Nature-based sinks for CO_2 and sources of carbon feedstocks

Final 25% Series Paper

Oxford Smith School of Enterprise and the Environment

May 2021

Katherine Collett, Vanessa Schreiber, Mike Mason and Cameron Hepburn

Acknowledgements

The authors would like to thank the dinner attendees who engaged so actively in discussions. In particular, we thank Nathalie Seddon and Steve Smith for very valuable, expert input to the report. Sir Chris Llewellyn Smith has been integral to the Final 25% Series throughout. The authors would like to thank him for his vital role in organising the meetings, insightful input and constructive comments on the text. Brian O’Callaghan provided early-stage contributions to the report and helpful involvement in the Final 25% Series which is greatly appreciated. This Final 25% Series as a whole was made possible by generous financial support from Mike Mason and Richard Nourse.

Final 25% series

The Final 25% project at the Oxford Smith School of Enterprise and the Environment aims to identify the landscape of key technological solutions for the final stages of the essential transition to net-zero, and then net-negative, CO_2 emissions.

The underlying premise is that 80% of emission reduction can be achieved by decarbonising electricity generation, transport and heating, and by improving energy efficiency, using technical solutions which are already the focus of significant research and development. The remaining 20% of global emissions are perceived to be difficult to decarbonise and currently lack clear reduction pathways. Research attention must be directed to these emissions sources now, so that necessary technologies and business models can be developed over time.

Net-zero emissions are unlikely to be enough to stabilise planetary temperature below a 1.5°C rise. It is likely that temperatures will overshoot; therefore, in order to limit climate change repercussions, there is a need to go net-negative, by absorbing between 2 and 20 Gt CO_2 per year by 2100 [1]. At the least, this is a further 5% reduction on top of eliminating present-day emissions.

The **Final 25% Series** focuses on the hard-to-abate sectors which form the final 20% of emissions, as well as ways of achieving 5% net-negative CO_2.

A key part of the project is a series of dinners convened in Oxford and London. The Oxford dinners, where selected guests include leading scientists, engineers and technologists, focus on the science and technology research and development needed to reduce emissions and achieve net-negative. The London dinners, where guests include leaders from finance, industry and government, explore how these new ideas can be funded and deployed at scale to make a material contribution.

This report series describes the conclusions of the discussions, offering recommendations based on the insights of experts working closest to these topics. The subjects covered in this ongoing series include nature-based CO_2 sinks, long-term energy storage, the future of cooling, alternatives to fossil carbon for industrial products and processes, bankable carbon capture and storage, and the climate impact of alternative proteins.

Executive summary

To mitigate climate change, around 2–20 Gt per year of greenhouse gases, particularly CO_2, may need to be removed from the atmosphere by 2100. Removing and storing atmospheric CO_2 to mitigate climate change is a public good – markets will not deliver this at the appropriate level without government intervention – which means it is particularly important to examine processes and mechanisms that are cheap, scalable and effective. Simultaneously, to foster a transition from industrial use of fossil carbon to sustainable carbon, alternative sources of carbon for economic uses will be required.

Nature can provide both a CO_2 sink and a source of carbon feedstock. Here we examine three promising nature-based solutions. The first is ***crop growth in agriculturally unfavourable lands.*** Plants which grow on semi-arid land, such as those using Crassulacean acid metabolism (CAM), halophytes (which grow on saline land), and algae can draw down CO_2 and provide carbon feedstocks for economic use (ie bio-feedstocks), with minimal agricultural competition. The second is ***forest restoration***, which provides an in-situ sink for CO_2 and can offer ecological benefits if effectively implemented. Biodiverse forests can offer ecological benefits and a CO_2 sink, whereas monoculture plantations may not. In order to be able to reforest a region, the service currently provided by the land must be met by some other means. Often deforested land in the tropics is used for grazing or crop growth for livestock. Thus, there is a need for alternative protein production in order to release lands for reforestation. The third is ***increasing soil carbon***, a CO_2 sink which may also increase crop yields.

To examine and scale up any of these solutions, interdisciplinary research is needed, supported by in-situ trials in global geographies. In regions with appropriate land conditions (eg semi-arid, saline, tropical, regions suitable for forest restoration), collaboration with governments, local authorities, and communities will be paramount. Four main research areas are identified. First, further research is required to map land suitability and potential availability, particularly with reference to the need to avoid competition with food crops and other important land characteristics (eg biodiversity). Second, advances in alternative proteins, which could release lands for use as CO_2 sinks, as discussed in the accompanying report *The climate impact of alternative proteins* [2]. Third, genetic and technological research into the three highlighted nature-based solutions is required to understand and optimise these processes. Technical knowledge gaps exist mainly with respect to the suitability of different plant varieties as a source of bio-feedstocks (the need for bio-carbon is discussed in the accompanying report *Industrial need for carbon in products* [3]), the production of sterile strains, and measuring increases in soil carbon (to create a market for this service). Fourth, analyses of the wider ecosystem and socioeconomic impacts of different nature-based solutions are required.

As HMG and UKRI have recognised, the early stage research will require government funding as greenhouse gas removal is a public good, and the current lack of any market precludes sufficient private sector investment. The global nature of this challenge leads to the suggestion that funding from DFID would be valuable in developing technical pathways that are internationally applicable, financing overseas demonstrator projects, and facilitating international co-operation and policy evolution. Ultimately, it is important to develop policies, regulation and financing options to create the appropriate markets and encourage private sector engagement.

Table of contents

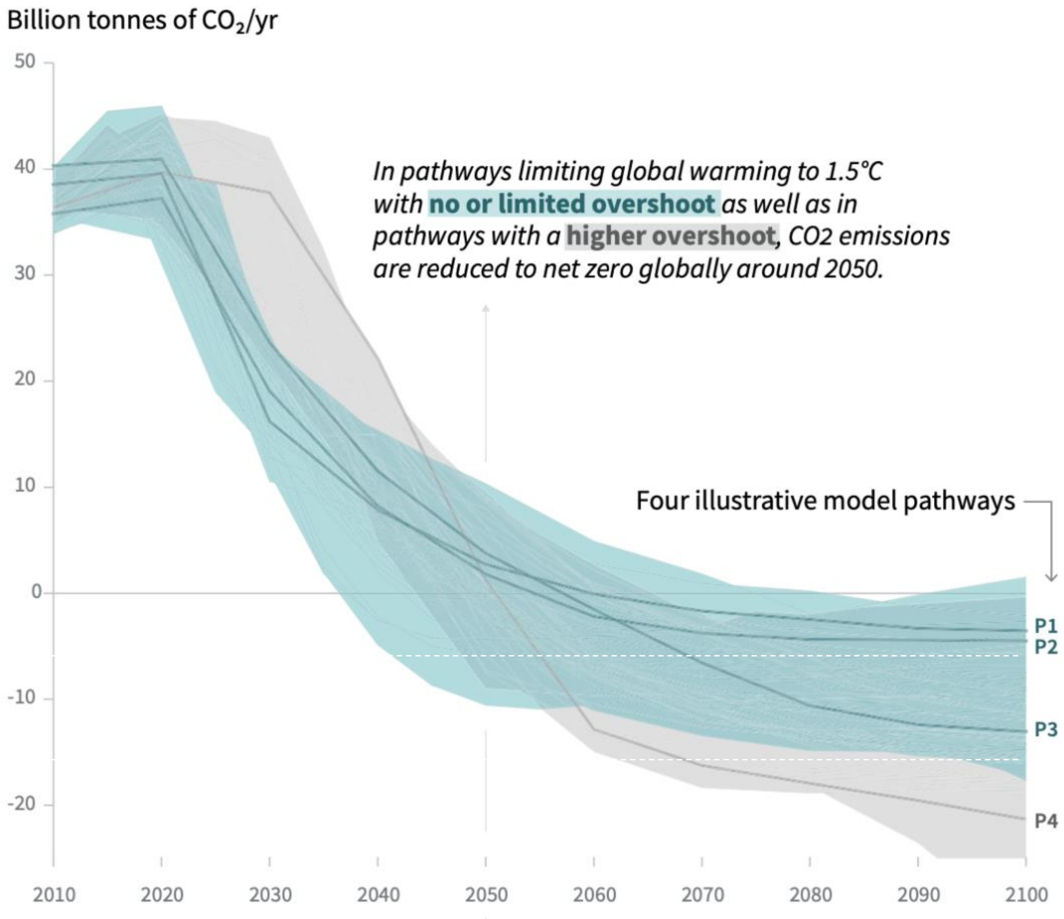
1 The need for CO_2 sinks and sources of carbon feedstocks

Mitigating climate change requires greenhouse gas removal (GGR). Globally, to meet the goals of the Paris Agreement, net-negative CO_2 emissions (ie sequestering CO_2 [1]) may be required to limit cumulative concentrations of atmospheric CO_2 and temperature increases [4]. The Intergovernmental Panel on Climate Change (IPCC) Special Report on the Impacts of Global Warming of 1.5°C [1] estimates that the necessary drawdown of CO_2 from the atmosphere will be between 2 and 20 Gt CO_2 per year in 2100, depending on the pathway taken and the speed of action, as shown in Figure 1. This is roughly 5-50% of present-day emissions, which are around 40 Gt CO_2 per year. However, the fact that the capture of atmospheric CO_2 to mitigate climate change is a public good poses political, economic and financing challenges [5], as well as technical challenges. Initiatives will require government funding and will need to be implemented at a large scale, hence an effective, affordable and scalable sink for CO_2 is required.

In recent years, this subject has attracted attention. The Royal Society and Royal Academy of Engineering, with contributions from academic experts, published a state-of-knowledge report on GGR [6]. In 2019, *Nature* published a comprehensive techno-economic study from the University of Oxford investigating CO_2 removal and utilisation pathways [7]. Both reports identify nature-based solutions as a key pathway for GGR and highlight the need for further research. Furthermore, UKRI has recently made a call for GGR demonstrator projects, recognising the potential market size and importance of UK industry developing expertise in this area.

2–20 Gt CO_2 per year is the scale of GGR required by 2100

This value is the amount of removal in pathways to 1.5°C with little or no overshoot. These pathways also assume widespread and deep reductions in emissions across sectors, including land use. To the extent that these reductions are not realised, the level of GGR needed for 1.5°C will be greater.



In pathways limiting global warming to 1.5°C with ***no or limited overshoot*** *as well as in pathways with a* ***higher overshoot****, CO2 emissions are reduced to net zero globally around 2050.*

Figure 1 Global net CO_2 emissions pathways limiting global warming to 1.5°C. From the IPCC Special Report on Global Warming of 1.5°C [1]**.**

Currently, petrochemicals are the dominant source of carbon for use in products (eg polymers, pharmaceuticals), and account for 14% of oil production, equivalent to 12 million barrels per day [8]. In a negative-emissions scenario, it is plausible that the current petrochemical business model will no longer be viable due to electrification, alternative fuels, and cheap renewable energy generation. The scale of the need for carbon is considered in the accompanying report: *Industrial need for carbon in products* [3]**.** To replace the use of fossil carbon, an alternative source of carbon will be required.

Nature can assist in solving these two challenges, acting as both a sink for CO_2 [9]–[12] and a source of carbon [6], [13]. Plants use atmospheric CO_2 for growth via the process of photosynthesis, thus the carbon they contain can either be stored (CO_2 sink) or extracted for use (carbon feedstock). The rest of this report outlines the potential role of nature in capturing CO_2 and providing carbon. It contains detailed descriptions of three mechanisms through which nature can take on these roles: crop growth in agriculturally unfavourable places, forest restoration and increasing soil carbon. Actions are recommended which should be taken now by policy makers to increase research into the use of nature as a CO_2 sink and carbon source, to develop market mechanisms and to foster private investment where possible.

2 The potential of nature-based solutions

Nature has the potential to act as both a CO_2 sink – also termed greenhouse gas removal (GGR) – and as a carbon feedstock source. The latter can take place through bio-refining crops. The former occurs through two main routes: plant growth or increasing soil carbon. Nature-based solutions [11] are not the only potential sink for CO_2 [6], [7], [13], [14]. A much-discussed alternative is direct air capture (DAC). DAC requires significant energy and is currently comparatively expensive [15], [16], with estimates suggesting that the cost of DAC at more than double that of bioenergy with carbon capture and storage (BECCS) [14], [17], although this will depend on the cost of energy. Nature-based solutions depend on very few external resources, are cheap and have widespread application [6], [7], [18]. Figure 2 demonstrates some of the pathways by which nature can act as a CO_2 sink or a carbon source.

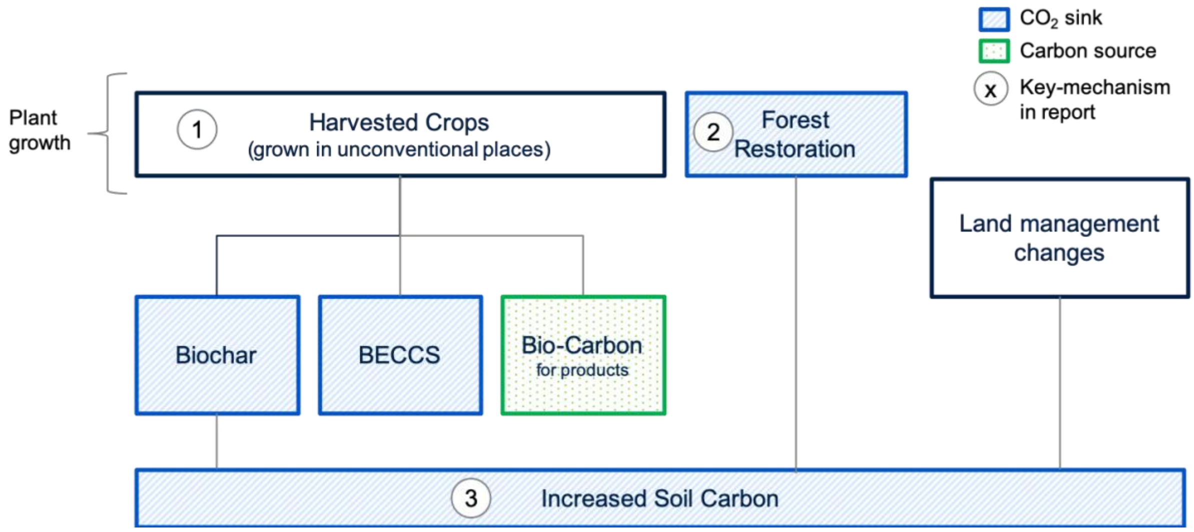


Figure 2 Nature-based solutions to a sink for carbon dioxide (blue hash) or bio-carbon feedstock source (green dots).

As a sink for CO_2, plants can be selected to suit the relevant environment and could range from forests to grasslands. They can be annually harvestable crops (eg sugar cane) or planted and left to grow indefinitely (eg forests). Harvestable crops offer the benefit of requiring only a finite area of land. However, they cannot be left to rot because this would release most of the CO_2 previously captured by the plant back into the atmosphere. Instead, harvested crops can be processed in three main ways in order to provide a long-term carbon store. As in Figure 2, they can be pyrolysed to produce biochar (a soil additive that may hold promise as a means to increase soil carbon, increase crop yields and possibly reduce water use); they can be used for bio-energy with the by-product CO_2 captured and stored (BECCS); or harvested crops could provide carbon for use in products [3].

Harvested crops can be used as a source of carbon in the form of bio-feedstocks. Plant matter is predominantly carbon, oxygen, hydrogen and nitrogen atoms, which can be processed in a bio-refinery to produce useful platform chemicals, replacing petrochemicals. Over the full lifecycle of the crop [19], bio-based carbon is effectively CO_2-neutral (provided there is no land use change) because any CO_2 released at the end of the product life was absorbed during the growth of the crop. However, not all plant species produce easily extractable, useful base chemicals for industry; research is needed to identify which species should be used. As calculated in the report *Industrial need for carbon in products* [3], if the entire polymer feedstock in 2050 were replaced with bio-carbon it would result in the need for these crops to absorb at least an additional 4.5 Gt CO_2 per year to produce enough carbon—see grey box on page 10 for further details.

For crops to be socially accepted as a sink for CO_2 or source for carbon, they must meet three important criteria; specifically, they:

i) **must not compete with food crops** or other important local land uses. Conventional, productive land for food crops is already in high demand. This indicates the need for biomass *crop growth in agriculturally unfavourable lands* [20] – one of the key mechanisms, discussed in Section 3.1;

ii) **must enrich global biodiversity** [11], the loss of which is recognised as a global risk [21]. Efforts must be made to support local ecosystems and biodiversity [11], [22], [23], and any localised negative impact must be carefully considered and weighed against improvements in biodiversity that a change may create elsewhere. Introduction of new crops must be controllable so that the species do not become invasive in a given region [24], [25]; and

iii) **must respect social safeguards** and protect the land rights of locals [11].

Bio-carbon for products in 2050 could require an additional 4.5 Gt CO_2 per year to be captured by crops

Polymer feedstocks in 2050 could require over 1.2 Gt carbon per year. If this demand is met by bio-carbon, for every 1 Gt of carbon atoms 3.7 Gt CO_2 must be absorbed due to the difference in molecular weight. Therefore, 4.5 Gt CO_2 would need to be absorbed by crops to produce 1.2 Gt of carbon. This assumes perfect conversion from CO_2 to carbon within a plant and from bio-feedstock to useful bio-carbon chemicals.

Between 2010 and 2015, there was a net loss of forested land of 3.3 million hectares per year [26]. This accounted for emissions of 5 Gt CO_2 per year [27], over 10% of annual global emissions. Deforestation destroys the local ecosystems and the replacement land-use can lead to land degradation. There is an urgent need to cease deforestation because reforestation may need a long time to replace the ecosystems lost due to deforestation [28] and newer forests are thought to store less carbon than old, established forests [11], [29]. However, in the case of already deforested regions, ***forest restoration*** is the next best thing, and is one of the key mechanisms examined in this report. Forest restoration provides both the carbon capture mechanism [30] and the store (the carbon is secured within the wood of the tree [7]), and can provide rich, biodiverse ecosystems [18], [23], [31]. It is important to note that the CO_2 sequestration rate of forest ecosystems is not indefinite [6]. Instead, the important metric is how much they are able to store cumulatively. Deforestation in the tropics occurs predominantly to provide land for animal agriculture [32]. To release this land for reforestation, this service (ie protein production) must be met by other means. Alternative proteins could play a major role in freeing-up this land for forest restoration [2].

There are many forms of broader restoration and land stewardship, which are important nature-based solutions for CO_2 drawdown [6], [29]. For example, mangroves are able to sequester carbon at rates 45 times that of boreal forests, and peat lands hold 25% of the global carbon stores [29]. These carbon stores must be protected and restored where currently depleted. However, this report focuses on forest restoration in particular.

Over past decades, peat lands have been depleted and soil carbon has been reduced [33]. By changing land management, globally, soil could be used to harness atmospheric carbon to restore and ***increase soil carbon*** levels while acting as a sink and store for carbon [18], [23], [31], [34]. This is one of the key mechanisms discussed in the report.

3 Key nature-based solutions

In this section, we expand on the three promising mechanisms, outlined above, by which nature can be used as a sink for CO_2 and source of carbon. These are: crop growth in agriculturally unfavourable lands, forest restoration, and increased soil carbon. The benefits and challenges of each mechanism are summarised in Table 1.

3.1 Crop growth in agriculturally unfavourable lands

Crop growth in locations unfavourable to traditional agriculture offers the key advantage of reduced competition with food crops. Significant research efforts have focused on more “conventional” sources of biomass (albeit mainly for energy use), such as waste, food crops, and grasses [35]–[37]. However, three plant categories have been under-investigated and are focused on in this report due to the regions in which they grow. These are: Crassulacean acid metabolism (CAM) plants, which grow in semi-arid regions; halophytes, which are able to grow in highly saline areas; and algae, which are aquatic plants.

3.1.1 CAM plants

CAM plants are highly water efficient and grow on semi-arid or marginal lands, which are unsuitable for food crops. Globally, there are thought to be 5–6 billion hectares of drylands [38]–[40]. CAM crops have low rainfall requirements (they are reported to survive on as little as 25 mm annually [41]) and can cope with intermittent rain, thriving on 200–800 mm precipitation annually [40], [42]. Under ideal growth conditions (temperature, rainfall, radiation), species have been found to produce up to 40 tonnes dry mass/hectare/year [43], [44], with yields of 5 tonnes dry mass/hectare/year being more conservative [45]. This is equivalent to 2–20 tonnes carbon/hectare [45]. As an indication of scale, if each hectare were able to produce this, 240 million hectares of drylands could produce 1.2 Gt carbon/year [3], sufficient to meet the likely 2050 industrial need. This would require covering ~5% of the global drylands with CAM plants. To mitigate labour costs associated with re-planting, it would be preferable to use CAM plants which coppice so that the crop will regrow without the need to re-seed [43]. CAM plants, as all plants, have the potential to produce valuable platform chemicals [46], [47], and in some cases complex hydrocarbons [48], [49]. Due to their lower lignin content [40], they can be processed relatively easily. However, the use of CAM plants is not without challenges. There is a risk that some particularly vigorous CAM plants can become invasive pests [24], [25]. Research is needed to control the spread of crops. Fortunately, there are estimated to be over 16,000 CAM species to select from in the search for the most useful properties [50]. Species selection for bio-carbon feedstocks has received little research attention. Most of the limited previous research has focused on CAM plants as bio-energy crops [40], [44].

3.1.2 Halophytes

Halophytes are able to grow in regions of high salinity, including land salinised by over-irrigation, and some desert areas [51], [52]. It is unclear how many species of halophytes exist, but it is thought to be over 1,500 [53]; a database is being curated by Sussex University [54]. Some of these have been used to produce valuable compounds [55], [56], including liquid biofuels [56] and edible oils [56], [57]. Halophytes also have the potential to decrease soil salinity by storing salts in their tissue, theoretically making the land suitable for more-varied crop growth [51], [56], [58]. So far there has been a lack of research into the many species, agronomy and species interaction with water availability and salinity concentrations.

3.1.3 Algae

Algae are fast-growing aquatic plants that effectively draw down CO_2 [59] and are dense sources of protein, discussed in the accompanying report *The climate impact of alternative proteins* [2]. Algae can produce useful lipids, surfactants and polymers [60]–[63]. Large-scale farming of micro-algae is often carried out in cement raceways or closed, transparent photobioreactors [64], [65]. These are both expensive to build, meaning micro-algae are currently only considered viable for high-end value-added products [64], [65]. Both farming methods are location agnostic, although the process requires sufficient renewable energy supply [64]. Despite substantial international funding of micro-algae biofuel production projects over the past decade, challenges still exist associated with efficient growth and scale-up [66]. An alternative is growing macro-algae (seaweed) in oceans; in 2018, SeaGrown [67] set up a commercial farm in the North Sea. The applications of algae as a biofuel or protein source [2] has been gaining interest, and their potential as a bio-carbon feedstock has been demonstrated by UK start-up Notpla which produces algae-based polymers [68]. Despite this, further research into conversion from algae biomass to a wide range of useful products is deemed valuable [61].

3.2 Forest restoration

Forest growth can be either afforestation (forests grown in habitats that have been treeless for a significant period, so as to be considered naturally treeless) or reforestation (forests grown in recently deforested areas). Whichever technique is employed, it is important to avoid the introduction of fast-growing monocultures, which do not offer biodiversity advantages, and in some cases can be damaging to ecosystems and existing carbon stores [11], [29]. Moreover, the ability of monoculture forests to store carbon over the long term is believed to be impaired by their lack of resilience [11], [29]. Instead, species-diverse forest restoration is the credible option for GGR (ie forests which aid recovery of an ecosystem in collaboration with local people to provide long-term social and ecological benefits [28]). Forestry plantations where the trees are harvested for products such as paper and mulch, which have a short use-life, are not to be considered a CO_2 store.

Forest restoration can replenish soil carbon stores [6], improve soil health, and prevent further soil degradation leading to CO_2 release. Calculations have shown the potential of forests as a CO_2 sink could be in the range of 0.5–3.6 Gt CO_2 per year by 2050 [16], [69]. However, if all grazing land within forested ecosystems were to be reforested, this capacity could be in the region of 2.7–17.9 Gt CO_2 per year [70] – although this is unlikely to be achievable as forests may no longer be able to grow in all of these regions or they may now be populated by rural communities. The range for CO_2 drawdown is large due to the knowledge gap surrounding available land. However, forests do not absorb CO_2 indefinitely. After 20–100 years, they reach equilibrium and no longer act as CO_2 absorbers [6] – the total sink rather than the rate of sequestration is the important metric. It is challenging to find calculations of the total sink available.

The major challenges surrounding reforestation are ecological, social and concerned with land availability. Ecologically, appropriate combinations of plants must be planted in each reforested region; there is no one species that can be uniformly rolled out [71]. Socially, the majority of deforested land is now being used for other purposes, often crops for animal feed or grazing land for cattle. Unless a market develops to incentivise forest restoration and the global demand for protein can be met in some other way, there will be land availability challenges. Market creation to give GGR and biodiversity services value is of utmost importance, although this probably needs to be complemented with advances in alternative proteins which could provide a vital route to releasing deforested land for forest restoration [2]. The provision of alternative jobs for locals, who previously relied on livestock farming for income, must also be considered in GGR market evolution.

3.3 Increasing soil carbon

Increasing the carbon content of soils, either by changing land management (ie agricultural practices [18], [31]) or through the introduction of treatments such as biochar, allows the soil to act as a carbon store. Globally, the technical potential for soils as a CO_2 store has been calculated to be between 4.4 and 14 Gt CO_2 per year [72], [73]. The “4 per 1000” initiative aims to increase carbon in the top 1 metre of soil, globally, by 0.4%, aiming for a sink of 9 Gt CO_2 per year [74]. However, other research has suggested significantly reduced upper limits for soil carbon sequestration of 5 Gt CO_2 per year [69]. Increased soil carbon is achieved by changes in agricultural practices (such as cover-crop rotation, use of mulch, reduced tillage and management of animals, nutrients, fire and water [6], [9]). The main challenges are that (i) there is a chance that CO_2 will escape over a decadal time scale [7], [75] so practices must be maintained even as the sink saturates [76], and (ii) that, at present, there is no accredited metric for monitoring soil carbon levels, resulting in challenges to quantify and build regulated markets for this service.

Biochar is produced from heating biomass in the absence of air (pyrolysis). The resulting char is a stable form of carbon that can be stored in soil [77], [78]. It can be made from most reasonably dry biomass. The global potential for biochar as a CO_2 store is reported to be in the range of 1.8–4.8 Gt CO_2 per year [12], [76].

The added benefit of increased soil carbon is that, under certain conditions, it has been reported to increase crop yield [34], [76], [79], [80]. Thus, increasing soil carbon to improve crop yield could represent a viable stand-alone business model. There is uncertainty surrounding whether using biomass to produce biochar will be the most valuable use of biomass, which could otherwise be used to produce electricity, high-value products [3] or proteins [2]. The competition for biomass may quash any potential biochar business case. Additionally, the impact of biochar is unclear (it has been reported to vary between locations) and there is uncertainty surrounding its effect on emissions of other non-CO_2 GHGs, such as methane and nitrous oxide [76].

3.4 Land availability

Our World in Data has produced an indicative map, shown in Figure 3, which illustrates how the world's land is used showing total aggregate area by type of use and cover.

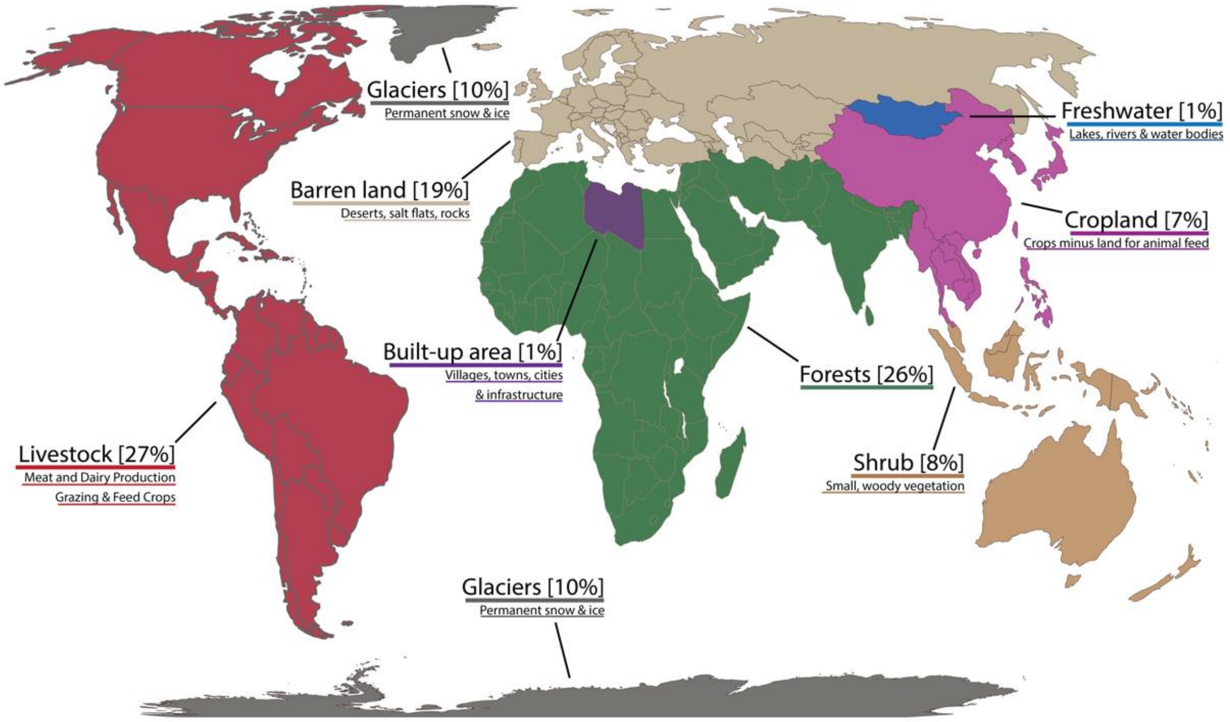


Figure 3 Map to indicate aggregated global land use. After Our World in Data [81], **using data from World Bank** [82] **and FAO** [83]**. Using Eckert IV map projections.**

The combined area of barren land and shrub area accounts for 27% of landmass (equivalent to the global cover of semi-arid and dry sub-humid land mass [38]). Not all of this land would be environmentally suitable and potentially available for vegetation growth; however, it highlights the scale of opportunity. There is an important differentiation to be made regarding land suitability, current availability and potential availability. The area of environmentally suitable land will vary drastically depending on the environmental filters which one applies [84] (eg slope, temperature, rainfall), with some areas achieving a higher potential yield depending on the environment [44], [84]. Of these environmentally suitable regions, land use from satellite data can be used to identify current land availability; however, this is unable to identify potential land availability (eg a low-margin pineapple plantation owner who is open to re-purposing their land). Determining the potential land availability is important and challenging; it is discussed further in Section 4.1.1.

Figure 3 highlights another important point. The land used for livestock (to grow crops for animal feed and for grazing) is 27%. Much of the land that was deforested in tropical regions over the last century is within this category. In order to restore forests in these regions, the services provided by this land (ie protein and lipid provision) will need to be met by an alternative, cost-competitive mechanism. Therefore, the evolution of the alternative proteins market, as discussed in the accompanying report *The climate impact of alternative proteins* [2], is highly integrated with forest restoration.

3.5 Summary of these three nature-based solutions

A summary of these three nature-based solutions, their application as a CO_2 sink or a carbon source, benefits and challenges is shown in Table 1.

Table 1: Benefits and challenges of specific nature-based solutions

Nature-based solution		**CO_2 Sink**	**Carbon Source**	**Benefits**	**Challenges**	**Research status**
Crop growth in agriculturally unfavourable places (Section 3.1)	CAM	✓	✓	• Do not compete with food crops • Do not need re-planting when harvested • Large areas of semi-arid land • Thousands of species, large range of potential products • Limited dependence on external resources	• Need sterile strains to avoid invasive spread • Unknown knock-on effects on ecosystem	Species extremely under-researched
	Halophytes	✓	✓	• Do not compete with food crops • Limited dependence on external resources • Large areas of salinised and degraded lands exist	• Unknown knock-on ecosystem effects	Species extremely under-researched
	Algae	✓	✓	• Do not compete with food crops	• Micro-algae production expensive	Use as source of carbon under-researched
Forest restoration (Section 3.2)		✓	-	• Improve ecosystem and soil quality • In-situ carbon store	• No one solution fits all – appropriate species must be planted in each location	Suitable land availability and ecosystem impact under-researched
Soil Carbon (Section 3.3)		✓	-	• May result in increased crop yield • In-situ carbon store	• CO_2 may escape over decades • Monitoring soil carbon levels	Effect on crop yield highly under-researched

4 Recommendations for action

Nature has the potential to play a major role in deep decarbonisation. However, there is a need for research and development in several areas. Additionally, appropriate policies and regulation will need to be introduced to encourage: i) market growth for CO_2 capture (a public-good commodity) and ii) private investment in scale up of nature-based sources of carbon feedstocks. These will need to be in line with the three criteria mentioned previously: avoiding competition with food crops, enriching global biodiversity, and respecting social safeguards.

Action is already being taken to develop UK industry to play a role in the future global GGR market, valued at a potential £400 billion [85]. UKRI recently called for GGR Demonstrator Projects including BECCS, biochar, and reforestation. However, there remain knowledge gaps that would benefit from additional R&D. This section highlights these gaps and emphasises the fact that GGR is a public-good global challenge, requiring international engagement and trials.

4.1 Priority areas for research and development

Further research is needed in four categories: i) mapping of land suitability and availability, ii) advances in alternative proteins to alleviate land for GGR, iii) research to fill knowledge gaps associated with the key nature-based solutions discussed in this report, and iv) analysis of the cross-cutting impacts. Each of these requires inter-disciplinary research and field work. UK-funded research will need to be implemented outside the UK, in regions with appropriate land types (eg semi-arid, saline, tropics, etc). Collaboration with governments, local authorities and communities in these regions will be paramount.

4.1.1 Mapping of land suitability and availability

Mapping is needed to identify regions suitable for reforestation and growth of CAM and halophyte crops. There are two stages to establishing suitable and available lands where these crops may grow. Firstly, the environmentally suitable regions must be identified and the future effects of climate change and human intervention considered. Secondly, it must be determined which of these regions are "available" (or have the potential to be, depending on market signals). It is interesting to note that there is debate surrounding classification as available land. As mentioned in Section 3.4, it is potentially available land which is of interest. Although remote sensing and satellite imagery is useful in identifying current land use, in suitable regions where the land availability is uncertain it will likely need to be accompanied by localised qualitative analysis.

Many technical datasets exist to help identify environmentally suitable regions (ie where there is appropriate rainfall, soil, temperature, slope), which can be combined to calculate the environmental productivity index in a region [44], [84] – ie how well the crop will grow. Although these datasets need to be kept up to date, the greatest challenge appears to come from identifying land availability.

The Food and Agriculture Organisation of the United Nations (FAO) [86] holds significant aggregate data at the country level about land cover and agricultural use, and several satellite imagery land maps exist, including from the European Space Agency GloCover Project [87] and NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) [88]. Between 2011 and 2017, a Geo-wiki crowdsourced dataset was established through four campaigns [89]. However, there are often discrepancies between datasets, and land use cannot always be identified from satellite imagery [89].

Although the above are useful tools, they are limited to identifying present (and recent historic) land-cover. As discussed, it is the potential use of the land which is important. After using global datasets to highlight environmentally suitable regions (eg for crop growth or reforestation) and employing satellite imagery to identify present-day land use, global mapping must extend to consider lands which may be available in the future, taking account of the accessibility of the land, any conflict of use, knock-on socioeconomic impacts, biodiversity hot spots and risk of diverting resources. This will likely require local interactions and engagement, and therefore will need to be targeted. The potential of land to be released from its current service will depend heavily on whether alternative mechanisms exist to provide this function (eg cost-competitive alternative proteins) and whether there is a viable business model for the future land use (eg GGR markets).

4.1.2 Advances in alternative proteins

Much of the land deforested in the last century is used for livestock grazing or crop growth, particularly the provision of proteins and lipids. In order to release these deforested lands and restore the forest ecosystems, the services provided by this land will need to be met in another way. Until an alternative, competitive protein source is available, it will be near impossible to reforest these regions. This topic is the focus of the accompanying report *The climate impact of alternative proteins* [2].

4.1.3 Research into key nature-based solutions

The following knowledge gaps were identified.

4.1.3.1 Growth in agriculturally unfavourable places: CAM, halophyte, and algae species

These crops can be grown either as a CO_2 sink or a carbon feedstock source. A comprehensive assessment of CAM, halophyte and algae species is needed to assess which are the most promising sources of carbon base-chemicals, which are the most promising carbon sinks, and where to grow them best. This insight, along with evaluation of scalability and costs, will help inform investment decisions. This crop evaluation must be used in conjunction with land availability studies to match the most promising species and regions in order to determine the potential for CO_2 sequestration and carbon feedstock. Alongside this, it is vital to research mechanisms to prevent the unwanted spread of introduced crops, eg through using spineless varieties controlled by grazing [90], or producing sterile strains.

4.1.3.2 Forest restoration

Forest restoration is not a quick fix as forests take time to be re-established; thus, urgent action is needed. Further studies are needed into forest restoration specifics taking an ecosystem approach rather than focusing only on trees (eg the combination of species to be planted, the sizes, configuration and ecosystem connectivity). Investigations are necessary to identify the most favourable available land, with the overarching goal to maximise ecological repair. Identification of suitable land will benefit from the previously mentioned mapping. As highlighted in Section 3.2, the uncertainty surrounding land availability has led to large ranges in the potential of forests for GGR; reducing this uncertainty is essential to GGR planning. Forest restoration is also not a permanent fix. Forests eventually reach equilibrium, after which they can no longer be considered a carbon sink. Therefore, values should be reported as total sink-potential, instead of annual rates, which can be misleading.

4.1.3.3 Soil carbon

Until a simple accredited metric exists to determine increases in soil carbon, it will be challenging to develop a market for soil carbon GGR. AECOM is currently running a 5-year living lab, rewilding land in Scotland, looking to develop metrics to assess Natural Capital gains [91], [92]. Academic funding to support the development of such metrics would assist government with market design and facilitate public financing by providing mechanism to track the effectiveness of the CO_2 sink.

4.1.4 Analysis of impacts

Two main themes cut across all the key solutions: the ecosystem and socioeconomic impacts. To assess these will require interdisciplinary collaboration across technical specialties (eg plant sciences, chemistry, biology, geography, anthropology).

4.1.4.1 Ecosystem impact

In-situ demonstration projects are required to assess the impact on ecosystem functions, services and their resilience to global change. Thorough trials can be lengthy and must therefore commence urgently as there is an immanent need for viable solutions.

4.1.4.2 Socioeconomic impact

Technical research needs to be accompanied by social and economic assessment of potential routes to implementation, with demonstration projects considering any trade-offs with other UN Sustainable Development Goals – especially for marginal communities using land where it would be desirable to implement solutions.

Key Research

- Mapping of land availability and suitability to identify which crops could be planted where
- Comprehensive assessment of CAM, halophyte and algae species
- Studies into sterilisation of crops to prevent introducing invasive weeds
- Investigations into appropriate forest restoration mechanisms and locations
- Research into the influence of increased soil carbon on crop yield and measurement techniques
- In-situ trials to assess ecosystem and socioeconomic impact of crop introduction

4.2 Policy

There are very limited circumstances where CO_2 capture for climate mitigation may result in stand-alone business models. The only example in this report is the potential increase in crop yield which may be a product of increased soil carbon. Instead, CO_2 capture must be considered a public good and as such will require public R&D financing and the service provision will need to be engaged by the state. Policy and regulation will be imperative to incentivise action.

The UK is leading with policy frameworks for implementation on home turf, as laid out in the Land Use report from the Committee on Climate Change [93] and the Natural Capital Committee Annual Report [33]. The recent UKRI call for GGR Demonstrator Projects is another example of the UK recognising GGR as a future key technology. However, the UK must engage international governments to develop policy and strategy that works at a global scale, due to the global need for CO_2 sequestration. This is especially important due to the likely need to use land that is concentrated in certain territories and may have equity and sovereignty issues that will need to be addressed. This could be assisted by funding from DFID to develop technical pathways that are applicable on international soils, to finance demonstrator projects overseas, and to facilitate international co-operation and policy evolution.

As it is unlikely that universal approval will be achieved, it may be beneficial to develop policies that do not require complete global cooperation, but which are easily expanded and applied to other countries. Policies must address the challenge of financing CO_2 sequestration as a public good by creating market structures or national budgets and investing in R&D, as this is unlikely to attract private sector investment. Clearly structured policy will need to be implemented in good time [94]; therefore, urgent consideration is needed with assistance from academic thought leaders and technology experts.

In contrast, carbon feedstocks derived from nature-based activities could result in the evolution of a private market because the carbon can be used to create valuable products. This will probably rely on either regulation or aggressive pricing to drive fossil-sourced carbon out of the marketplace in at least the early stages of market development, until cost reductions make bio-carbon sources competitive. It will likely need public funding of early stage and speculative research and development.

Financing will be predominantly from the public purse

- Nature-based solutions as a sink for CO_2 will not attract significant private investment as it is a public good
- Public financing of R&D into nature as a sink for CO_2 is vital
- Support and funding from DFID would assist with international cooperation and financing of international demonstrator trials situated outside the UK
- Government should support private sector financing of early stage R&D into nature-based sources of carbon through policy, financing or public–private partnerships
- The findings from R&D into nature-based sources of carbon may be useful for nature-based solutions as a sink for CO_2

5 Conclusions

To mitigate climate change, there is a need to remove 2–20 Gt CO_2 from the atmosphere per year by 2100 [1]. Nature-based solutions are a promising sink for CO_2. In addition, the petrochemical industry will need to move from using fossil fuels to using sustainable carbon sources. If nature is used as the sole source of carbon, replacing petrochemicals could require plants to absorb an additional 4.5 Gt CO_2 per year by 2050. The use of nature-based solutions must avoid competition with food crops, negative ecological impacts and must ensure social safeguarding.

Three promising nature-based solutions are highlighted:

i) crop growth in agriculturally unfavourable places, which will not compete with food crops. The focus was on three under-researched categories: CAM plants (which grow in semi-arid land), halophytes (which are suitable for saline regions), and both micro- and macro-algae. These plants can act as a sink for CO_2 or a source of carbon to produce products – see the report on *Industrial need for carbon in products* [3];

ii) forest restoration, which provides an in-situ sink for CO_2 and can offer ecological benefit. This is not commercial forestry plantations, which do not provide the same ecological or carbon sequestration benefits as forest restoration. Much of the land required for forest restoration is currently used for grazing or crop growth for livestock; these services would need to be displaced in order to release this land for forest restoration. The development of the alternative proteins market could play an important role – see the report on *The climate impact of alternative proteins* [2], as would the evolution of a GGR market;

iii) increasing soil carbon. This is a CO_2 sink, which may also increase crop yield.

In order to scale up any of these solutions, interdisciplinary research is needed into mapping land suitability and potential availability, crop suitability, and ecosystem and socioeconomic impacts, supported by in-situ trials in countries outside of the UK. There are technical knowledge gaps surrounding which CAM, halophyte and algae species are preferable sources of carbon, the production of sterile strains, alternative proteins to release land for forest restoration, and monitoring increases in soil carbon. This research will require government funding as it is unlikely to receive sufficient private sector investment, due to a lack of business cases and global markets for GGR services, and also the urgency of the climate crisis. As CO_2 absorption is a public good, it is of utmost importance to develop policies, regulation and financing options to create the appropriate markets and encourage private sector engagement. Funding from DFID to facilitate overseas trials would benefit progress in this field technically, politically and socially.

References

[1] IPCC, “Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,” 2018.

[2] K. A. Collett, B. O’Callaghan, M. Mason, C. L. Smith, C. Godfray, and C. Hepburn, “Final 25% Series: The climate impact of alternative proteins,” Smith School of Enterprise and the Environment, University of Oxford, Oxford, 2021.

[3] K. A. Collett, B. O’Callaghan, M. Mason, C. L. Smith, and C. Hepburn, “Final 25% Series: Industrial need for carbon in products,” Smith School of Enterprise and the Environment, University of Oxford, Oxford, 2021.

[4] M. R. Allen *et al.*, “Warming caused by cumulative carbon emissions towards the trillionth tonne,” *Nature*, vol. 458, no. 7242, pp. 1163–1166, 2009.

[5] D. Bodansky, J. Brunnée, and L. Rajamani, “International Climate Change Law: Introduction,” in *International Climate Change Law*, 2017, pp. 1–3.

[6] Royal Society and Royal Academy of Engineering, “Greenhouse Gas Removal,” 2018.

[7] C. Hepburn *et al.*, “The technological and economic prospects for CO2 utilization and removal,” *Nature*, vol. 575, pp. 87–97, 2019.

[8] “The future of petrochemicals,” International Energy Agency, 2018.

[9] M. Obersteiner, H. Böttcher, and Y. Yamagata, “Terrestrial ecosystem management for climate change mitigation,” *Curr. Opin. Environ. Sustain.*, vol. 2, no. 4, pp. 271–276, 2010.

[10] Y. Malhi *et al.*, “Climate change and ecosystems: Threats, opportunities and solutions,” *Philos. Trans. R. Soc. B Biol. Sci.*, vol. 375, no. 1794, 2020.

[11] N. Seddon, A. Chausson, P. Berry, C. A. J. Girardin, A. Smith, and B. Turner, “Understanding the value and limits of nature-based solutions to climate change and other global challenges,” *Philos. Trans. R. Soc. B Biol. Sci.*, vol. 375, no. 1794, 2020.

[12] S. Roe *et al.*, “Contribution of the land sector to a 1.5 °C world,” *Nat. Clim. Chang.*, vol. 9, no. 11, pp. 817–828, 2019.

[13] N. MacDowell *et al.*, “An overview of CO2 capture technologies,” *Energy Environ. Sci.*, vol. 3, no. 11, pp. 1645–1669, 2010.

[14] M. Bui *et al.*, “Carbon capture and storage (CCS): The way forward,” *Energy Environ. Sci.*, vol. 11, no. 5, pp. 1062–1176, 2018.

[15] D. W. Keith, G. Holmes, D. St. Angelo, and K. Heidel, “A Process for Capturing CO2 from the Atmosphere,” *Joule*, vol. 2, no. 8, pp. 1573–1594, 2018.

[16] P. Smith *et al.*, “Biophysical and economic limits to negative CO2 emissions,” *Nat. Clim. Chang.*, vol. 6, no. 1, pp. 42–50, 2016.

[17] D. W. Keith, M. Ha-duong, and J. K. Stolaroff, “Climate Strategy with CO2 Capture from the Air,” *Clim. Chang.*, vol. 74, pp. 17–45, 2006.

[18] D. Read *et al.*, “The role of land carbon sinks in mitigating global climate change,” The Royal Society, 2001.

[19] P. Lamers and M. Junginger, “The ‘debt’ is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy,” *Biofuels, Bioprod. Biorefining*, vol. 7, pp. 373–385, 2012.

[20] E. F. Lambin, “Global land availability: Malthus versus Ricardo,” *Glob. Food Sec.*, vol. 1, no. 2, pp. 83–87, 2012.

[21] World Economic Forum, “Global Risks Report 2019,” 2019.

[22] HM Treasury, “The Economics of Biodiversity: The Dasgupta Review,” pp. 1–8, 2019.

[23] The Royal Society, “Climate Change and Ecosystems,” The Royal Society, 2018.

[24] S. Raghu and C. Walton, “Understanding the Ghost of Cactoblastis Past: Historical Clarifications on a Poster Child of Classical Biological Control,” *Bioscience*, vol. 57, no. 8, pp. 699–705, 2007.

[25] B. Osmond, T. Neales, and G. Stange, “Curiosity and context revisited: Crassulacean acid metabolism in the Anthropocene,” *J. Exp. Bot.*, vol. 59, no. 7, pp. 1489–1502, 2008.

[26] Food and Agriculture Organisation of the United Nations, “Global Forest Resources Assessment 2015,” 2015.

[27] IPCC, “Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems,” 2019.

[28] R. L. Chazdon, “Climate 2020: Not all forests are equal,” 2020. [Online]. Available: https://www.climate2020.org.uk/not-all-forests-are-equal/.

[29] N. Seddon, B. Turner, P. Berry, A. Chausson, and C. A. J. Girardin, “Grounding nature-based climate solutions in sound biodiversity science,” *Nat. Clim. Chang.*, vol. 9, pp. 82–87, 2020.

[30] G. Grassi, J. House, F. Dentener, S. Federici, M. Den Elzen, and J. Penman, “The key role of forests in meeting climate targets requires science for credible mitigation,” *Nat. Clim. Chang.*, vol. 7, no. 3, pp. 220–226, 2017.

[31] The Royal Society, *Soil structure and its benefits An evidence synthesis: Summary*. 2020.

[32] Food and Agriculture Organizations of the United Nations, “Forests and Agriculture: Land-Use Challenges and Opportunities,” 2016.

[33] Natural Capital Committee, “State of Natural Capital Annual Report 2019,” 2019.

[34] A. J. Sykes *et al.*, “Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology,” *Glob. Chang. Biol.*, vol. 26, no. 3, pp. 1085–1108, 2020.

[35] J. Dauber *et al.*, “Bioenergy from ‘surplus’ land: Environmental and socio-economic implications,” *BioRisk*, vol. 50, no. 7, pp. 5–50, 2012.

[36] F. Creutzig *et al.*, “Bioenergy and climate change mitigation: An assessment,” *GCB Bioenergy*, vol. 7, no. 5, pp. 916–944, 2015.

[37] M. Nijsen, E. Smeets, E. Stehfest, and D. P. van Vuuren, “An evaluation of the global potential of bioenergy production on degraded lands,” *GCB Bioenergy*, vol. 4, no. 2, pp. 130–147, 2012.

[38] Food and Agricultural Organisation of the United Nations, “Water and Cereals in Drylands: Drylands, people and land use,” 2008.

[39] Food and Agriculture Organsiation of the United Nations, “Trees, forests and land use in drylands: the first global assessment,” 2019.

[40] P. M. Mason, K. Glover, J. A. C. Smith, K. J. Willis, J. Woods, and I. P. Thompson, “The potential of CAM crops as a globally significant bioenergy resource: Moving from ‘fuel or food’ to ‘fuel and more food,’” *Energy Environ. Sci.*, vol. 8, no. 8, pp. 2320–2329, 2015.

[41] A. M. Borland, H. Griffiths, J. Hartwell, and J. A. C. Smith, “Exploiting the potential of plants with crassulacean acid metabolism for bioenergy production on marginal lands,” *J. Exp. Bot.*, vol. 60, no. 10, pp. 2879–2896, 2009.

[42] M. Louhaichi and R. Mata-González, “A Preliminary Model of Opuntia ficus-indica (L .) Mill . Suitability for Jordan,” *Acta Hortic.*, 2015.

[43] P. M. Mason, “DPhil Thesis: Maximising the Potential of Anaerobic Digestion,” University of Oxford, 2015.

[44] N. A. Owen, K. F. Fahy, and H. Griffiths, “Crassulacean acid metabolism (CAM) offers sustainable bioenergy production and resilience to climate change,” *GCB Bioenergy*, vol. 8, no. 4, pp. 737–749, 2016.

[45] M. Mason, “Private Communications.” 2020.

[46] F. C. Stintzing and R. Carle, “Cactus stems (Opuntia spp.): A review on their chemistry, technology, and uses,” *Mol. Nutr. Food Res.*, vol. 49, no. 2, pp. 175–194, 2005.

[47] B. R. Hastilestari *et al.*, “Euphorbia tirucalli L.-Comprehensive Characterization of a Drought Tolerant Plant with a Potential as Biofuel Source,” *PLoS One*, vol. 8, no. 5, pp. 1–12, 2013.

[48] G. S. Alemán-Nava, I. A. Gatti, R. Parra-Saldivar, J. F. Dallemand, B. E. Rittmann, and H. M. N. Iqbal, “Biotechnological revalorization of Tequila waste and by-product streams for cleaner production – A review from bio-refinery perspective,” *J. Clean. Prod.*, vol. 172, pp. 3713–3720, 2018.

[49] M. Calvin, “Hydrocarbons from plants: Analytical methods and observations,” *Naturwissenschaften*, vol. 67, no. 11, pp. 525–533, 1980.

[50] K. Winter and J. A. C. Smith, *Crassulacean acid metabolism : biochemistry, ecophysiology and evolution*. Berlin; London: Springer, 1996.

[51] T. J. Flowers and T. D. Colmer, “Plant salt tolerance: Adaptations in halophytes,” *Ann. Bot.*, vol. 115, no. 3, pp. 327–331, 2015.

[52] T. J. Flowers and A. Muscolo, “Introduction to the special issue: Halophytes in a changing world,” *AoB Plants*, vol. 7, no. 1, pp. 1–5, 2015.

[53] E. P. Glenn, J. J. Brown, and E. Blumwald, “Salt Tolerance and Crop Potential of Halophytes,” *CRC. Crit. Rev. Plant Sci.*, vol. 18, no. 2, pp. 227–255, 1999.

[54] University of Sussex, “eHALOPH.” [Online]. Available: https://www.sussex.ac.uk/affiliates/halophytes/.

[55] A. Buhmann and J. Papenbrock, “An economic point of view of secondary compounds in halophytes,” *Funct. Plant Biol.*, vol. 40, no. 9, pp. 952–967, 2013.

[56] S. Panta, T. Flowers, P. Lane, R. Doyle, G. Haros, and S. Shabala, “Halophyte agriculture: Success stories,” *Environ. Exp. Bot.*, vol. 107, pp. 71–83, 2014.

[57] D. J. Weber, R. Ansari, B. Gul, and M. Ajmal Khan, “Potential of halophytes as source of edible oil,” *J. Arid Environ.*, vol. 68, no. 2, pp. 315–321, 2007.

[58] M. Hasanuzzaman *et al.*, “Potential use of halophytes to remediate saline soils,” *Biomed Res. Int.*, vol. 2014, 2014.

[59] A. N. Mistry, U. Ganta, J. Chakrabarty, and S. Dutta, “A review on biological systems for CO2 sequestration: Organisms and their pathways,” *Environ. Prog. Sustain. Energy*, vol. 38, no. 1, pp. 127–136, 2019.

[60] P. M. Foley, E. S. Beach, and J. B. Zimmerman, “Algae as a source of renewable chemicals: Opportunities and challenges,” *Green Chem.*, vol. 13, no. 6, pp. 1399–1405, 2011.

[61] L. M. L. Laurens *et al.*, “Development of algae biorefinery concepts for biofuels and bioproducts; a perspective on process-compatible products and their impact on cost-reduction,” *Energy Environ. Sci.*, vol. 10, pp. 1716–1738, 2017.

[62] H. P. S. A. Khalil *et al.*, “Seaweed based sustainable films and composites for food and pharmaceutical applications : A review,” *Renew. Sustain. Energy Rev.*, vol. 77, pp. 353–362, 2017.

[63] T. Mathimani and A. Pugazhendhi, “Utilization of algae for biofuel, bio-products and bio-remediation,” *Biocatal. Agric. Biotechnol.*, vol. 17, pp. 326–330, 2019.

[64] R. Slade and A. Bauen, “Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects,” *Biomass and Bioenergy*, vol. 53, pp. 29–38, 2013.

[65] P. T. Pienkos, L. Laurens, and A. Aden, “Making Biofuel from Microalgae,” *Am. Sci.*, vol. 99, no. 6, pp. 474–481, 2011.

[66] L. Barsanti and P. Gualtieri, “Is exploitation of microalgae economically and energetically sustainable?,” *Algal Res.*, vol. 31, pp. 107–115, 2018.

[67] SeaGrown, “SeaGrown.” [Online]. Available: https://www.seagrown.co.uk.

[68] Notpla, “Notpla.” [Online]. Available: https://www.notpla.com.

[69] S. Fuss *et al.*, “Negative emissions - Part 2: Costs, potentials and side effects,” *Environ. Res. Lett.*, vol. 13, no. 063002, pp. 1–47, 2018.

[70] B. W. Griscom *et al.*, “Natural climate solutions,” *Proc. Natl. Acad. Sci. U. S. A.*, vol. 114, no. 44, pp. 11645–11650, 2017.

[71] A. Caparrós and F. Jacquemont, “Conflicts between biodiversity and carbon sequestration programs: Economic and legal implications,” *Ecol. Econ.*, vol. 46, no. 1, pp. 143–157, 2003.

[72] R. Lal, “Sequestering carbon in soils of agro-ecosystems,” *Food Policy*, vol. 36, pp. S33–S39, 2011.

[73] R. Lal, “Managing Soils and Ecosystems for Mitigating Anthropogenic Carbon Emissions and Advancing Global Food Security,” *Bioscience*, vol. 60, no. 9, pp. 708–721, 2010.

[74] B. Minasny *et al.*, “Soil carbon 4 per mille,” *Geoderma*, vol. 292, pp. 59–86, 2017.

[75] B. Walsh *et al.*, “Pathways for balancing CO2 emissions and sinks,” *Nat. Commun.*, vol. 8, 2017.

[76] P. Smith, “Soil carbon sequestration and biochar as negative emission technologies,” *Glob. Chang. Biol.*, vol. 22, pp. 1315–1324, 2016.

[77] K. Kleiner, “The bright prospect of biochar,” *Nat. Clim. Chang.*, vol. 1, no. 906, pp. 72–74, 2009.

[78] UK Biochar Research Centre, “UK Biochar Research Centre.” [Online]. Available: https://www.biochar.ac.uk/index.php.

[79] R. Lal, “Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands,” *L. Degrad. Dev.*, vol. 17, no. 2, pp. 197–209, 2006.

[80] S. Jeffery *et al.*, “Biochar boosts tropical but not temperate crop yields,” *Environ. Res. Lett.*, vol. 12, no. 053001, 2017.

[81] H. Ritchie and M. Roser, “Land Use,” *Our World in Data*, 2019. [Online]. Available: https://ourworldindata.org/land-use.

[82] World Bank, “World Bank Data.” [Online]. Available: https://data.worldbank.org.

[83] Food and Agriculture Organsiation of the United Nations, “FAO Statistics.” .

[84] C. Buckland and et al., “(Forthcoming).”

[85] Biotechnology and Biological Sciences Research Council, “UKRI: Greenhouse Gas Removal Demonstrators.” [Online]. Available: https://bbsrc.ukri.org/funding/filter/2019-greenhouse-gas-removal-demonstrators/.

[86] Food and Agriculture Organsiation of the United Nations, “FAOSTAT.” .

[87] European Space Agency, “European Space Agency GloCover.” [Online]. Available: http://due.esrin.esa.int/page_globcover.php.

[88] NASA, “MODIS: Moderate Resolution Imaging Spectroradiometer.” [Online]. Available: https://modis.gsfc.nasa.gov/about/.

[89] S. Fritz *et al.*, “A global dataset of crowdsourced land cover and land use reference data,” *Sci. Data*, vol. 4, pp. 1–8, 2017.

[90] H. N. Le Houérou, “The role of cacti (Opuntia spp.) in erosion control, land reclamation, rehabilitation and agricultural development in the Mediterranean Basin,” *J. Arid Environ.*, vol. 33, no. 2, pp. 135–159, 1996.

[91] Energy Live News, “AECOM launches ‘living laboratory’ in the Scottish Highlands.” [Online]. Available: https://www.energylivenews.com/2019/08/05/aecom-launches-living-laboratory-in-the-scottish-highlands/. [Accessed: 23-Apr-2020].

[92] AECOM, “AECOM launches pioneering Natural Capital Laboratory in the Scottish Highlands.” [Online]. Available: https://aecom.com/uk/press-releases/aecom-launches-pioneering-natural-capital-laboratory-in-the-scottish-highlands/. [Accessed: 23-Apr-2020].

[93] Committee on Climate Change, “Land use: Policies for a Net Zero UK,” 2020.

[94] Vivid Economics, “Greenhouse Gas Removal (GGR) policy options - Final Report,” 2019.