation occurring in oceans can be accelerated through ocean alkalinity enhancement (OAE). As the name suggests, this involves adding alkaline substances into oceans, which accelerates the process of pulling carbon out of the solution and locking it into rocks and sediment. Alternative to spreading over the ocean surface, plants can be built that physically extract acidified ocean water, perform the mineralisation and extract the sediments, and then return deacidified water back to the ocean.

Enhanced weathering does not need to be restricted to land. Natural carbonisation processes occur in the oceans too, and - like on land - can be accelerated to support carbon drawdown efforts.

OAE could involve spreading pulverised silicate and carbonate minerals onto the sea surface or performing these reactions ‘in-house’ at specialised plants. The exposed minerals enhance chemical weathering reactions where CO_2 is locked away. These strategies could be applied widely across the ocean without worry of air pollution in dust and would not affect the use of these areas for shipping and fishing. Increasing alkalinity would actually go some way to mitigate the decline in the pH of the oceans as a result of increased absorption of carbon (acidification of the ocean).

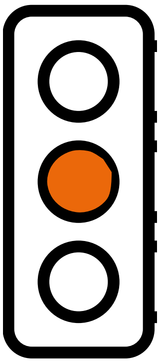
Currently, most research on OAE is being carried out in laboratories and it will be many years before any wide-scale solutions can be deployed. With the risk of ruining the delicate balance of the ocean’s ecosystem, this method seems unlikely to succeed.

Cost of Implementation



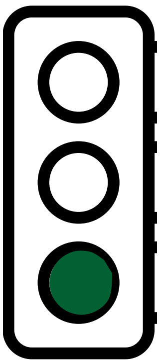
The cost of deploying this strategy varies with the complexity of the system adopted. A one-time spreading of these materials will inevitably be cheaper than running plants which continually pump and add alkalines to seawater. However, costs are estimated to be between $50 to $200 per tonne.

Complexity of Implementation



Like the cost, the complexity of implementing this technology varies greatly. Spreading rock dust from a ship would be straightforward, but building an entire pumping plant would be significantly complex. However, acquiring this material and effectively spreading it over a wide area would be a complex procedure - more so than if these processes were just occurring from natural mineral exposure.

Capacity



The massive capacity of the deployment of this technology really makes it shine. It has very large long-term potential due to sequestration into non-saturable sinks - the ocean will not ‘run out of space’. Therefore, it has the capacity to capture 1-27 Gt of CO_2 per year through ocean alkalinisation. The cumulative amount, using mineralisation on both land and sea, could reach between 100 and 367 Gt of CO_2 by the end of the century.

Example

This technology has already been deployed in the real world. Heimdal, founded by Erik Millar and Marca Limar, has built an extraction plant system that performs these enhanced mineralisation reactions, claiming that they extract a tonne of CO_2 at $475. Hemidal hopes to improve this technology to capture 5,000 tonnes of CO_2 per year at an operation cost of $200 per tonne.

Heimdal's technology pumps saltwater into a machine that uses electricity to change how the molecules in the water are arranged in order to remove acid from the water. The de-acidified water can absorb more CO_2 and convert it into minerals.

This alkaline water is then added back to the ocean, where it naturally absorbs CO_2 and converts it into carbonate minerals that will stay in the ocean for thousands of years.

Pumping Seawater

This artificial upwelling of cold water sends nutrient-rich water to phytoplankton, increasing their rate of photosynthesis.

Pairing this upwelling with the downwelling of oxygenated water from the surface also helps to counteract the anoxic (oxygen-depleted) conditions of coastal dead zones.

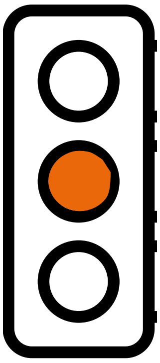
Pumping seawater from the bottom of the oceans up to the surface helps to accelerate phytoplankton activity and increases carbon sequestration.

This system works because phytoplankton reside in the surface layers of water to access sunlight for undertaking photosynthesis. However, this surface water is also low in nutrient content and its photosynthetic rate is limited by nutrient availability. Therefore, by upwelling nutrient-rich water from lower layers of the water column, carbon sequestration is accelerated.

This increases biomass at the bottom of the food chain therefore increasing the populations of the trophic levels above; increasing populations risks decreasing the levels of dissolved oxygen in the water, which would result in anoxic regions and dead zones. Fortunately, pairing upwelling with downwelling activity renews oxygen in these deeper waters, combating the formation of these dead zones.

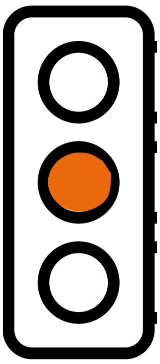
There is still a clear danger of affecting the delicate ocean ecosystem. Moving water into different areas will affect the concentration of minerals at different depths in the ocean and - while the benefits of carbon absorption have been studied - more studies into its side effects must be conducted.

Cost of Implementation



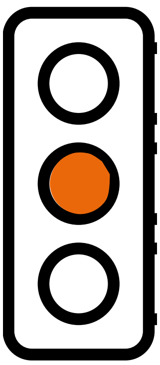
The initial installation of these pipes and pump systems would require some significant investment to initiate the upwelling and downwelling processes. Of course, this initial cost would be significantly lower than building entire plants to undertake these processes. However, because this pumping would need to be near constant, energy and maintenance costs would also be high.

Complexity of Implementation



As mentioned, this technology does come with great environmental risk. Boosting biomass requires more oxygen, which is simply not available in lower regions of the water column, creating the risk of forming anoxic dead zones. Fortunately, this can be combated by pairing upwelling with downwelling systems. This requires additional installation, energy and maintenance, all adding to the complexity of this strategy.

Capacity

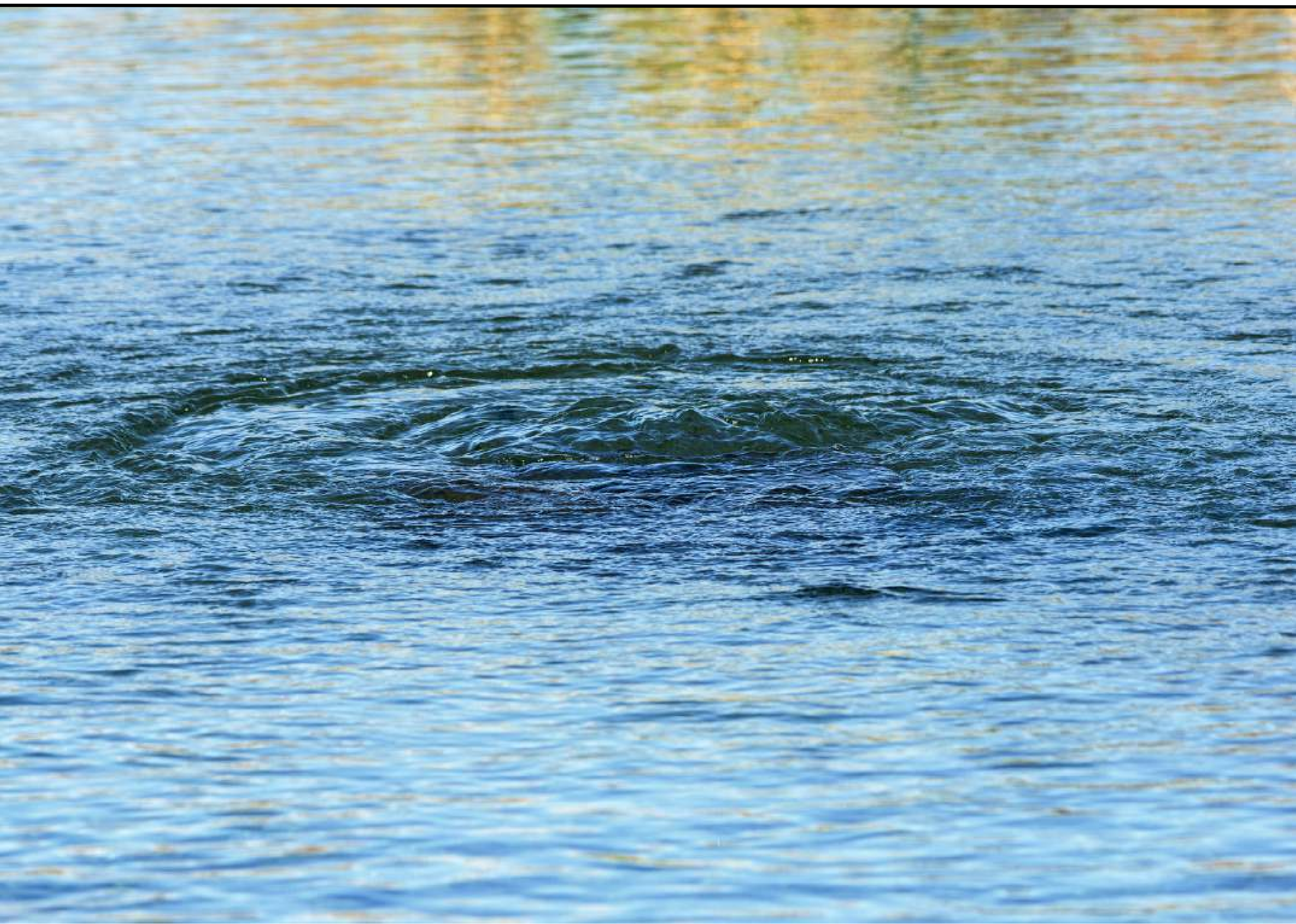


The potential capacity for this technology is debatable. Obviously, the more upwelling sites, the greater the capture potential. The sinking carbon has the potential to be captured on the ocean floor for a few hundred years. However, some of this will be intercepted by creatures eating it on the way down. Like other technologies utilising the natural capability of phytoplankton to lock away carbon through photosynthesis, this strategy is still in its theoretical stage and so not widely utilised.

Example

It must be noted that this technology is still in its very early stages. This strategy hinges on enhancing the photosynthetic rate of the phytoplankton through turnover of the water column structure. Despite improving nutrient availability in the open ocean, there are potential dangers associated with this method. Freshwater nutrient enhancement leads to: eutrophication (an increase in microorganisms, decreasing the oxygen available in the water), anoxia (depletion of dissolved oxygen in the water) and the death of freshwater ecosystems. As far as we are aware, widespread field studies and applications have not yet been implemented.

An example strategy of implementation would resemble oil-rig stations. Pipes could be installed in the water to balance the artificial upwelling enhancing phytoplankton photosynthesis alongside the downwelling pipes, therefore preventing anoxic regions forming. However, the logistics of making this work on a larger scale are very unclear.



Fertilising Oceans

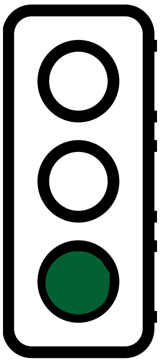
Tiny organisms called phytoplankton live in seawater and they carry out photosynthesis. Like our land plants, their photosynthesis absorbs CO_2, which they turn into food to help them grow. Therefore, like adding fertilisers to agricultural fields, enhancing the nutrient availability to phytoplankton boosts their photosynthetic rate, increasing not only carbon drawdown but also the biomass at the bottom of the marine food chain and so benefiting the entire ecosystem.

As the name suggests, adding nutrients (including iron, phosphorus and nitrogen) to the oceans could serve to increase carbon sequestration.

In natural ecosystems, phytoplankton growth is limited by nutrient availability. Therefore, enhancing these nutrients would increase their productivity and growth, increasing photosynthetic reactions and increasing CO_2 sequestration. Furthermore, enhanced biomass at the bottom of the food chain would help to sustain all trophic levels of the food web above, so may help to enrich entire ecosystems, wherever this technology is deployed.

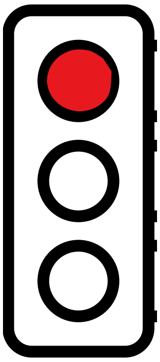
However, land runoff of nutrients into freshwater systems leads to eutrophication, anoxia and the widespread death of freshwater life, so this theoretical solution must be subject to rigorous field testing before widespread deployment can be considered. The urgency that faces us with the current climate situation means that we simply do not have time to undergo years of rigorous testing before deploying a solution.

Cost of Implementation



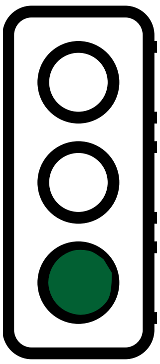
This technology has the potential to carry very low cost, since all that is involved is enriching the iron content of sea water and letting phytoplankton flourish under the new nutrient rich conditions. Studies suggest this enrichment could cost between <$100 per tonne CO_2 at the Antarctic Shelf to well over $1000 in the Southern Oceans.

Complexity of Implementation



Despite the apparent cost effectiveness of dumping additional nutrients into oceans, this technology carries some massive complexities. In recent years, conservationists have tried to convince governments to limit the use of fertilisers in order to avoid nutrient runoff and widespread death of freshwater/marine ecosystems as a result of eutrophication. Therefore, if this technology were to be deployed, it must be very carefully managed and regularly assessed to ensure that the whole marine ecosystem does not collapse, and with it the loss of food resources and wider carbon sequestration strategies.

Capacity

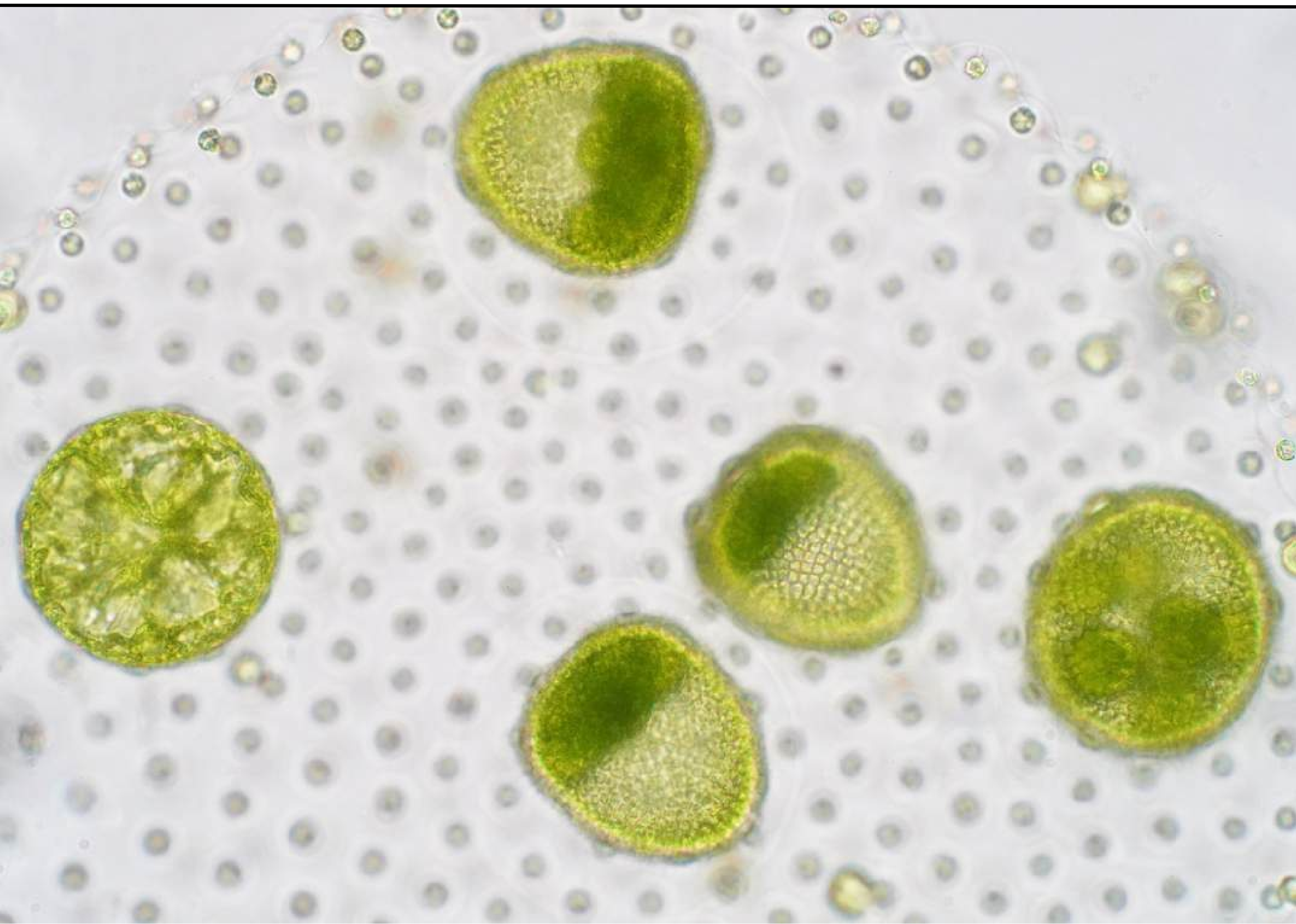


As mentioned, current phytoplankton activity is limited to nutrient availability, so the extent of increased sequestration would mirror the abundance of these phytoplankton and the amount of nutrients that would be added. However, as this strategy is not widely deployed in current systems, the real capacity for such technology is disputed.

Example

As mentioned, this technology is still in its very early stages. This strategy hinges on accelerating the photosynthetic rate of the phytoplankton through increasing the nutrients available in the open ocean. However, the aforementioned risks of eutrophication, anoxia and death of freshwater ecosystems, must again be taken into consideration. Due to a lack of widespread field studies into this method, our knowledge of fertilising oceans in practice is limited.

Example strategies for implementation could be specific, such as the selective addition of certain nutrient components (such as iron) at very particular locations, or more comprehensive, such as the wider application of fertilisers directly to the seawater surrounding whole ecosystems. Until more research is conducted in this area, however, we cannot be sure.



Biomass Carbon Removal and Storage

Biomass carbon removal and storage (BiCRS) describes processes which use the power of biomass from plants and algae in order to remove carbon from the atmosphere and store it underground or in long-lasting products. Furthermore, it is essential that these processes do not have any effect on other key values such as food security, rural livelihoods and biodiversity conservation.

Previously, there was mainly a focus on BioEnergy with Carbon Capture and Storage (BECCS) as a way to provide energy without emissions as harmful as those from burning greenhouse gases. Although, in most cases, this biofuel still emitted some carbon, which ideally was then caught and stored underground.

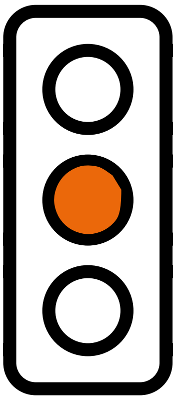
Recently, suggestions to rename BiCRS show a change in strategy; rather than focusing on providing energy, the removal of carbon is now being prioritised.

There are three key aims for BiCRS:

1. Do no harm
2. Social acceptability is key
3. Technology development should reflect social priorities

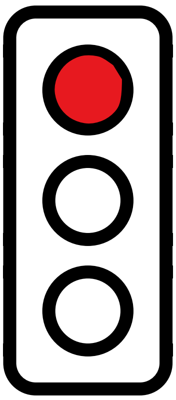
Another key idea is not just to use crops as the source for biomass, but instead to use biomass that is already produced, such as: roots, leaves and twigs from fallen trees, waste biomass from industry, food and micro/macroalgae. Gathering biomass from these sources can ensure that the community gets a net positive from the other benefits of these processes.

Cost of Implementation



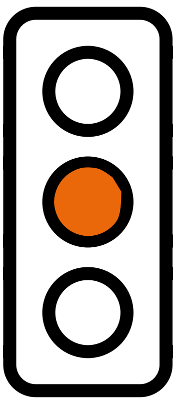
While most BiCRS strategies do involve setting up large processes to capture the carbon from the atmosphere, running costs of operational BiCRS would not be too high. Nora Cohen Brown, Head of Market Development and Policy at Charm Industrial, estimates that they can get costs of BiCRS down to around $100-200 per tonne of CO_2 captured. This is not as cheap as more natural solutions but it is better than direct ones.

Complexity of Implementation



Currently, most processes of BiCRS are at a developmental stage and, therefore, still very difficult to implement practically. However, there is huge potential for many of the different ideas behind using biomass. Furthermore, a lot of BiCRS schemes have high land usage and land is a finite resource which is rapidly increasing in demand.

Capacity



A study from the Innovation for Cool Earth Forum suggests that the potential capacity for BiCRS is 2.5-5.0 $GtCO_2/y$, which gives it a healthy potential capacity, but it does not have the potential to solve climate change on its own. As a lot of biomass comes from other processes, BiCRS is limited by the amount of biomass that is created.

Example

One example of biomass use is biochar, pictured below, which is where biomass is heated in a low-carbon environment to make a carbon-rich soil additive known as biochar. Therefore, biochar captures carbon from the atmosphere and stores it in the soil, which is believed to increase the amount of nutrients in the soil as well.

The US company, Charm Industrial, is one example of a company deploying biochar and bio-oil as a form of BiCRS to sell carbon credits. They take the parts of corn that are usually discarded during harvesting and instead break down the material into a mix of biochar and bio-oil.

As a result, the biochar can be used in the soil again, increasing its supply of carbon and nutrients, however they produce more bio-oil than biochar as biochar is a by-product of the reaction. The bio-oil is pumped deep underground for storage, preventing the carbon from escaping. Companies such as Microsoft and Shopify pay Charm $600 for each tonne of carbon it locks underground.

Farming Underwater

A rapidly increasing global population and decades of intensive land-degrading farming practices are culminating in a worsening situation where more and more deforestation is taking place to create farmland. A new solution has been imagined: creating underwater farms.

When it comes to underwater farming, there are two main approaches. The first involves farming crops that are traditionally found underwater, such as seaweed and kelp. This is, in many ways, simpler than a lot of traditional land-based farming, since the growth of these plants is so natural.

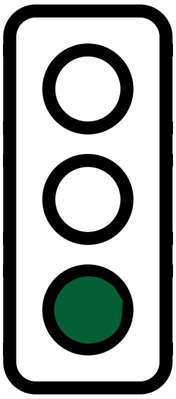
Furthermore, these plants absorb CO2 found in the ocean, so a farm acts as a carbon sink, as well as a direct source of food for humans. Alternatively, the UN suggests that feeding livestock crops grown in the ocean could reduce methane emissions by 90%.

The second idea for underwater farming is to create biospheres for land-based crops to grow in, which has several benefits over land-based farming.

No land space is used, a key benefit since land is quickly becoming the most sought-after resource on the planet due to its finiteness. The majority of worldwide deforestation is done to create land for farming, so moving farmland underwater would prevent a lot of deforestation from happening.

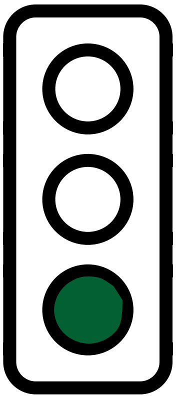
Furthermore, since the crops are in secure biospheres, no pesticides or even soil is needed, as plants can be directly fed air and nutrients, speeding up growth and reducing the risk of disease.

Cost of Implementation



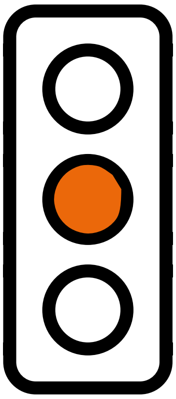
Water-based plants are very cheap to grow since you just have to plant them and let them grow, which they will continue to do if sustainably harvested. While growing land-based plants in biospheres has additional costs, the cost per plant - when a project like this increases in scale - does reduce. Moreover, it is comparable to the cost of land and pesticides when farming above water.

Complexity of Implementation



Simpler solutions for underwater farming involve growing water-based plants, such as kelp, since the plants are being grown in their natural environment. Providing underwater farms for land-based crops is more expensive, as those crops must be contained in plastic pods and supplied with air and nutrients, though neither soil nor pesticides are needed.

Capacity



The capacity of the oceans is obviously vast. The UN estimates that by using just 2% of the ocean floor for sustainable farming, we could create enough protein to feed 12 billion people. However, to achieve high levels of carbon absorption, vast numbers of farms must be made. Therefore, while underwater farming will certainly be a useful tool going forward, it must be used in combination with other ideas.

Examples

Kelp Blue is a company based in Namibia, which has started underwater farming on the Namibian coastline to produce seaweed, which can be harvested for use in fertilisers, textiles and pharmaceuticals. Kelp is one of the fastest-growing plants on the planet and it creates a habitat for many marine animals. Kelp Blue only harvests the canopy of the kelp forests, which ensures that they continue to grow sustainably and can be a useful tool for future generations.

An example of an underwater biosphere is Nemo's Garden (pictured below) off the coast of Italy, which consists of 6 air-filled plastic pods anchored to the bottom of the ocean. They are suspended approximately 5-10 metres below the ocean's surface and have sensors to measure key environmental factors such as CO_2 levels and humidity. They have grown tomatoes, courgettes, beans, mushrooms, lettuces, orchids and aloe vera plants, amongst many others, and are continuing to expand in the future.


Farming Smarter

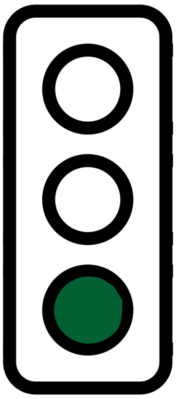
Effective farming techniques can allow soil to remain healthy and sequester carbon. Through maintaining safe, healthy levels of fertilisers, further damage to waterways and long-term soil quality can be avoided. It is important to note that, though some would claim the globe would struggle for food if we changed our current farming system, more efficient and environmentally sustainable solutions are possible.

More effective farming can yield the same - or a higher - volume of crops, whilst creating a better climatic environment. Techniques such as tilling can improve the quality of the soil. By covering crops and reducing fertilisers, precise farming allows for a better ecosystem for local and global living organisms, while also allowing less carbon to escape from the soil. Eco-farming is becoming popular, particularly considering its more efficient methods of yielding crops and livestock.

The problems of the farming world can also be attributed to the consumers - that is to say, the choices we make are directly impacting the modes of farming used. Most of us in the UK eat off-season foods, eat more than we need, and dismiss new ideas which could improve the efficiency of farmers (such as using AI to monitor growth). When food is placed in the context of climate change, it can be highly politicised and we have more power than ever.

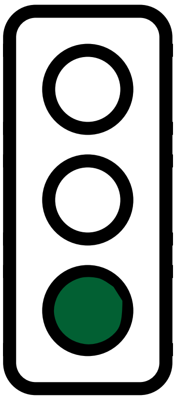
This idea of ‘regenerative farming’ is going to be crucial for the future to maintain food security and to avoid a worldwide food shortage - not to mention the practice’s added benefit of storing carbon - all reasons which make this a crucial strategy.

Cost of Implementation



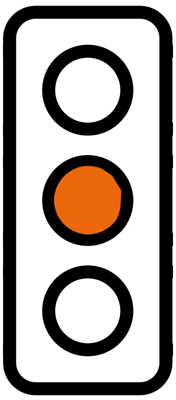
Comparatively, the cost of improving farming is very low. It is not a process of building a new technological system, but rather of realigning our current approaches to farming. There may be costs of re-educating people and paying for equipment - £700 million is recommended in the UK to enable farmers to adapt their farming land for sequestering more carbon.

Complexity of Implementation



Practices such as tilling and varied crop growth are not particularly complex. Rather, they would simply be different to traditional farming. Some methods do require extra equipment that the farmers will have to invest in. That said, these extra costs will pay off over time with better yields, though some farmers remain sceptical about investing in them. The complexities arise from changing people's perspectives on the benefits of alternative farming methods.

Capacity



Farming smarter has two positives: the capacity to prevent further emissions, while also removing carbon from the atmosphere. In the US alone, the agriculture industry is responsible for 11% of the country's greenhouse gas emissions. A reduction in these, along with the moderate ability of soil to sequester carbon, can lead to some improvements to the climate.

Example

Smart farming is one of the more advanced branches of 'smarter farming'. While natural farming and diversification is one method of smarter farming, smart farming involves the use of technology in the farming industry. For many, this has included the introduction of AI to monitor the growth of crops and actions of livestock. Drones, for example, provide a bird's-eye view which gives farmers an advantage that previously wouldn't have been possible. They also have sensors that can detect vermin, making farming more efficient and less wasteful.

One example of a smarter farming technique is the Precision Livestock Farming system, enabling the monitoring of behaviour, feeding patterns and general health. By using this, farmers can optimise feeding in a sector which is extremely polluting. As an added benefit, this monitoring can identify the presence of lameness or disease in cattle or livestock, which have the potential to damage food supplies. By being more efficient with livestock, grazing can be limited to only what is necessary and the release of greenhouse gases (particularly methane) can be reduced.


Coastal Preservation

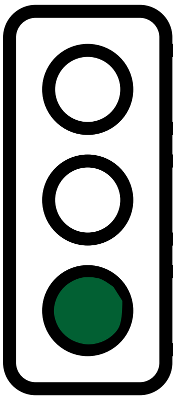
Coastlines naturally hold the potential to sink a moderate amount of carbon due to their low-oxygen environment. The mangroves, salt marshes and meadows that grow along the coastlines can act as a large carbon sink, while also being a great natural defence against flooding, rising sea levels and erosion. With such an effective system naturally occurring, it is in our best interests to minimise the damage we do to our coastlines.

Unfortunately, research has shown that only 16% of our coastlines are in good condition, despite their ability to capture carbon moderately and physically protect us from the results of our own failings. Within the ecosystem, coastlines are key for rivers to discharge into, for mangrove forests to exchange nutrients with the water, and for organisms to reproduce. Due to their low-oxygen environment, they are perfect areas for carbon sinking, which can also benefit the natural environment that resides there.

From a human perspective, mangrove forests can provide the physical protection from flooding that many coastal communities need. It is estimated that around 15% of the world's population - 1 billion people live within 10 kilometers of the coast. This may seem like a large radius, but with the realities of flooding and predicted sea level rise, it is a valid issue that needs consideration. Preserving the coast can help natural systems, infrastructure, humans and wildlife.

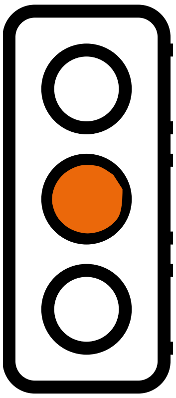
Mangrove forests are also particularly important, since they absorb very large quantities of carbon, both in above-ground biomass and below-ground sediments.

Cost of Implementation



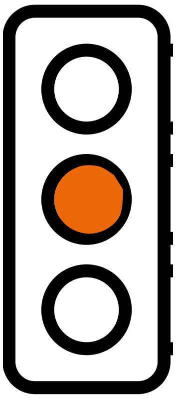
The cost of coastal preservation is very low compared to other methods of carbon offsetting. Simply put, it is a protective process, with funding for restoration (including collecting litter and re-planting diverse plant species) being beneficial. The social cost must also be taken into account.

Complexity of Implementation



In theory, implementing this is not as difficult because it is a naturally occurring system. By allowing the ecosystem to thrive without our artificial intervention, we could theoretically allow for a functioning sink for additive carbon. The issues come from preserving the coast, whilst also ensuring that those who rely on livelihoods from fishing and shipping would be able to maintain a good standard of living. Investment is also needed for the restoration of damaged coastlines.

Capacity



Coastal regions are by no means a final solution to the climate crisis, but they can work well in conjunction with reforestation efforts and other technologies. The coast itself provides moderate carbon sinking. Most countries on Earth have coastline, meaning there is a lot of potential for this to be a global solution that can be worked on together, making better coastal areas for all.

Example

Considering the passion many feel for the natural beauty of our environment in the UK - particularly surrounding the coastlines and beaches - it is no wonder that organisations such as the UK Centre for Ecology and Hydrology are working to preserve or restore coastlines. One main way they are doing this is to restore salt marshes and sand dunes.

Though sand dunes may be a common sight, the removal of such natural structures has been common to give way to relaxing beaches. Restoring sand dunes is a great way of introducing multiple benefits with one act of ecological work. Firstly, they can act as a habitat for organisms that can themselves act as a carbon store. Plants and algae that can grow there could create amazing carbon stores. For other organisms, it could provide protection and a place to thrive. Finally, they are great natural barriers to flooding or high sea levels. It is proposed that over the next 2000 years, the sea level will rise by many metres, so it is clear we will need as many defences as possible. Sand dunes are a key example of a natural defence.

Restoring Ecosystems

Ecosystem restoration applies to both land and marine systems. Restoring grasslands with wildflower seeds helps to improve terrestrial ecosystems, while allowing marine systems to recover promotes the movement of carbon from surface waters to the seafloor through currents and food chains.

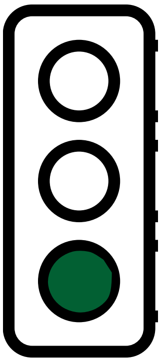
One of the easiest and most obvious strategies for increasing carbon drawdown is to restore natural ecosystems.

Soils and vegetative cover are natural carbon stores. If they are carefully nurtured to be healthy and diverse, they help to draw down and capture significant amounts of carbon. Better sustainable land management increases the soil's organic carbon and part of this management involves incorporating more diversity at the ecosystem level.

There are many key ways we can go about restoring ecosystems and a lot of these will be up to consumers to implement, such as reducing food waste or switching to plant-based diets. Both of these will reduce the amount of land needed for growing food, allowing for land that humanity has transformed into farms to be returned to its original - often forested - state.

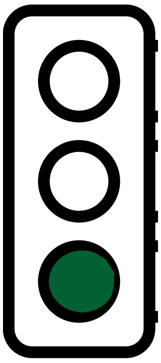
Another key way will be to protect the ecosystems we still have left, since these are still being destroyed at an alarming rate, despite the threat of climate change. Allowing these naturally occurring carbon sinks to remain in place is obviously something that must be done.

Cost of Implementation



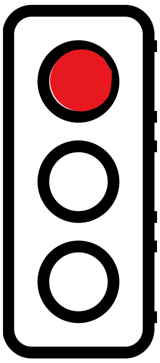
Like most of the other strategies involving working with natural ecosystems, the cost of implementation is very low. For the most part, costs will come from the acquisition of materials to reintroduce species to ecosystems and restoring marine ecosystems, such as kelp forests. However, labour costs should be low, since most of these teams can be volunteers.

Complexity of Implementation



Similar to the cost, the complexity of implementing this strategy is also very low. The strategy can be simply summarised as letting nature take its course and ecosystems will become better established and restored over time. Most of the complexity will come from implementing the policies and regulations that will ensure these ecosystems are left alone in order to be restored.

Capacity



Unfortunately, the capacity of restoration strategies is also quite low. The capacity is obviously limited to the areas of habitats that currently exist (since this is a matter of restoration, not expansion). According to a study by the Crowther Lab at ETH Zurich, the degradation of forests means they stand 328 gigatonnes of carbon below their natural capacity. However, if allowed to recover, these measures would only increase capture by 226 gigatonnes through reconnecting patchworks of habitats separated by farmland and protecting forests currently in existence.

Example

These restoration projects are not limited to NGO organisations such as wildlife and woodland trusts. China has launched a number of national restoration projects to restore degraded ecosystems. One project being the Three-North Shelter Forest Programme in 1978 where 30 million hectares of trees were planted to combat desertification. The Master Plan for National Key Ecosystem Protection and Restoration Major Projects (2021-2025) aims to expand forest cover to 26% of China's land area and 60% vegetation coverage in grasslands by 2035.

Between 2001 and 2010, these areas acted as a carbon sink for approximately 132 million tonnes of CO_2 per year, of which over 50% was attributed to these restoration projects. Such a massive restoration project is clearly having a good effect on the planet and, with plenty of other benefits for humans and wildlife, this is a great project to replicate across the world.

Growing Forests

Supporting the expansion of forests in rural Kenya is one of the most efficient and trustworthy ways businesses can offset their carbon emissions. Trees are natural carbon sinks. They also provide a first line of defence against floods and landslides. Their existence is incredibly beneficial to the soil because they allow high levels of organic matter to flourish in it, which helps prevent soil erosion. Furthermore, they support humans, wildlife and biodiversity in countless additional ways.

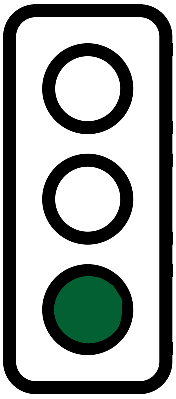
The tropics should be an especially important area of focus for growing trees. In places such as Kenya, for example, trees grow up to 10 times faster than in Northern latitudes. Far greater concentration is needed on improving afforestation in these areas if they are to be optimised as effective carbon sinks.

These fast-growing trees provide much needed shade and safe habitats for humans, wildlife and a wide range of other organisms, resulting in improved biodiversity for the area too. Many rural communities rely heavily on the commodities from forests for their livelihoods and recognise them as a critical source of food, shelter and income.

Unfortunately, due to mankind's exploitation of the natural world for profit, the full potential of trees is being squandered. This introduces a key point of contention around growing new forests: environmental education is urgently needed for those abusing the forests. They must learn that it is more beneficial to leave the ecosystems alone or put in restorative measures. They also need education on sustainable alternatives for income generation.

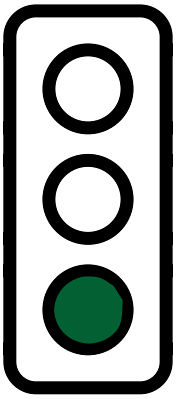
Trees deliver so many benefits besides simply being carbon sinks - yet another reason for why investing in reforestation, particularly in rural Kenya, offers an outstanding solution to mitigating our climate crisis.

Cost of Implementation



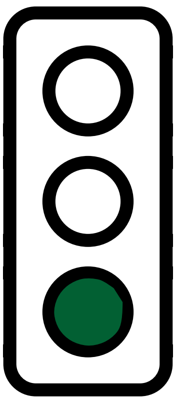
Sourcing land and management costs must be factored into any project. When you take all the other methods discussed in this report into account, afforestation is a remarkably low cost endeavour, even when you factor in renting the land and paying people to plant and provide onward care for the saplings in the early months. The cost of stopping people from farming the land must also be incorporated. Contrary to this point, however, is the fact that trees can provide medicine and food, alleviating hunger and poverty, as well as drawing down and locking in CO_2.

Complexity of Implementation



It is easy to implement the planting and growing of trees, in theory, at any rate. All you need to do is pot seeds, water them until they turn into saplings, plant them, cover them with water-retaining mulch and continue to water them until they put down tap roots. The problems with growing forests come in the form of securing appropriate parcels of land and raising the finances required to pay people to maintain or protect the growing project. Once land has been unlocked and employment secured, it is the most efficient way to sink carbon, as it has been for millions of years.

Capacity



On average, a tree planted in rural Kenya can sink 1/4 of a tonne of CO_2 in 5-7 years. Kenya has approximately 10% canopy cover and trees there grow up to 10 times faster than in Northern latitudes. There is a great deal of land that could be utilised and transformed into life-giving forests to benefit humankind and wildlife and create a practically inexhaustible way to capture carbon. There is huge untapped potential for offsetting carbon, especially in the tropics but in other countries too. Given that it can be implemented relatively easily, it should be prioritised globally.

Example

Word Forest is a UK charity on a mission to reforest Kenya. It has planted around 1.4 million trees and delivered over 100k hours of environmental education on seed/sapling/tree related topics, income generation and more.

Planting trees alone is not enough to ensure carbon-sinking abilities are maximised. Word Forest puts a raft of supportive measures in place to best enhance the trees' potential. These include facilitating community learning that has women's empowerment at its heart. They also provide fencing to protect saplings from marauding wildlife, as well as shading and structures covered by insect nets in their nurseries. This ensures sapling rearing is more water-efficient and it protects them from swarms of unwanted pests.

Word Forest brings further benefits with their reforestation projects by building classrooms and running income generation workshops, so communities can build resilience and support themselves financially. In turn, the community plants trees and ensures they have the best possible circumstances to grow to maturity. Word Forest's successful projects highlight the vital importance of caring for the people who care for the trees.

Dominic Hurndall
Partner, Oaklin
Corporate Partner Word Forest

Conclusion

In Clare Nasir's introduction, she challenged us to consider which carbon drawdown method provides the rapid, consistent and reliable solution we need to address the threat of climate change. In truth, there is no 'silver bullet' solution to the problems we face. Such is the scale of the challenge and the complexity of the transition ahead, that no single mechanism for carbon reduction will provide the solution on its own.

Not all the technologies identified in this report will reach operational viability, but we need many of them to do so, on an industrial scale, as quickly as possible. As the report makes clear, however, many of the carbon capture technologies are dependent upon new renewable sources of energy if they are to be effective at reducing CO_2 levels. This in turn calls for a radical overhaul of how we produce, distribute, and consume energy. We are used to the linear models of fossil fuel supply chains. The future is likely to be very different. New technologies will harness different niches of the daily energy production cycle, while industrial and domestic battery storage will transform energy markets into two-way networks of hubs and nodes built around agile sources of energy production and consumption.

While we are rightly focused on the existential challenge of climate change, in truth the world faces three environmental crises. The first is climate change, however, society must also address the linked problems of biodiversity loss and environmental pollution. Only one of the carbon reduction mechanisms in this report helps to tackle all three of these areas: planting trees. The restoration of forests, and the wider ecosystems that naturally accompany them, is the single most effective and least costly mechanism to address the climate emergency.

As the report makes clear, the potential from tree planting is huge, but in order for trees to be planted in a manner that is effective at scale, societies must find a way of valuing the contribution the trees make. We must create a 'return on investment' from the utilisation of land for the restoration of large and biodiverse forests. Whether it's through measures like offsetting carbon emissions, or tax credits for creating habitats that benefit society at large, mechanisms to appreciate the value that tree planting offers are urgently needed.

When we say 'forests', we should not miss the need to extend the term to include marine forests; ecosystems on coasts and in the oceans, which have the potential to capture colossal amounts of carbon if they are returned to health and managed well. It is heartening to see marine carbon reduction featured so prominently in the report, alongside the better understood and more prominent efforts of terrestrial reforestation.

Whether it's trees, oceans, carbon capture technology or remineralisation, our focus must remain on the widespread adoption of carbon reduction measures and the restoration of biodiversity, in a manner that is valued by the societies it sustains. The individual efforts of organisations like Word Forest offer inspiring examples of what can be achieved with corporate partner support. It shines a light on the willingness of so many in society to address these problems and show how even small efforts can make a huge difference.

Their efforts give us all hope that societies large and small will come together to support new habits and to value new ways of producing and consuming sustainable energy. The scale of the challenge, however, will only be addressed by bringing policy makers, investors, industry leaders, landowners, insurers, developers and scientists into a single facilitated dialogue. It will be hard to achieve in any one country, but as nature is oblivious to boundaries, efforts must transcend borders. An internationally coordinated response must be achieved if the worst effects of the climate crisis are to be managed and overcome.

In their report, Word Forest has given us a glimpse of some of the carbon reduction technologies that will become a routine part of our future energy infrastructure. Above all, however, their analysis highlights that it is the simple act of planting a tree that has the greatest and most cost effective impact. In parallel to investing in upgrading national electricity grids and building the carbon capture technologies of tomorrow, we would do well to ask ourselves why we can't kickstart the energy transition by simply planting lots more trees, today.

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