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Assessment of Optimal Conditions for the Performance of Greenhouse Gas Removal Methods

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Abstract
In this study, a comparative literature-based assessment of the impact of operational factors such as climatic condition, vegetation type, availability of land, water, energy and biomass, management practices, cost and soil characteristics was carried out on six GGR methods. These methods which include forestation, enhanced weathering (EW), soil carbon sequestration (SCS), biochar, direct air capture with carbon storage (DACCS) and bioenergy with carbon capture and storage (BECCS) were accessed with the aim of identifying the conditions and requirements necessary for their optimum performance. The extent of influence of these factors on the performance of the various GGR methods was discussed and quantified on a scale of 0-5. The key conditions necessary for optimum performance were identified with forestation, EW, SCS and biochar found to be best deployed within the tropical and temperate climatic zones. The CCS technologies (BECCS and DACCS) which have been largely projected as major contributors to the attainment of the emission mitigation targets were found to have a larger locational flexibility. However, the need for cost optimal siting of the CCS plant is necessary and dependent on the presence of appropriate storage facilities, preferably geological. The need for global and regional cooperation as well as some current efforts at accelerating the development and deployment of these GGR methods were also highlighted.

Keywords
Forestation; Enhanced weathering; Soil carbon sequestration; Biochar; Carbon capture and storage

1 Introduction
In order to mitigate against climate change, the need to limit the average global temperature rise to under 2 °C by the end of the century as stated in the Paris Agreement cannot be overemphasised (UNFCCC, 2015). Meeting this target will involve a combination of proactive zero emission technological approach as well as a reactive approach of reducing the amount of greenhouse gases (especially carbon dioxide (CO_2)) currently present in the atmosphere (IPCC, 2018; Smith, 2016). For the latter approach, a number of greenhouse gas removal (GGR) methods, sometimes referred to as negative emission technologies (NETs) or carbon dioxide removal (CDR) techniques (McLaren, 2020), have been proposed. These include forestation, enhanced weathering (EW), soil carbon sequestration (SCS), biochar, direct air capture with carbon storage (DACCS), bioenergy with carbon capture and storage (BECCS), ocean fertilisation and wetland restoration among others. While some of these methods like forestation and SCS have been fully developed and can be conveniently deployed for the purpose of CO_2 removal, the other technologies are at various levels of technological readiness (Lomax et al., 2015; The Royal Society, 2018).

Several reviews on the state of development of these GGR methods have been reported in the literature. These studies which cover diverse areas provide salient information that are necessary for the development of these technologies to levels of safe and efficient deployment.

A summary of these review studies and reports on multiple GGR methods published over the past decade are presented in Table 1.

Table 1. Summary of existing review studies/reports on a suite of GGR methods

Reference	Study area of focus
McLaren (2011)	Technical assessment of NETs and their implications for climate policy.
McGlashan et al. (2012)	Techno-economic assessment of NETs.
Smith et al. (2015)	Assessed the potential biophysical and economic limits to be associated with the large-scale deployment of NETs.
Minx et al. (2018)	Assessed the role of NETs in mitigation scenarios, ethical implications and deployment challenges.
Fuss et al. (2018)	Reviewed and assessed the costs, potentials and side-effects of seven selected GGR technologies.
Nemet et al. (2018)	Reviewed the innovations and scaling challenges to be addressed to ensure effective NETs deployment.
The Royal Society (2018)	Provided a robust report on the range of globally available GGR methods with special focus on their effective deployment potential in the UK.
Haszeldine et al. (2018)	Assessed the progress journey of NETs within the framework of their readiness for deployment and contribution in meeting the emission mitigation target.
Hepburn et al. (2019)	Reviewed ten CO_2 utilisation and removal pathways with focus on their techno-economic prospects.
Roe et al. (2019)	A combined review of modelled pathways and literature on mitigation strategies aimed at assessing the contribution of the land-based GGRs to attaining the mitigation target.
Smith et al. (2019)	Assessed the opportunities and risks of land management based GGR options based on their impacts on ecosystem services and United Nations Sustainable Development Goals (SDGs)
Hilaire et al. (2019)	Reviewed NETs systematically while providing adequate linkage between the literature findings and the 1.5 °C/ 2 °C scenario evidence data.
Gough & Mander (2019)	Assessed the contribution of social science in enhancing the large-scale implementation of CCS and BECCS technologies.
Pires (2019)	Assessed recent works on NETs with the focus on project findings and probable challenges.
Goglio et al. (2020)	Reviewed the challenges and advances associated with life cycle analysis of GGR technologies.
Waller et al. (2020)	Reviewed the political and social dimensions of large scale GGR with focus on BECCS and forestation.

Though the various reviews covering suites of GGR methods do address different focus areas as seen in Table 1, they however do generally agree that no single GGR method will be sufficient in meeting the climate warming target alone. There is therefore a need for a combination of various technologies which will also reduce risks of poor performance that could be associated with adopting a single method (McLaren, 2020). Though no particular combination of methods has been explicitly adopted on account of the uncertainties associated with large-scale deployment (Thoni et al., 2020), Integrated Assessment Models (IAMs) scenarios however consider BECCS and forestation as major applicable options in meeting the mitigation target (IPCC, 2018).

As summarised in Table 1, several existing review works have been reported covering broad focus areas ranging from techno-economic to scaling and deployment issues as well as socio-political aspects. While reviews covering realistic deployment perspectives in regards to the extent of carbon removal and cost (Fuss et al., 2018) as well as biophysical limits (Smith et al., 2015) have been reported, a review to identify conditions for optimum performance of these GGR methods as well as perspectives on quantification of the impact of operational factors on the performance of these GGR methods are lacking.

With the performance of these GGR methods dependent on prevailing bio-geophysical, techno-economic and socio-political factors, there is a great need to assess the conditions that will ensure optimum performance of the various GGR methods regarding locational characteristics. This knowledge is very important for the rapid scale up deployment of these technologies as it will assist in providing a pool of information that will aid policy makers and stakeholders at various levels in making decisions. Thus far, no review has been carried out in this regard, hence the need for this work.

The study will involve a literature-based assessment of the impact of operational factors such as climatic condition, vegetation type, availability of land, water, energy and biomass, cost and soil characteristics on six GGR methods, namely: forestation, EW, SCS, biochar, DACCS and BECCS. The assessment will be carried out with a view to identify conditions for optimum performance. The choice of this six GGR method was made based on their carbon removal potential, technological readiness level (shown in Figure 1) and relative social acceptability especially considering their existing applications in agriculture and enhanced oil recovery.

The paper is divided into three main sections. The first section covers the review of the major operational factors on the various GGR methods under consideration. In the second section, a comparison and assessment of the levels of impact of the various factors on the respective GGR methods will be carried out with a final section that briefly covers current trends and future outlook on GGR methods development.

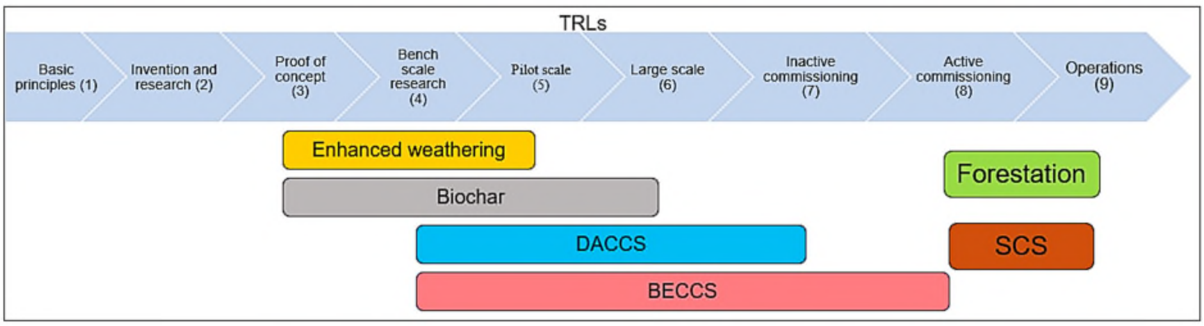

Figure 1. TRLs of assessed GGR methods

2 Assessing the GGR technologies

In this section, the applicable operational factors required for optimum performance of the six selected GGR methods were assessed from published works obtained from available academic literature. This section consists of six sub-sections dedicated to the respective GGR methods under consideration. Each assessment is preceded by a concise introduction covering the operational principle, co-benefits, advantages and disadvantages of the respective GGR method and concludes with a summary table highlighting the identified conditions and requirements for optimum performance.

2.1 Forestation

The growth and development of plants is dependent on the process of photosynthesis which is characterised by CO_2 absorption from the environment as shown in Figure 2. As a means of exploiting this natural means of CO_2 removal, the planting of trees which is collectively referred to as forestation has been identified as one of the GGR techniques. This can be done by planting of trees on lands not previously forested (afforestation) or on previously forested lands that have been harvested (reforestation) as well as the restocking of recently depleted land (restoration) with an emphasis on restoring ecological processes (Anderson et al., 2011). The estimated potential for GGR from forestation has been reported to vary from 3 to 12 $GtCO_2$ pa by 2100 with variations dependent on factors such as land availability, location, forest type and management as well as economic and biophysical constraints (The Royal Society, 2018).

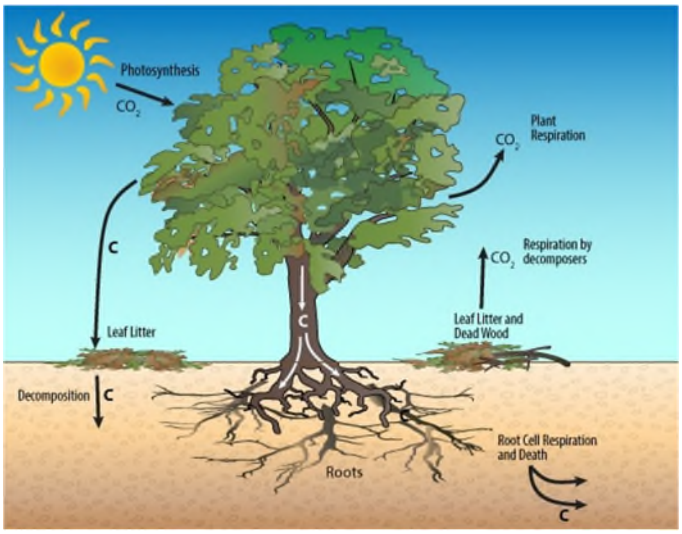

Figure 2. Carbon cycle in a single tree (TERC, 2020)

Aside carbon sequestration, co-benefits of this technique have been identified to include production of food, fuels and fibre, regulation of water services and air quality (Bonan, 2008), habitat for biodiversity (Ellison et al., 2017), erosion control, small floods mitigation, job creation as well as recreation (Smith et al., 2019). Alternatively, risks and negative consequences such as natural disturbances, fire, climate variability (e.g. drought), enhancement of GHG fluxes from soils, permafrost thawing, deforestation, land use changes as well as albedo change especially in northern latitudes have also been identified (Doelman et al., 2019). The aspect of reversibility due to climate changes and/or direct human actions (Canadell and Raupach, 2008) as well as reduction in effectiveness of forestation with time on account of growth rate and land constraints have also been raised (Nunes et al., 2020). Smith (2016) even reports that forestation, potentially, may not be available after 2050 or less effective if implemented too soon.

In order to optimally apply this GGR technology, it is necessary to assess the major factors that affect its implementation with a view to identifying the optimum conditions for performance.

2.1.1 Land availability

The availability of land has been identified as a major constraint to the effective implementation of this GGR method on account of its competing use in agricultural, social and economic applications (Kreidenweis et al., 2016). Smith et al. (2015) reported a global land requirement of 320 to 970 Mha (about 2.3 – 6.5% of the global land mass) in order to attain the expected GGR potential by 2100 with a land intensity of forestation estimated at around 0.1 – 0.6 ha per tCO_2 pa. In order to maximise this scarce resource for GGR while ensuring that other land uses don't suffer, various forest management techniques and practices such as thinning optimisation, improved rotation as well as agroforestry among others have been prescribed. Abbas et al. (2017) identified agroforestry as a favourable management practice that ensures a good combination of environmental sustainability and agro-based activities.

2.1.2 Climatic condition

It is generally reported that carbon sequestration rate declines as latitude increases (Hartman, 2017; Mykleby et al., 2017). Tropical forests have been reported to have the highest aboveground carbon density and carbon sequestration potential compared to the subtropical, temperate and boreal forests and are thus best suited for GGR by forestation (Bala, 2014; Goodman and Herold, 2015). This is due to factors such as higher productivity, increased evapotranspiration and increased surface reflectivity (albedo) effects which results in net cooling in the tropical forests (Fuss et al., 2018). Aside from local cooling, The Royal Society, (2018) also reports other favourable effects such as air and water filtering as well as rainfall recycling.

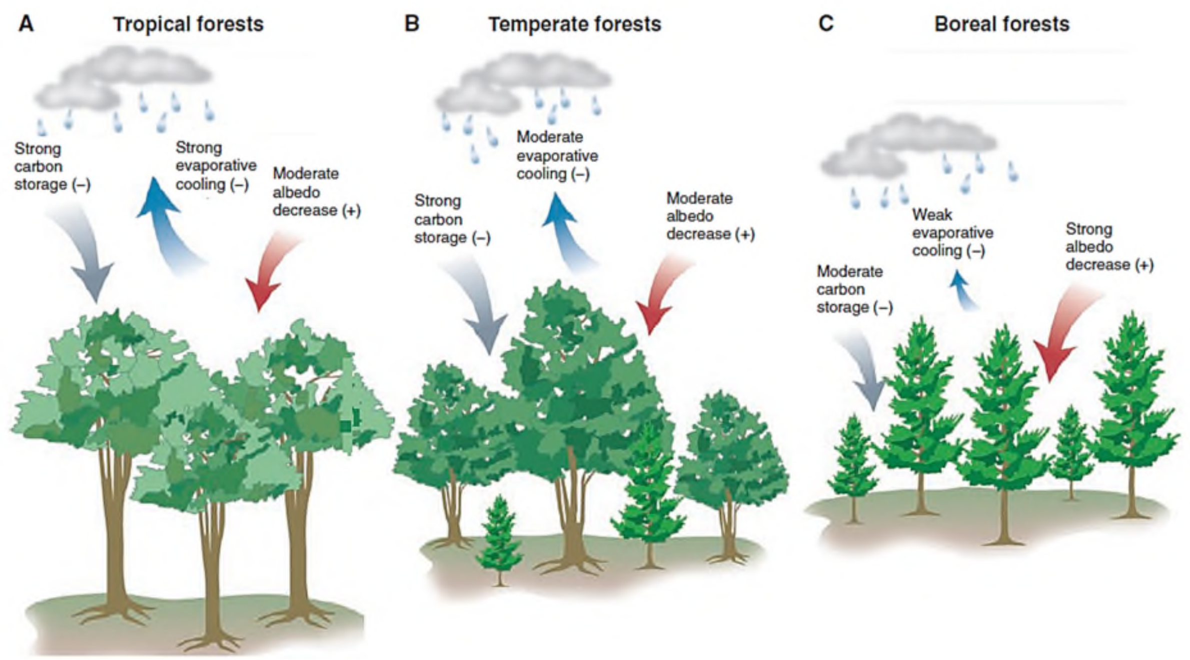

Figure 3. Climate services in tropical, temperate and boreal forests (reprinted with permission from Bonan (2008), Copyright 2008 Science)

Tropical forests are typically characterised by high tree growth rate and carbon sequestration rate of about 1 to 3.4 tC/ha pa (Abbas et al., 2017) capturing about 2.2–2.7 GtC pa (Goodman and Herold, 2015) which is up to three times that of boreal forests per unit of land (Arora and Montenegro, 2011). The effects of afforestation in the various climatic regions with variations in details (shown in Figure 3.) was summarised as follows: cooling in the tropics, negligible or variable effects in temperate regions, and warming in higher latitudes. This warming effect is generally attributed to the reduction in albedo (heat-absorbing forest), changes in land cover as well as rate and magnitude of evapotranspiration (Favero et al., 2018; Kreidenweis et al., 2016).

2.1.3 Vegetation

While Hartman (2017) reported varying results for the impact of coniferous and deciduous forest species on carbon sequestration potential, Naudts et al., (2016) reported how an increase in afforestation in Europe (for over two and half centuries) did not result in net CO_2 removal from the atmosphere on account of reversibility effects (release of carbon stored in the biomass, litter, dead wood, and soil carbon pools) and change in vegetation type (from the deciduous broadleaf species to evergreen coniferous species (27% increase)). This change in species, which was commercially motivated, led to a reduction in evapotranspiration, thus decreasing atmospheric emissivity due to changes in albedo and canopy structure leading to warming (0.08 °C increase) rather than mitigating it. They therefore recommended deciduous species for GGR via forestation. Similar recommendation was made by Bonan (2008) and Anderson et al. (2011) who reported that deciduous species generally had a higher albedo and higher evapotranspiration in comparison to evergreen coniferous species.

In regards to choice of species and distribution, there is general agreement on the need to use diverse species of native origin (Mader, 2019; Matthies and Valsta, 2016). Hall et al. (2012) and Locatelli et al. (2015) explained that the use of native species in afforestation was considered superior in comparison to plantations for habitat quality and species diversity. They listed benefits to include reduced vulnerability to local conditions, greater variety of subsistence products and services, enhanced local management and acceptability. Hartman (2017) also identified reduction in catastrophic losses due to insect outbreak, disease, and fungal infection. Alvarez et al. (2016) reported a higher carbon sequestration potential for forest comprising of mixed wood species in comparison to monocultures. Similar result was reported by Hartman (2017), for both native and non-native mixed species plantations.

2.1.4 Other considerations

GGR using forestation is characterised by relatively very low if not negligible energy requirement thus making it applicable in areas of poor energy availability. In regards to water requirement, the proper siting of forest in high rainfall regions ensures that this requirement is typically low and mostly insignificant as irrigation is often not required.

In regards to forest management practices, Naudts et al. (2016) reported that not all forest management practices contributed to climate change mitigation. Practices such as application of fertiliser can sometimes lead to emission increase depending on fertiliser type, application rate and soil characteristics (Snyder et al., 2009). For soil characteristics, Bouwman et al. (2002) on analysis of over 900 NOx emission measurements reported increased nitrous oxide (N_2O) emission to be favoured by fine soil texture, restricted drainage and neutral to acidic soil conditions with that of nitric oxide (NO) emissions enhanced by well-drained, coarse textured neutral soils. Monoculture planting has also been reported to increase runoff and reduce evapotranspiration (Anderson et al., 2011). As a means of managing competing land uses and conserving existing biomes, agroforestry (planting trees within agricultural environments) (Abbas et al., 2017; Ellison et al., 2017) and reforestation (Bond et al., 2019) have been recommended.

In regards to cost, Raihan et al. (2019) identified afforestation to be the most low-cost carbon sequestration option in comparison to other forestry options such as reforestation and forest management. While Fuss et al. (2018) reported the global afforestation cost per tCO_2 to range from US$2-150/$tCO_2$, Raihan et al. (2019) reported that a consideration of other management options will give a larger marginal cost per tCO_2 captured ranging from US$0-433/$tCO_2$ in 2011 prices (US$0-497.75 in 2020 prices). At the regional level, they reported that the cost of afforestation to be highest in Europe ranging from US$158-185/$tCO_2$ (US$180-210/$tCO_2$ in 2020 prices) and lowest in tropical regions ranging from US$0-7/$tCO_2$ (US$0-8.08/$tCO_2$ in 2020 prices). This was corroborated by Fuss et al. (2018) who opined that the global cost of afforestation could be reduced to a range of US$5-50/$tCO_2$ if afforestation were to be constrained for deployment in 500 Mha of tropical lands. This regional cost discrepancy is hinged on factors such as higher tropical tree growth rate and carbon sequestration rate, labour availability, labour cost as well as land opportunity cost.

2.2 Enhanced Weathering

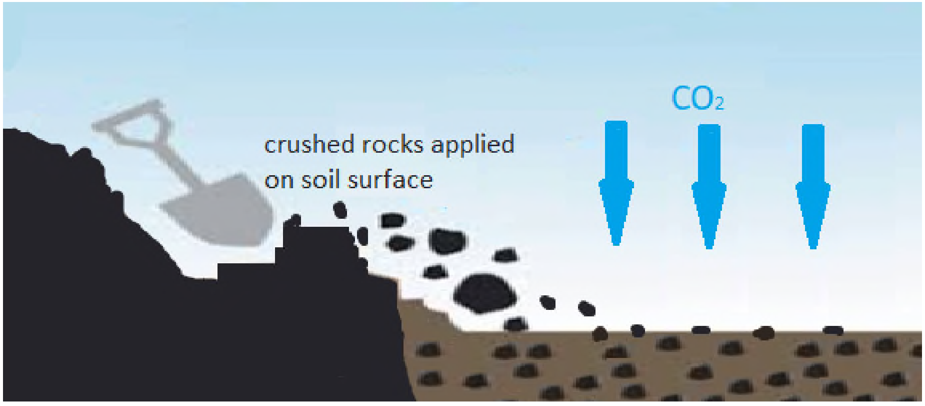

Figure 4. Enhanced weathering process

Enhanced weathering involves the artificial stimulation (acceleration) of the natural weathering process thus transforming it from a geological to a humanly relevant time scale (Andrews & Taylor, 2019; Hartmann et al., 2013). As shown in Figure 4, it involves the grinding of selected rocks usually of calcium or magnesium content and spreading the resulting small grain sized rock over land (top-soils) or ocean surfaces which serve as storage sites for the CO_2 removed from the atmosphere. The grinding is aimed at increasing the reactive surface area and thus enhancing the mineral dissolution and CO_2 removal either as dissolved inorganic carbon and/or as carbonate minerals (Bach et al., 2019). Aside natural rocks, Fuss et al. (2018) identified other applicable materials to include mine waste, concrete or alkaline waste. Global removal potential by this GGR method assuming application in 900 Mha (two-thirds of croplands) is estimated to be between 0.5 and 4.0 $GtCO_2$ pa by 2100 (The Royal Society, 2018).

Some of the advantages of this GGR method include; little or no additional land requirement as it can be co-deployed with the feedstocks for BECCS and biochars as well as no carbon capture and storage requirement. Aside carbon sequestration, a number of potential co-benefits include; soil productivity improvement, reduced N_2O loss through pH buffering, ocean acidity reduction, reduced usage of fertilisers as well as reduced cultural eutrophication (De Oliveira Garcia et al., 2020; Strefler et al., 2018). Alternatively, the mining process could lead to challenges in health (e.g. respiratory issues), ecological and environmental negative impacts (Edwards et al., 2017) as well as ethical considerations (Lawford-Smith and Currie, 2017).

With temperature, pH, biological vectors (worms, fungi) and moisture generally identified as the major factors regulating the rate of natural weathering (Oelkers et al., 2018), it is necessary to assess these and other factors that affect enhanced (artificial) weathering process with a view to determining the optimum conditions for performance and application of this GGR method.

2.2.1 Climatic condition

Considering the factors of water availability (for the chemical weathering reaction) throughout the year as well as elevated temperature to enhance a faster weathering process, warm tropical climates as well as humid regions have been generally reported to be most suitable for the application of this GGR method (Bach et al., 2019; Meysman and Montserrat, 2017). Strefler et al. (2018) while recommending average ambient temperature requirement of 25 °C also identified best suited locations capable of realizing 75% of the global potential to include India, Brazil, South-East Asia and China. Water requirement is typically low estimated at 1.5 m^3/tCO_2 (Smith et al., 2015) and it is expected to be based on precipitation.

2.2.2 Geology

The two major rocks with a GGR potential of 4 $GtCO_2$ pa recommended for the application of this method are basalt and dunite rock (Köhler et al., 2010; Schuiling, 2017). The dunite rock is an ultramafic, low silica rock consisting of forsteritic olivine. Though it would ordinarily be considered as best suited on account of its high weathering efficiency, its usage is however hindered by the presence of harmful trace elements (specifically Ni and Cr), which can potentially be released into the environment during dissolution (Amann et al., 2020; Strefler et al., 2018). Basalt (a mafic rock with olivine) on the other hand, though characterised by a lower weathering efficiency (higher grinding cost) is the most recommended option. This is as a result of its advantages and co-benefits such as widespread abundance accounting for about 6.8M km^2 of the earth's surface (about 4.56% of the world's land mass), and significantly more beneath the surface and under the oceans (Kantola et al., 2017). It is also characterised by fewer trace elements as well as the presence of nutrients such as phosphorus, magnesium, and calcium, whose application are highly beneficial to croplands (Strefler et al., 2018).

In regards to the most suitable soil for spreading of the weathered rocks, deeply weathered acidic tropical soils have been generally recommended (De Oliveira Garcia et al., 2020; Taylor et al., 2016). This is on account of the soil alkalinity-increasing effect of the added rock powder.

2.2.3 Energy and Cost

GGR by enhanced weathering is characterised by significant energy requirement estimated at 46 GJ/tCO_2 pa covering the areas of rock extraction (mining and crushing), grinding and transportation which account for 77–94% of the energy requirements collectively (Renforth, 2012). In addition to this high energy requirement, additional CO_2 emissions released during the mineral processing are expected to reduce gains made by enhanced weathering by an estimated 5–30% of potential C sequestered (Kantola et al., 2017). Strefler et al. (2018) reported a target grain size-dependent electricity demand for grinding with a best estimate ranging from 0.07 GJ/t rock for 50 μm to 3 GJ/t rock for 2 μm. This shows that the smaller the target grain size, the higher the overall energy demand.

Closely associated with the energy requirement of this GGR method is the significant cost covering the already identified process areas as well as the distribution on croplands. Fuss et al. (2018) estimated the annual cost requirement for a potential of 2-4 $GtCO_2$ from 2050 to be in a range of US\$50–200/tCO_2. This estimate did not include biological storage in plants brought about by soil fertilisation effect of the applied weathered rock. They also explained that the cost was very much dependent on the chosen technology for rock processing and transport adopted as well as the rock source. The impact of rock source on the cost was reported by Strefler et al. (2018) with costs of carbon removal for dunite around US$60 per tCO_2 and that of basalt about US$200 per tCO_2. This result was corroborated by Renforth (2012) who assessed the impact of the rock source on the operational costs. He reported operational cost of US$24–123/$tCO_2$ for ultramafic rocks (dunite) and US$70–578/tCO2 for mafic rocks (basalt). The relative cheapness of dunite over basalt as shown in these assessments lies in the high weathering efficiency characteristics of dunite which ensures a lesser grinding energy requirement. Despite this seemingly advantage, basalt still remains the most suitable option on account of its previously discussed advantages and co-benefits.

Overall, Renforth (2012) estimates the cost of enhanced weathering to be in the range of US$52-480/$tCO_2$, dominated by mineral processing and transport. While this significant energy and associated cost requirement could hinder the application of this GGR method in developing areas of the world (characterised by insufficient energy despite having an abundance of the suitable rocks and required climatic conditions), Fuss et al. (2018) offers hope by insisting that the energy requirement would decrease significantly in the future on account of expected transition to renewable energies and technological advancement.

2.2.4 Other considerations

The need for dedicated land requirement is very minimal with land intensity value reported to be less than 0.01 ha/tCO_2 (Smith et al., 2015). This is because aside the mining site and space for processing, the distribution of the milled rocks can be co-deployed on land serving other functions like forests, feedstocks for BECCS and biochars. Agricultural and arable lands have been recommended as most viable options for application of the weathered rocks on account of the logistics cost associated with distribution of the weathered rocks and biological impact (plant roots, organic acids) in increasing weathering rates (Amann et al., 2020; Andrews and Taylor, 2019). Kantola et al. (2017) however called for caution on the choice of farm management practice adopted as carbon losses from agricultural soils could occur due to soil disturbance, crop harvest and microbial activity. To minimise respiratory issues, Strefler et al. (2018) recommends the use of slurry in the application of fine particles as a means of minimising the risk of dust and respiratory hazards.

2.3 Soil carbon sequestration (SCS)

Soil carbon sequestration (SCS) is a GGR method that involves deliberate change in land management practices with the aim of increasing the soil organic carbon (SOC) content, thus removing CO_2 from the atmosphere (Lal, 2013). Stockmann et al. (2013) however added that not all increases in SOC were a true net transfer of carbon from the atmosphere to land as some are just a movement from one terrestrial carbon pool to another, and have no influence either positive or negative, on climate change. Hence the land management practice should be deliberately applied for the GGR purpose relating to either crop, soil nutrient, vegetation, animal or fire. Common forms of SOC include surface plant residue, buried plant residue, particulate organic matter, humus, resistant organic carbon (biochar).

The global annual potential of SCS stands between 1.1 and 11.4 $GtCO_2$ as reported by The Royal Society (2018). The advantages of this GGR method includes low impact on land, water use, albedo, energy requirement and cost (aside the usual cost incurred by farm practices). Co-benefits include improvement in soil health, plant growth and production, thus enhancing food security, increasing biodiversity as well as environmental protection (Abdullahi et al., 2018). Alternatively, SCS is limited by issues of reversibility, feasibility and cost of measuring, monitoring, verification and sink saturation. Smith (2016) reported a default saturation time of 20 years and Goh (2004) gave a range of 15-50 years (longer in colder regions). The rate of SCS decreases with time with its efficacy reported to be greatest in the short to medium term (Lassaletta and Aguilera, 2015). Sykes et al. (2019) also identified issues of environmental heterogeneity and differences in agricultural practices as challenges to the practical implementation of SCS.

SCS depends on a variety of factors such as existing SOC, soil type, climate and management practices coupled with social and economic conditions in place such as labour cost and food production needs (Kumar, 2017). The impacts of these factors are assessed in the following sections with a view to identifying the conditions for optimal performance.

2.3.1 Management Practices

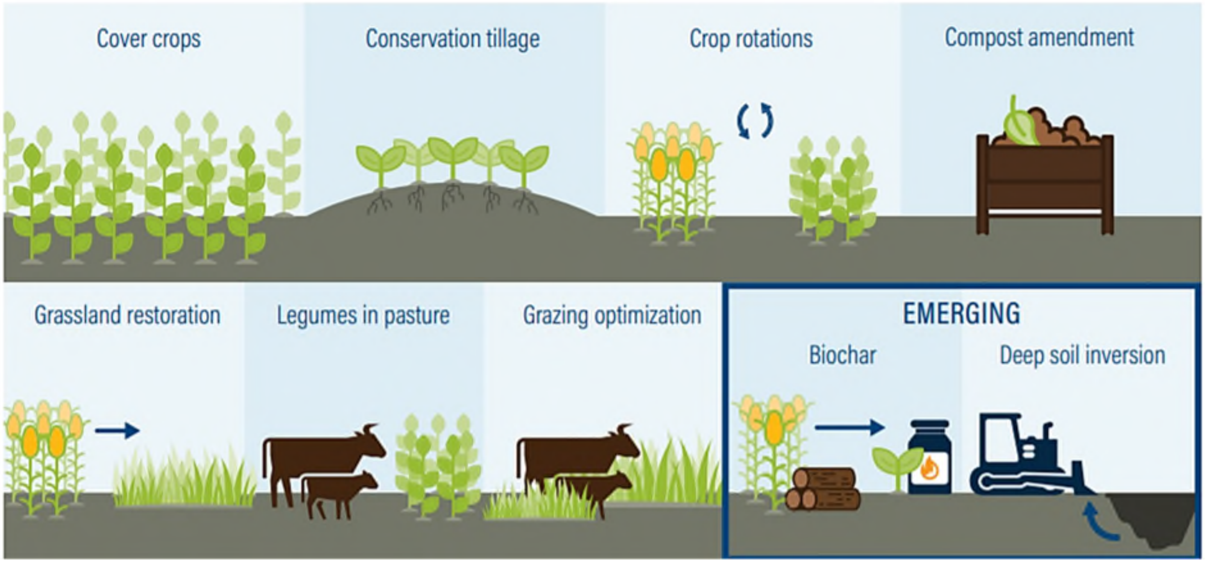

Figure 5. Land management practices for SCS (reprinted with permission from Mulligan et al. (2020), Copyright 2020 World Resources Institute). Biochar sequestration is discussed in a separate section.

Sykes et al. (2019) identified the broad classes of management practices to include: soil structure (prevent or control soil erosion, optimise fire frequency and timing, practise reduced or zero tillage), grazing land (optimise stocking density, renovate unimproved pasture), improved rotation (extend perennial phase of crop rotations, implement cover cropping), inorganic resource (optimise soil synthetic nutrient input, practise mineral carbonation of soil, manage soil pH), organic resource (optimise use of organic amendments, retain crop residues, apply biochar), soil water (optimise irrigation (Olsson et al., 2014)) and agroforestry systems implementation (Magnússon et al., 2016). Some of these practices are presented in Figure 5.

Considering the large number of management practices in existence, the specific choice applicable to a particular land area is dependent on factors such as region (climate and vegetation), use, maturity and resource availability. Aside these factors, it is recommended that the ease of deployment of the chosen management practice by farmers and land managers should also be considered. For GGR application, it is recommended that chosen practice should be able to sequester carbon for a long time and improve soil characteristics. Conservation agriculture (including no-till agriculture, cover cropping, and crop rotation) have been reported to perform fairly well in this regard as it ensures that the soil structure isn't disturbed while carrying out agricultural activities (Hunt et al., 2020; Kumar, 2017). Powlson et al. (2014) and Powlson et al. (2016) however added that its implementation was however limited by factors such as land area constraint, availability of suitable machinery as well as likelihood of rapid decomposition at elevated temperatures. They therefore recommended other practices related to water and nutrient management (manure) as well as through improved feeding practices and management of ruminant livestock. The use (planting) of perennial grass on account of its deep root system that assists in hiding carbon has also been recommended (Franzluebbers, 2012; Whitmore et al., 2015).

In regards to land use change, Stockmann et al. (2013) reported based on reviewed literature that land use change from cropland to pasture or cropland to permanent forest resulted in the greatest gains of SOC. De Stefano & Jacobson (2017) in a meta analytic study went further to report changes in SOC on account of land use change with increase for cropland-agroforestry (26-34%), pasture-agroforestry (9-10%), uncultivated land to agroforestry (25%) and decrease in the case of forest-agroforestry (26-24%) in top soil layer. These changes were mainly due to minimised carbon losses brought about by tillage and other soil structure distorting activities.

Lal (2008) outlined best management practices for temperate and tropic climatic regions on the basis of potential rates of carbon sequestration. Conservation tillage and soil restoration in humid conditions had highest sequestration for temperate climatic biomes (0.5 – 1.0 tC/ha pa). For tropical climatic biomes under humid condition, soil restoration (0.8 – 1.2 tC/ha pa), improved grazing (0.4 – 0.8 tC/ha pa) and agroforestry (0.4 – 0.8 tC/ha pa) had highest sequestration potentials.

2.3.2 Climate

The impact of temperature and precipitation on the sequestered carbon has also been assessed. While Sykes et al. (2019) reported that the high susceptibility of SOC to erosion in areas with high amount of rainfall could impede SCS performance, Stockmann et al. (2013) explained that there was room for further investigation on erosion impact as eroded SOC were likely to be reburied in a different location via terrestrial sedimentation. Godde et al. (2016) reported that SOC sequestration decreased with increase in both temperature and rainfall on account of increased soil water content and high soil temperature that enhanced SOC decomposition. There is a general agreement in the literature on the enhancing effect of high temperature on the SOC decomposition with Stockmann et al. (2013) making a case for cool/cold, humid climate regions as viable options for this GGR method. This was corroborated by Anderson et al. (2011) and Lal et al. (2015) who reported that the rate of SOC sequestration was higher in soils of cool and humid than warm and dry climates. Godde et al. (2016) however, reported that high temperature and rainfall could also increase SOC sequestration under certain conditions by enhancing plant growth and subsequent biomass return to the soil. They concluded that the influence of climate on SOC was dependent on other variables such as soil characteristics and adopted farming practices.

2.3.3 Vegetation and Soils

In regards to SOC sink capacity, boreal or snow forest (Taiga), tropical forest as well as temperate grassland/ savannah were reported to have the highest storage capacity (471 GtC, 316 GtC and 295 GtC respectively) in comparison to other biomes regardless of the soil depth considered (Stockmann et al., 2013). They also reported a fairly large SOC storage capacity for tropical grassland/shrubland as well as wetlands and added that increased plant diversity could increase SOC.

For soil type, Laganière et al. (2010) reported that clay-rich soils (>33%) had a greater SCS capacity than soils with lower clay content on account of its fine particles which assist in the stabilisation of organo-mineral complexes. This was corroborated by Lal et al. (2015) who reported that the rate of SOC sequestration was higher in soils of heavy or clayey than light or sandy texture and added that soils of agroecosystems (such as croplands, grazing lands, drastically disturbed and degraded lands) were also favourable or SCS on account of their large carbon sink capacity (high potential for SOC).

2.3.4 Other considerations

Additional land requirement is almost negligible on account of no land use associated competition in the deployment of this GGR method. Smith (2016) however puts the average land requirement per-t-C of negative emissions at 1–33 ha (which could be cropland, grassland and/or degraded land restoration). Cost is typically low and dependent on adopted management practice with Fuss et al. (2018) reporting an estimate of US$0–100/t$CO_2$. Lal et al. (2015) reported the effect of governance policy in regards to land right and supporting policy as a major factor that could contribute to soil degradation especially in the developing countries of the world.

2.4 Biochar

Biochar is obtained from the thermal degradation of organic material in the absence of oxygen (pyrolysis) (Shackley et al., 2013). Other thermochemical processes for producing biochar include gasification, hydro thermal carbonization (HTC) and torrefaction (Qambrani et al., 2017). Considered to be more stable than soil organic matter, biochar ensures long time sequestration of carbon on the soil in which it is applied with mean residence time estimated between 1000 – 4000 years (Brassard et al., 2016; Lorenz and Lal, 2014). Though this method has an estimated global GGR potential in the range of 1.8 to 4.8 GtCO_2 pa, its application has been partly limited by cost factors as well as limited availability of pyrolysis facilities and biomass (The Royal Society, 2018). Considering these limitations, Fuss et al. (2018) estimated a lower potential range of 0.3–2 GtCO_2 pa by 2050.

The advantages of GGR using biochar have been reported to include lower impact on land, water use, nutrients, albedo, energy requirement and cost (Blanco-Canqui, 2017). In addition to soil carbon sequestration, other co-benefits of biochar application include energy production from the pyrolysis process (syngas), soil improvement, waste treatment and as fuel (bio-oil) (Tisserant and Cherubini, 2019). Negative aspects of biochar application covering contamination (heavy metals, polycyclic aromatic hydrocarbons (PAHs)), alteration to soil properties, alterations to soil biota, probable wind and water (erosion) effects, soil darkening leading to increase soil temperature, as well as increase in GHG emissions in some cases brought about by factors such as abiotic release of inorganic carbon, the decomposition of labile components of biochars, and the decomposition of organic matters or humus by biochar have been reported in the literature (V. D. Nair et al., 2017; Tisserant & Cherubini, 2019).

This GGR method is dependent on factors such as biomass availability and source, land use, climatic condition, soil characteristics as well as socio-economic factors (Bajamundi et al., 2019; Zimmerman et al., 2011). An assessment of the impact of these factors is carried out in the succeeding sections with a view to identifying the optimal conditions suitable in applying this GGR method.

2.4.1 Land availability

GGR by biochar application has a very low land requirement estimated to be less than 1ha/tCO_2 (Smith, 2016). For the annual GGR potential of 1.8 to 4.8 GtCO_2, The Royal Society (2018) estimated the land requirement for biochar spreading to range from 14 and 26 Mha (less than 0.18% of global land area) at an application rate of 50 t biochar per ha. Both studies agreed on the need for additional land to cultivate dedicated biomass feedstock, with the latter reporting a value of over 50 Mha to account for over 50% of the total required biomass.

2.4.2 Biomass Feedstock

Several sustainable sources of biomass feedstock for biochar production have been identified in the literature to include biodegradable materials such as forestry slash, dead biomass, crop residues, and urban yard wastes from carpentry, municipal areas, mills, and factories as shown in Figure 6. Brassard et al. (2016) and Tisserant & Cherubini (2019) recommended lignocellulose and woody biomass as a viable option for biochar production on account of their carbon richness and enhanced stability in soils. the former however cautioned on the need to ensure that biomass cultivation did not compete with food production. Blanco-Canqui (2017) however argued that biochar from herbaceous feedstocks enhanced soil physical properties better than woody biomass with Liu et al. (2019) suggesting the use of feedstock from crop residue as best option for biochar production on the basis of overall cost reduction. Though the literature mostly recommends plant-based biomass for biochar production, there is need to also incorporate available animal biomass or manure, as biochar from this source has been reported to have higher pH than those pyrolyzed from plants (Li et al., 2018; Zhang et al., 2019).

2.4.3 Soil

The potential of biochar as a GGR method when applied to soils is very much determined by the complex interaction of various factors such as the soil type, soil moisture content, initial soil pH, biochar type, biochar application rate as well as soil organic carbon (SOC) effect (Nair et al., 2017). It is also important to note that in most reported studies, the extent of performance of GGR by biochar varied for the different greenhouse gases (Li et al., 2018; Wang et al., 2020).

In regards to the impact of soil pH and texture, conflicting results do abound in the literature. Tisserant & Cherubini (2019) and Zhang et al. (2019) reported that the greatest positive influence of biochar occurred in acidic and neutral soils. This was attributed to the liming effect of biochar which generally has a high pH with Brassard et al. (2016) reporting an average value of 8.6. Senbayram et al. (2019) on the other hand, reported an increase in greenhouse gas (GHG) emissions (CO_2 and N_2O) in acidic sandy soils on addition of the biochar which they linked to stimulated microbial activity and positive priming driven by biochars liming. A 12% reduction in CO_2 emissions with no significant effect on N_2O emissions was however reported for alkaline clay soil.

For soil texture impact, Zhang et al. (2019) reported that sandy and paddy soils (wet/flooded arable soil for planting crops like rice) had significant GHG reductions. Tisserant & Cherubini (2019) however favoured soils of high clay content on account of their decomposition reducing property. The results of these studies were further compounded by that of Liu et al. (2019) who reported that soil pH and texture generally had little impact on the response of GHG intensity to biochar application. A general explanation for these discrepancies of observations which is largely reported in most literature lies in the fact that biochar effects on soil are biochar-, soil-, and plant-specific.

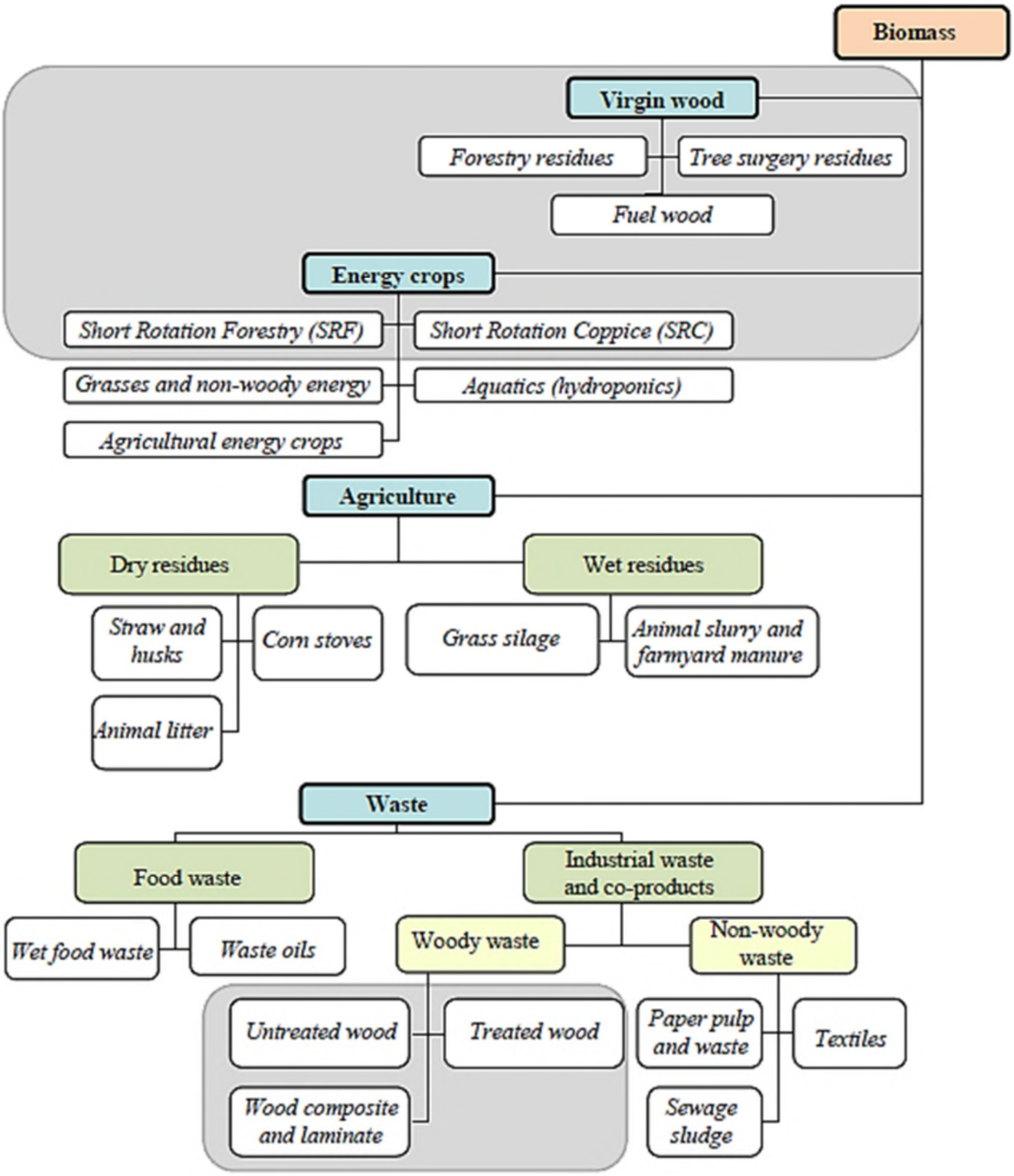

Figure 6. Sources of biomass (Ladanai and Vinterbäck, 2009)

More often than not, the biochar sequesters carbon in the soil alongside existing SOC. While Zhang et al. (2019) explained that such interactions could accelerate SOC loss, thus reducing biochar carbon sequestration potential, Brassard et al. (2016) and Majumder et al. (2019) reported that such interactions could enhance biochar stability in high clay content soils as well as well-drained sandy soils with lower SOC and lower total nitrogen contents. Qambrani et al. (2017) made a case for soil moisture content impact noting that higher contents of greater than 70% moisture promoted the anaerobic conditions that enhanced denitrification, thus mitigating N_2O production.

In order to ensure that the co-benefits of soil improvement and increased yield are optimised, it has been largely suggested that biochar be applied on soils with naturally low fertility (Lorenz and Lal, 2014; Woolf et al., 2010; Yadav et al., 2017). Brassard et al. (2016) recommended agricultural soils for biochar application with Li et al. (2018) making a case for forest soils.

Overall, the extent of impact of GGR using biochar is specific to the particular soil characteristics, the biochar as well as the management factors.

2.4.4 Other considerations

Biochar is typically one of the products of an energy generation process. According to Sykes et al. (2019), except in cases involving wet feedstock, the energy required for biochar production can be recovered from the gases produced in pyrolysis. Smith (2016) estimated an energy generation potential of 20-50 GJ per tC of biochar, out of which 10% and 20% are process energy cost and energy loss in pyrolysis plants, respectively.

A key characteristic of biochar that distinguishes it from SOC is its stability in the soil over a very long period of time. This high residence time can be lowered under higher temperature typical in tropical and sub-tropical regions coupled with acidic soils (Zimmermann et al., 2012). Brassard et al. (2016) recommended areas with mean annual temperature of 20 °C to ensure stability over a few centuries.

For cost, Fuss et al. (2018) on assessment of the various literature-based cost estimates, reported between US$90-120/t$CO_2$ with actual cost expected to be dependent on factors such as feedstock availability, applied biochar production technology and application (spreading) strategy adopted.

2.5 Direct Air Carbon Capture and Storage (DACCS)

This GGR technology involves the exposure of sorbents with high CO_2 affinity to the atmosphere with the aim of removing the atmospheric CO_2 through the formation of chemical bonds with these materials. These sorbents are then recovered by a regeneration process for re-use with the captured CO_2 separated and either utilised or stored as presented in Figure 7. It is important to note that this technology is not fully developed with a number of demonstration and pilot scale efforts reported in the literature (Fasihi et al., 2019; Viebahn et al., 2019) and large-scale commercial application predicted to be available from 2030 (Bui et al., 2018). With a global GGR potential estimate of between 0.5-5 GtCO_2 annually in 2050 and around 40 GtCO_2 by 2100 (Fuss et al., 2018), this technology is expected to play a major role in attaining the goals of the Paris Agreement on climate change contributing about 15-20% of global CO_2 emissions reduction by 2050 (Haszeldine et al., 2018).

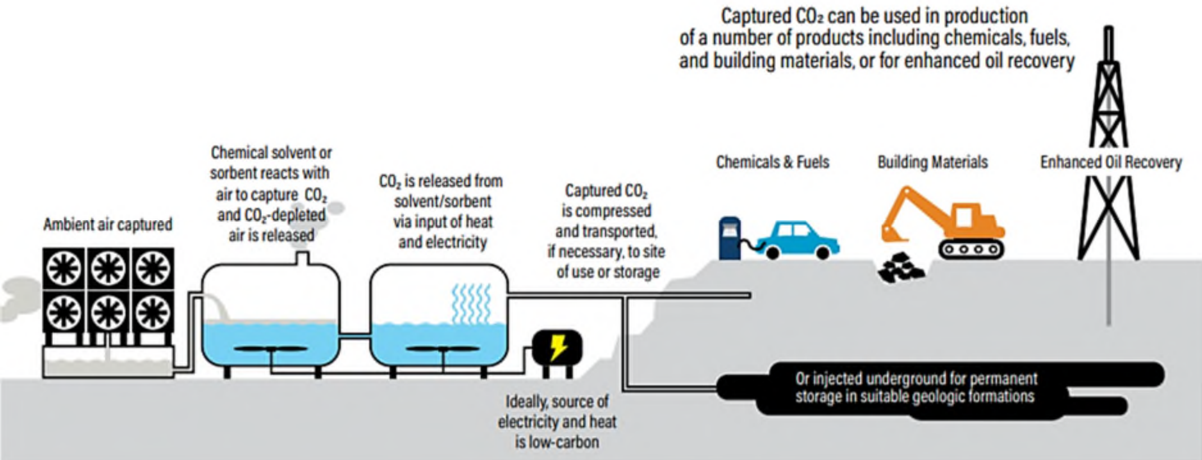

Figure 7. Schematic illustration of DACCS (reprinted with permission from Mulligan et al. 2020), Copyright 2020 World Resources Institute).

Some advantages of this technology, though with uncertainties as reported by Gambhir & Tavoni (2019) includes its minimal overall land use, water removal and ecosystem health impact in comparison to other GGR technologies. Though it can be applied at any location worldwide thus making capture possible in regions without concentrated CO_2 sources, herein also lies some of its major challenges of decreased system efficiency brought about by the large flows of air required for a relatively small amount of CO_2 captured with Bui et al. (2018) reporting about 80,000 m^3/s of air required to capture 1 $MtCO_2$ pa. While this will increase the overall capture cost, other constraints and concerns have also been identified to include storage, monitoring and leakage considerations, energy and material intensiveness as well as probable environmental impact (Fasihi et al., 2019; Sanz-Pérez et al., 2016).

Though the captured CO_2 could be utilised as feedstock for power, transport and industrial applications with its attendant benefits of value addition and probable offset of capture cost (Anwar et al., 2020), this however poses a risk to the carbon mitigation effort with large scale deployment (enhanced oil recovery (EOR)-CCS industry) reported to account for about 4-8% of the mitigation challenge (Mac Dowell et al., 2017). Other concerns associated with the utilisation option include its low incentive offering for investment since CO_2 supply vastly exceed demand (Boot-Handford et al., 2014), efficiency of the conversion process as well as the high likelihood of reversibility (Hepburn et al., 2019), thus making it a distraction and a not-so-good idea if emissions targets are to be met.

Various types of DACCS technologies exist mainly dependent on the type of sorbent used which could be in aqueous solution form with common examples being potassium hydroxide (KOH) and sodium hydroxide (NaOH), or in the solid state like the amine-based sorbents (Boot-Handford et al., 2014). On the basis of sorbent type and regeneration mechanism, Fasihi et al. (2019) reviewed and categorised the major DACCS technologies into high temperature aqueous solutions (HT DAC) and low temperature solid sorbent (LT DAC) systems. Examples of these technologies (which are best identified by the name of their respective developing companies) are shown in Figure 8.

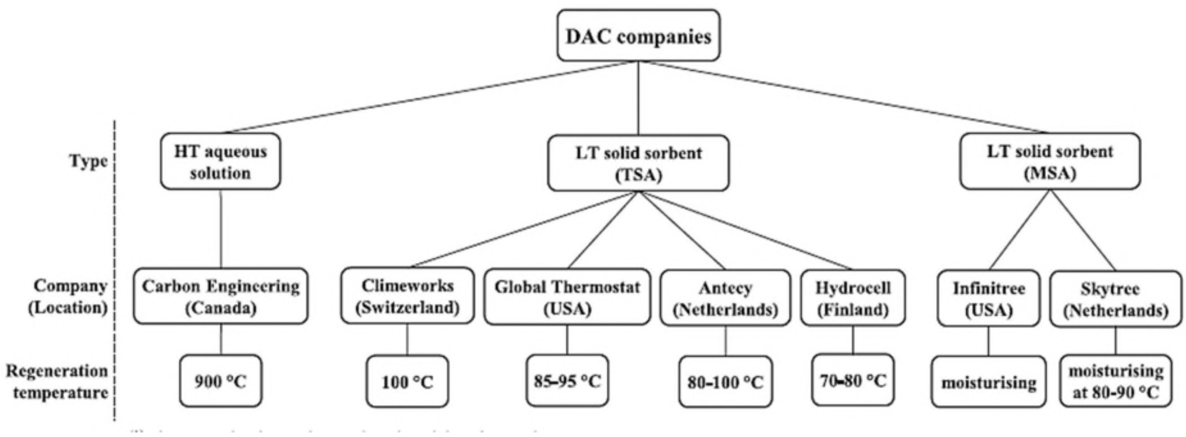

Figure 8. Companies active in the field of CO_2 DAC. Abbreviations: moisture swing adsorption, MSA, temperature swing adsorption, TSA (reprinted with permission from Fasihi et al., (2019), Copyright 2019 Elsevier).

Aside these major adsorption based technologies (TSA and MSA), other approaches such as electrochemical systems, ion-exchange resin systems, nanofactory based filters, photocatalytic approach, membranes technology and crystallisation-based systems have also been proposed and reviewed (Fasihi et al., 2019; Sanz-Pérez et al., 2016). It is important to note that pressure swing adsorption (PSA) technology which is highly effective in point source capture from flue gases has been generally reported as a non-viable option for direct air capture on account of the energy-intensive compression requirement of the feed air (Elfving et al., 2017; Stuckert and Yang, 2011; Wurzbacher et al., 2011). A faradaic electro-swing reactive adsorption system has also been proposed with high CO_2 capture effectiveness reported to be limited to flue gases and confined ambient environments (0.6-0.8% CO_2 concentration) (Voskian and Hatton, 2019).

To ensure economic viability, it is recommended that DACCS plants be sited anywhere that assures the availability of low-carbon energy inputs, appropriate CO_2 Storage and/or transport facilities to appropriate storage sites (Bui et al., 2018). It is therefore necessary to assess the impact of these and other factors on DACCS performance with a view to identifying the optimum conditions.

2.5.1 Land

The annual estimated specific land use of the various types of DAC processes has been reported to be less than 0.001ha/tCO_2 (Smith et al., 2015; Viebahn et al., 2019). Though these values did not include the area set aside for energy generation and other auxiliary facilities. A positive aspect of DACCS land use is that lands existing between the units can be co-applied for other purposes like agriculture.

2.5.2 Water

The water requirement for this GGR technology is dependent on the sorbent and regeneration process adopted, with the HT aqueous solution DAC systems reported to require varying values ranging from 1-30 m^3/tCO_2 (Viebahn et al., 2019). While this could serve as a constraint to the locational flexibility of this technology especially in dry and remote desert regions, Fasihi et al. (2019) however reported that this constraint can be avoided by the application of the LT DAC systems which have no demand for external water. Quite to the contrary, the LT DAC produces water as a by-product which can be utilised for other industrial applications. They reported the amount of water produced to be about 0.9-2.7 m^3/tCO_2 captured.

2.5.3 Energy

While passive DACCS processes, like artificial trees require significant land areas and have very low power requirement as they depend on natural circulation of air through the capturing agent, energy (whether electrical or thermal) plays a major role in the operation of most DACCS technologies. This includes the energy for releasing CO_2 from the sorbent, regenerating the sorbent, for fans and pumping, as well as for pressurizing the CO_2 for transportation (Fuss et al., 2018). On account of the CO_2 concentration in the atmosphere, Viebahn et al. (2019) reported that DACCS would require two to four times as much energy as the capture of exhaust gases from a power plant (point source capture) with (Smith et al., 2015) placing the annual energy requirement value at 47 GJ/tCO_2 removed.

In regards to consumption rate, while The Royal Society (2018) reported a theoretical minimum thermal energy requirement estimate of 0.68 GJ/tCO_2, Fajardy et al. (2019) reported a much larger estimate of about 9-10 GJ/tCO_2 and recommended the need for low carbon energy sources to ensure economic viability and sustainability of the system. Gambhir & Tavoni (2019) suggested probable low carbon sources applicable to include renewable energy sources as well as natural gas combined with capture of the CO_2 released by the gas' combustion.

Fasihi et al. (2019) however recommended the use of the LT DAC systems characterised by lower energy requirement (200-300 kWh_{el}/tCO_2, 1500-2000 kWh_{th}/tCO_2) and costs on account of the possibility of using cheaper low-grade waste heat from other systems (such as electrolysers, industrial plants, or synthesizing plants).

2.5.4 Storage

Fuss et al. (2018) reported a broad estimate of 200-50,000 $GtCO_2$ covering aquifers, depleted oil and gas fields, coal beds and structural traps. Underground geological storage option has been generally recommended as the most viable choice on account of favourable economic factors, wide geographical distribution and environmental concerns (Aminu et al., 2017; Bui et al., 2018). The Royal Society (2018) reported an estimated global capacity of 900 $GtCO_2$ if only currently existing depleted oil and gas field are to be used. It is also important to note that geographical storage poses some risks such as leakage, unfavourable seismic events and water contamination, hence the need for adequate monitoring.

2.5.5 Cost

DACCS cost requirement is quite high consisting of capital investment, energy costs of capture and operation, energy costs of regeneration, sorbent loss and maintenance as well as post capture costs covering CO_2 compression, transportation and storage. Current studies estimate the cost to range from US$600-1,000/$tCO_2$ with general expectation of decrease to US$100-300/$tCO_2$ by 2050 on account of expected technological advancement with time (Fuss et al., 2018; Psarras et al., 2017). The overall cost can however be minimised by locating DAC systems in cost optimal sites considering factors such as proximity to storage facilities, renewable energy applicability as well as co-locating with waste heat emitting industries, minimal transport and grid cost. Choice of sorbent is also an important factor to consider with Azarabadi & Lackner (2019) stating that a sorbent is expected to survive between tens to hundreds of thousands of loading and unloading cycles to be considered economically viable. Fuss et al. (2018) while making a case for the probable use of wastewater treatment as a means to capture ambient CO_2 also recommended solid sorbent systems (LT DAC) as a cheaper option in comparison to the aqueous solution type as it required less heat for regeneration. This was also corroborated by Fasihi et al. (2019) who referred to it as the more favourable option for today and the future.

2.6 Bioenergy with Carbon Capture and Storage (BECCS)

It involves a combination of biomass combustion in various applications (through power generation, biofuels production, hydrogen plants, bio-synthetic natural gas, heating, and industrial processes) and carbon capture and storage (CCS) (Bhave et al., 2017; Fajardy et al., 2019a). This combination achieves GGR by taking atmospheric CO_2 temporarily locked in plants and storing it permanently in geological formations, while using the biomass to generate energy in various form as shown in Figure 8. With an annual bioenergy potential of over 100 EJ (Smith, 2016) and global GGR potential ranging from 1.3-10 $GtCO_2$ pa, BECCS implementation offers a great option for the achievement of the less than 2 °C warming target by the end of the century.

Despite its seemingly high prospects coupled with low vulnerability to reversal, it is however characterised by uncertainties and limitations such as availability of land and sustainable biomass (Al-Qayim et al., 2015), the availability of suitable and secure CO_2 sequestration sites globally, environmental and ecological impacts, technical considerations, costs, financing, legal liabilities (Bhave et al., 2017) and public acceptance (Gough and Mander, 2019). Other concerns include impact on food security and prices, biodiversity, water and nutrients.

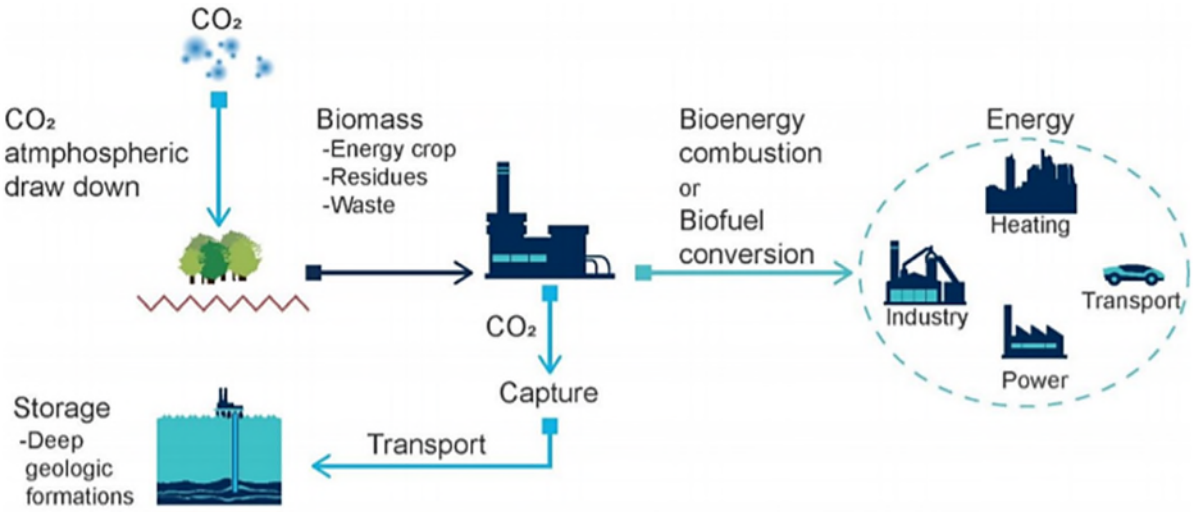

Figure 9. Schematic illustration of BECCS (reprinted with permission from Consoli (2019), Copyright 2019 Global CCS Institute).

Unlike DACCS which has a very high flexibility in choice of location, the siting of BECCS plant is very much dependent on a consideration of factors such as proximity to biomass source, carbon storage site as well as transport cost (either in moving the biomass or the captured carbon). These and other factors are assessed briefly as presented in various literature in the following sections with a view to identifying applicable options that will ensure optimal performance of the BECCS system.

2.6.1 Land and water requirement

With these requirements dependent on the choice of biomass feedstock, The Royal Society (2018) reported annual land requirement to range from 0.03 to 0.06 ha/tCO_2 removed and water requirement of about 60 m^3/tCO_2 (not including the CCS use). Higher range of 0.1–1.7 ha/tCO_2 was reported by Smith et al. (2015) with forest residue feedstock accounting for the highest land requirement. They also reported a very large water requirement of about 218 m^3/tCO_2 pa which was obtained by adding bio-energy water use to CCS water use. Aside the probable need for water in the biomass production, water is also needed in the capture process with the amount required dependent on the cooling technology adopted.

2.6.2 Biomass

There exists a relatively wide range of applicable sustainable biomass. These include lignocellulosic and herbaceous bioenergy crops (primary sources requiring dedicated plant growth), urban and industrial wastes, agricultural and forest residues (secondary sources), as well as algae (see section 2.4.2). Lignocellulosic feedstocks like wood, Miscanthus, switchgrass and agricultural residues have been generally recommended in the literature either for dedicated planting or importation as they are less likely to compete with food supply (Smith et al., 2015; The Royal Society, 2018). This biomass can be used as single fuel source for power generation (dedicated use) or in combination with other conventional fossil fuels, such as coal and gas (co-fired generation) especially considering its higher moisture content and a lower heating value in comparison to conventional fossil fuels (Pires, 2019).

2.6.3 Other considerations

Same storage concerns as discussed under DACCS (section 2.5.4) also apply for BECCS coupled with the added aspect of likely carbon emissions from the soil brought about by land-use practices that might be associated with the biomass management.

In regards to energy generation, Smith et al. (2015) reported the net generating capacity of BECCS to range from 3-40 GJ/tCO_2 pa with actual value dependent on the biomass source ranging from forest biomass to crop residues respectively. In regard to cost of deployment, Fuss et al. (2018) reported literature estimates to range from US$15-400/t$CO_2$ with actual cost highly sensitive to factors such as biomass cost, electricity sales price, transport and logistics, technology adopted, plant lifetime and efficiency. They however projected a range of US$100-200/tCO2 by 2050 hinged on the management intensity that will be required to ensure sustainable deployment and land use.

3 Discussion

The review of the major operational factors required for the optimum performance of the various GGR methods under consideration has been carried out with a summary of identified factors presented in Table 2. The importance of this assessment cannot be over-emphasised as it provides a guide (point of reference) to policy makers at various levels as well as investors in the type of GGR technology that can be deployed in a particular area based on the locational characteristics and available resources. In this section, a comparison and assessment of the extent of influence of the various factors on the respective GGR methods is presented. It is concluded with the assessed levels of impact being quantified using a weighting scale of 0 – 5 (where zero (0) represents no impact and five (5) represents maximum impact) based on the authors' perspective as presented in Table 3.

In regards to land availability and considering the competing uses of this resource, there is need for a conservative approach in the deployment of the various GGR technologies (Fajardy et al., 2019b). While Afforestation typically has the highest requirement, EW and DACCS have the least, thus making them viable options for most areas as they can be co-applied alongside other activities. Land requirement for SCS is mostly dependent on the management practice adopted which could be very low if applied alongside forestation and high for no-tillage practice. Land requirement for BECCS and biochar are largely dependent on the choice of biomass feedstock.

Climate is a major factor in the performance of forestation, EW, SCS, and biochar though with varying levels of impact as shown in Table 3, thus limiting their global deployment to areas of favourable climate features. The performance of BECCS and DACCS are largely independent of climatic factors and thus applicable in most locations. Despite the seemingly locational flexibility of these latter GGR technologies, the need for selection of cost-optimal sites cannot be over-emphasised with factors such as proximity to geological storage and biomass availability (in the case of BECCS) playing an indispensable role in their operation and performance.

Table 2. Optimal conditions and requirements for GGR methods.

	Forestation	**EW**	**SCS**	**Biochar**	**DACCS**	**BECCS**
TRL	8-9	3-5	8-9	3-6	4-7	4-8
Climatic condition	Tropical region (high rainfall and temperature)	Warm tropical and humid regions (Ave. temperature of 25 °C and high rainfall)	Temperate and humid tropical regions.	Temperate and humid regions (Ave. temperature of 20°C)	Very much applicable in any climatic area though cost optimal sites are highly recommended.	
Annual land requirement (ha/tCO_2)	0.1 – 0.6	<0.01	Dependent on adopted practice.	<1	< 0.001	0.1-1.7
Annual energy requirement (GJ/tCO_2)	Negligible	46	Negligible	10-50 (Potential energy generation)	10–47 (depending on type of technology)	10 (Potential energy generation)
Cost (US$/t$CO_2$)	0 – 8.08 (for afforestation in tropical regions)	52 – 480	0–100 (depending on adopted practice)	90-120	600-1000 (expected decrease to 100-300 by 2050)	100-200
Annual water requirement (m^3/tCO_2)	No additional water required in high rainfall regions.	1.5	-	-	1 - 30	60 – 218
Vegetation	Deciduous broadleaved native mixed species	-	Boreal forest (Taiga), tropical forest and grassland/ savannah	preferably crop residue and herbaceous feedstock	-	-
Geological storage	-	-	-	-	Applicable	Applicable
Other requirements/ recommendations	**Management practice:** Afforestation with agroforestry practice to maximise land use.	**Rock type**: Basaltic and or dunite rocks. Proximity of mining site to particle application site Renewable energy-based rock processing system	**Management practice**: Conservation tillage (temperate region) and improved grazing (tropical region)	Arable (agricultural) land for application	**Preferable technology**: Low Temperature (LT) DAC Plants. Low carbon energy sources are also recommended.	-

With vegetation closely linked with climate, biomass availability for BECCS and biochar could be impacted by climatic factors especially in cases where the feedstock is sourced from dedicated local seasonal crops. This is however minimal on account of the diverse options of feedstock sources ranging from domestic to industrial waste as well as importation from other locations that can be adopted. Extreme temperature however does affect biochar mean residence time (Fuss et al., 2018).

In the deployment of GGR technologies, energy requirement and cost are closely related with DACCS and EW ranking highest. While this could serve as a hindrance to the deployment of these GGR technologies especially in areas still grappling with sufficient energy and/or using fossil fuel-based power systems which could reduce the emission removal gains, the need to adopt low carbon emission energy sources in the operation of these technologies have been generally advanced coupled with optimistic projections of DAC cost reduction on account of technological improvement. BECCS and biochar are less expensive than DACCS and EW with the co-benefit of being a source of energy, thus making them viable options for areas with insufficient energy (Fajardy and Mac Dowell, 2018). Energy and cost requirement for forestation and SCS are typically low but could increase depending on the management system adopted which are subject to the prevailing ecological factors of the particular area.

Table 3. Impact weighting of GGR factors with respect to the various methods

		Forestation	**EW**	**SCS**	**Biochar**	**DACCS**	**BECCS**
Climatic condition		5	4	4	3	1	2
Soil	Type	3	2	4	3	0	2
	pH	1	3	3	4	0	1
*Land	Availability	4	2	2	2	1	2
	Quality	3	0	1	1	0	2
	Accessibility	1	3	3	3	1	2
Vegetation		4	0	3	2	0	3
*Water requirement		3	0	2	0	1	2
Energy requirement		1	4	1	2	3	2
Geography		2	4	2	2	1	1
Geological Storage		0	0	0	0	5	5
Cost		1	4	1	2	4	3

**Data for the GGR technologies, except SCS, is adapted from Fajardy, Patrizio, et al. (2019).*

Using the comparative analysis in Table 2 and discussions in the preceding paragraphs, a quantification of the importance of these factors on the performance of the six GGR methods is presented in Table 3. This quantification which is based on the authors' perspective was carried out by ranking each factor on a scale of 0 – 5. While a weight of zero (0) indicates that a factor has no impact and not required for the deployment of a GGR method, a weighting of five (5) indicates that a factor is highly important and indispensable in the deployment of a GGR method. For instance, while geological storage has been ranked a weight of 5 for DACCS and BECCS on account of its importance in the deployment of these two technologies; it was ranked 0 for the other four methods as they do not require geological storage. The other intermediate scores indicate varying levels of importance of these factors and the extent of dependence of the GGR methods on them as discussed in the preceding paragraphs.

With CCS-based technologies expected to play a major role in attaining the mitigation target on account of their versatility and potential and bearing in mind that no single GGR technology can individually shoulder the emission mitigation burden, an understanding of how these factors impact on the performance of the various GGR is key in making the appropriate choice of combination of the various technologies for particular areas.

4 Recent trends and outlook

It is agreed that the deployment of GGR methods is an indispensable option in meeting the 1.5 °C warming target with forestation and BECCS featuring prominently in most IAMs scenarios (IPCC, 2018). While natural solutions such as forestation and SCS, though having a lower carbon storage permanence, are matured and already being deployed at various scales. Other GGR methods with emphasis on the CCS-based methods are still at relatively lower TRLs as captured in Figure 1. These engineered solutions ensure high storage permanence thus require more attention and funding both from government and corporate bodies to deliver their prompt deployment.

On the commercialisation front, there has been an increased interest in investment in GGR methods in recent times. In January 2020, Microsoft announced a US$1billion climate innovation fund aimed at achieving a carbon negative goal by 2030. This commitment which is exclusively focused on projects that remove carbon from the atmosphere is currently funding projects from 15 organisations representing a combined removal potential of more than 1.3 $MtCO_2$ pa (Chay et al., 2021; Microsoft, 2021). Stripe, a global financial service company has also made its negative emission commitment with a pledge to invest a minimum of US$1 million per year in projects involving direct removal of carbon dioxide from the atmosphere (Cullenward et al., 2020; Orbuch, 2020). Other organisations providing major investments, incentives and collaborations for the development of GGR methods include Shopify, Audi, ExxonMobil as well as Elon Musk and the Musk Foundation who are currently funding a US$100 million XPRIZE carbon removal competition. These and other efforts if continued, will ensure an acceleration in the development and deployment of these GGR methods, providing continued governmental commitments to net zero and decarbonisation targets.

On account of the economic downturn and overall drop in energy demand brought about by the global coronavirus pandemic, the International Energy Agency estimated an 8% (about 2.8 Gt) drop in global CO_2 emissions in 2020 (IEA, 2020). This drop which had no detectable impact on atmospheric CO_2 or climate change is expected to be temporary as they do not actually reflect structural changes in economic, transport or energy systems (Le Quéré et al., 2020). The post-COVID era however offers governments of the global community a great opportunity to put in place structural adjustments that will maintain and even enhance this emission drop in the coming years. This can be achieved through the adoption of economic stimuli programmes centred around low carbon emission pathways (Le Quéré et al., 2020), increased investment as well as favourable policy incentives and legislations that will enhance technological development and social awareness regarding the scaling and deployment of GGR methods. With GGR methods expected to feature more prominently in the next round of submissions of countries' nationally determined contributions (NDCs), the need for sustainable global and regional co-operation will be key in the development and deployment of these GGR methods.

5 Conclusions

In this study, an assessment of the impact of operational factors on six GGR technologies (forestation, EW, SCS, biochar, DACCS and BECCS) has been carried out from the literature with a view to identifying the conditions and requirements necessary for optimum performance of these technologies. The factors considered include climatic condition, management practices, availability of land, water, energy and biomass, cost and soil characteristics. From the assessment, the extent of influence of these factors on the various GGR technologies have been discussed and highlighted on a 0 – 5 scale with the major findings as follows;

- For forestation, the tropical climatic region has been identified for deployment with afforestation and/or reforestation with agroforestry practice recommended to maximise land use and minimise cost while using deciduous broadleaved native mixed species.
- In the case of EW, warm tropical and humid regions have been identified for optimum deployment using the more common basaltic rocks on preferably arable land with acidic soil. Low carbon renewable energy sources have also been prescribed as means of reducing the high energy and cost requirement.
- For SCS, the boreal or snow forest has been identified for deployment with adopted management practices generally dependent on particular regions: conservation tillage (temperate region) and improved grazing (tropical region). Soils of heavy and clayey texture and agroecosystems lands have also been recommended for SCS deployment.
- For biochar, temperate and humid regions have been highlighted for optimum deployment in arable land characterised by well drained sandy soil with low SOC and naturally low fertility with pH preferably acidic and neutral. Plant-based biomass (preferably crop residue and herbaceous feedstock) have also been recommended as feedstock.
- Lastly, the CCS technologies (BECCS and DACCS) which have been largely projected as major contributors to the attainment of the emission mitigation target have been found to have a larger locational flexibility. However, the need for cost optimal siting of the CCS plant is very much necessary and dependent on the presence of appropriate geological storage facility.

Though specific regions have been identified for optimum performance of these GGR methods on account of favourable resource availability, the need for international co-operation and collaboration cannot be over-emphasised if the mitigation target is to be met. Socio-political factors are expected to also play a major role, with nature-based solutions like forestation and SCS expected to be highly favoured in this regard ahead of the engineered solutions (CCS). While these nature-based solutions are already being deployed owing to their low cost, technological maturity and social acceptance, their reliability and sustainability in the long run is however limited by factors such as permanence of storage, competing land use and lower removal potential. Hence, there is need for accelerated social sensitization and technological development of the CCS based methods which offer a higher removal potential and more reliable permanence of storage of the captured carbon.

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CRediT Author Statement

JOA – Conceptualisation, Methodology, Software, Formal Analysis, Investigation, Writing - Original Draft. PC - Conceptualisation, Writing - Review & Editing, Supervision, Project administration. SAN - Conceptualisation, Writing - Review & Editing, Supervision. VM - Conceptualisation, Writing - Review & Editing, Supervision.

References

Abbas, F., Hammad, H.M., Fahad, S., Cerdà, A., Rizwan, M., Farhad, W., Ehsan, S., Bakhat, H.F., 2017. Agroforestry: a sustainable environmental practice for carbon sequestration under the climate change scenarios—a review. Environ. Sci. Pollut. Res. 24, 11177–11191. https://doi.org/10.1007/s11356-017-8687-0

Abdullahi, A.C., Siwar, C., Shaharudin, M.I.I., Anizan, I., 2018. Carbon Sequestration in Soils: The Opportunities and Challenges. IntechOpen 13. https://doi.org/http://dx.doi.org/10.5772/intechopen.79347

Al-Qayim, K., Nimmo, W., Pourkashanian, M., 2015. Comparative techno-economic assessment of biomass and coal with CCS technologies in a pulverized combustion power plant in the United Kingdom. Int. J. Greenh. Gas Control 43, 82–92. https://doi.org/10.1016/j.ijggc.2015.10.013

Alvarez, S., Ortiz, C., Díaz-Pinés, E., Rubio, A., 2016. Influence of tree species composition, thinning intensity and climate change on carbon sequestration in Mediterranean mountain forests: a case study using the CO2Fix model. Mitig. Adapt. Strateg. Glob. Chang. 21, 1045–1058. https://doi.org/10.1007/s11027-014-9565-4

Amann, T., Hartmann, J., Struyf, E., De Oliveira Garcia, W., Fischer, E.K., Janssens, I., Meire, P., Schoelynck, J., 2020. Enhanced Weathering and related element fluxes - A cropland mesocosm approach. Biogeosciences 17, 103–119. https://doi.org/10.5194/bg-17-103-2020

Aminu, M.D., Nabavi, S.A., Rochelle, C.A., Manovic, V., 2017. A review of developments in carbon dioxide storage. Appl. Energy 208, 1389–1419. https://doi.org/10.1016/j.apenergy.2017.09.015

Anderson, R.G., Canadell, J.G., Randerson, J.T., Jackson, R.B., Hungate, B.A., Baldocchi, D.D., Ban-Weiss, G.A., Bonan, G.B., Caldeira, K., Cao, L., Diffenbaugh, N.S., Gurney, K.R., Kueppers, L.M., Law, B.E., Luyssaert, S., O’Halloran, T.L., 2011. Biophysical considerations in forestry for climate protection. Front. Ecol. Environ. 9, 174–182. https://doi.org/10.1890/090179

Andrews, M., Taylor, L., 2019. Combating Climate Change Through Enhanced Weathering of Agricultural Soils. Elements 15, 325–330. https://doi.org/10.2138/gselements.15.4.253

Anwar, M.N., Fayyaz, A., Sohail, N.F., Khokhar, M.F., Baqar, M., Yasar, A., Rasool, K., Nazir, A., Raja, M.U.F., Rehan, M., Aghbashlo, M., Tabatabaei, M., Nizami, A.S., 2020. CO2 utilization: Turning greenhouse gas into fuels and valuable products. J. Environ. Manage. 260. https://doi.org/10.1016/j.jenvman.2019.110059

Arora, V.K., Montenegro, A., 2011. Small temperature benefits provided by realistic afforestation efforts. Nat. Geosci. 4, 514–518. https://doi.org/10.1038/ngeo1182

Azarabadi, H., Lackner, K.S., 2019. A sorbent-focused techno-economic analysis of direct air capture. Appl. Energy 250, 959–975. https://doi.org/10.1016/j.apenergy.2019.04.012

Bach, L.T., Gill, S.J., Rickaby, R.E.M., Gore, S., Renforth, P., 2019. CO2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems. Front. Clim. 1. https://doi.org/10.3389/fclim.2019.00007

Bajamundi, C.J.E., Koponen, J., Ruuskanen, V., Elfving, J., Kosonen, A., Kauppinen, J., Ahola, J., 2019. Capturing CO2 from air: Technical performance and process control improvement. J. CO2 Util. 30, 232–239. https://doi.org/10.1016/j.jcou.2019.02.002

Bala, G., 2014. Can planting trees help to reduce global warming? Curr. Sci. 106, 1551–1552. https://doi.org/10.1111/ner.12135

Bhave, A., Taylor, R.H.S., Fennell, P., Livingston, W.R., Shah, N., Dowell, N. Mac, Dennis, J., Kraft, M., Pourkashanian, M., Insa, M., Jones, J., Burdett, N., Bauen, A., Beal, C., Smallbone, A., Akroyd, J., 2017. Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO2 targets. Appl. Energy 190, 481–489. https://doi.org/10.1016/j.apenergy.2016.12.120

Blanco-Canqui, H., 2017. Biochar and Soil Physical Properties. Soil Sci. Soc. Am. J. 81, 687–711. https://doi.org/10.2136/sssaj2017.01.0017

Bonan, G.B., 2008. Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. Science (80-.). 320, 1444–1449. https://doi.org/10.1126/science.1155121

Bond, W.J., Stevens, N., Midgley, G.F., Lehmann, C.E.R., 2019. The Trouble with Trees: Afforestation Plans for Africa. Trends Ecol. Evol. 34, 963–965. https://doi.org/10.1016/j.tree.2019.08.003

Boot-Handford, M.E., Abanades, J.C., Anthony, E.J., Blunt, M.J., Brandani, S., Mac Dowell, N., Fernández, J.R., Ferrari, M.C., Gross, R., Hallett, J.P., Haszeldine, R.S., Heptonstall, P., Lyngfelt, A., Makuch, Z., Mangano, E., Porter, R.T.J., Pourkashanian, M., Rochelle, G.T., Shah, N., Yao, J.G., Fennell, P.S., 2014. Carbon capture and storage update. Energy Environ. Sci. 7, 130–189. https://doi.org/10.1039/c3ee42350f

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Emissions of N 2 O and NO from fertilized fields: Summary of available measurement data . Global Biogeochem. Cycles 16, 6-1-6–13. https://doi.org/10.1029/2001gb001811

Brassard, P., Godbout, S., Raghavan, V., 2016. Soil biochar amendment as a climate change mitigation tool: Key parameters and mechanisms involved. J. Environ. Manage. 181, 484–497. https://doi.org/10.1016/j.jenvman.2016.06.063

Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., Fuss, S., Galindo, A., Hackett, L.A., Hallett, J.P., Herzog, H.J., Jackson, G., Kemper, J., Krevor, S., Maitland, G.C., Matuszewski, M., Metcalfe, I.S., Petit, C., Puxty, G., Reimer, J., Reiner, D.M., Rubin, E.S., Scott, S.A., Shah, N., Smit, B., Trusler, J.P.M., Webley, P., Wilcox, J., Mac Dowell, N., 2018. Carbon capture and storage (CCS): the way forward. Energy Environ. Sci. https://doi.org/10.1039/C7EE02342A

Canadell, J.G., Raupach, M.R., 2008. Managing forests for climate change mitigation. Science (80-.). 320, 1456–1457. https://doi.org/10.1126/science.1155458

Chay, F., Cullenward, D., Hamman, J., Freeman, J., 2021. insights from analyzing a new round of carbon removal projects / research / carbonplan [WWW Document]. CarbonPlan.

Consoli, C., 2019. Bioenergy and Carbon Capture and Storage, Global CCS Institute.

Cullenward, D., Hamman, J., Freeman, J., 2020. insights from our first project reports / research / carbonplan [WWW Document]. CarbonPlan.

De Oliveira Garcia, W., Amann, T., Hartmann, J., Karstens, K., Popp, A., Boysen, L.R., Smith, P., Goll, D., 2020. Impacts of enhanced weathering on biomass production for negative emission technologies and soil hydrology. Biogeosciences 17, 2107–2133. https://doi.org/10.5194/bg-17-2107-2020

De Stefano, A., Jacobson, M.G., 2017. Soil carbon sequestration in agroforestry systems: a meta-analysis. Agrofor. Syst. 92, 285–299. https://doi.org/10.1007/s10457-017-0147-9

Doelman, J.C., Stehfest, E., van Vuuren, D.P., Tabeau, A., Hof, A.F., Braakhekke, M.C., Gernaat, D.E.H.J., van den Berg, M., van Zeist, W.J., Daioglou, V., van Meijl, H., Lucas, P.L., 2019. Afforestation for climate change mitigation: Potentials, risks and trade-offs. Glob. Chang. Biol. 26, 1576–1591. https://doi.org/10.1111/gcb.14887

Dou, X., Zhou, W., Zhang, Q., Cheng, X., 2016. Greenhouse gas (CO2, CH4, N2O) emissions from soils following afforestation in central China. Atmos. Environ. 126, 98–106. https://doi.org/10.1016/j.atmosenv.2015.11.054

Edwards, D.P., Lim, F., James, R.H., Pearce, C.R., Scholes, J., Freckleton, R.P., Beerling, D.J., 2017. Climate change mitigation: Potential benefits and pitfalls of enhanced rock weathering in tropical agriculture. Biol. Lett. 13. https://doi.org/10.1098/rsbl.2016.0715

Elfving, J., Bajamundi, C., Kauppinen, J., 2017. Characterization and Performance of Direct Air Capture Sorbent. Energy Procedia 114, 6087–6101. https://doi.org/10.1016/j.egypro.2017.03.1746

Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Noordwijk, M. van, Creed, I.F., Pokorny, J., Gaveau, D., Spracklen, D. V., Tobella, A.B., Ilstedt, U., Teuling, A.J., Gebrehiwot, S.G., Sands, D.C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., Sullivan, C.A., 2017. Trees, forests and water: Cool insights for a hot world. Glob. Environ. Chang. 43, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002

Fajardy, M., Köberle, A., Dowell, N.M.A.C., Fantuzzi, A., 2019a. BECCS deployment: A reality check, Grantham Institute Briefing paper No 28.

Fajardy, M., Mac Dowell, N., 2018. The energy return on investment of BECCS: Is BECCS a threat to energy security? Energy Environ. Sci. 11, 1581–1594. https://doi.org/10.1039/c7ee03610h

Fajardy, M., Patrizio, P., Daggash, H.A., Mac Dowell, N., 2019b. Negative Emissions: Priorities for Research and Policy Design. Front. Clim. 1, 1–7. https://doi.org/10.3389/fclim.2019.00006

Fasihi, M., Efimova, O., Breyer, C., 2019. Techno-economic assessment of CO 2 direct air capture plants. J. Clean. Prod. 224, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086

Favero, A., Sohngen, B., Huang, Y., Jin, Y., 2018. Global cost estimates of forest climate mitigation with albedo: A new integrative policy approach. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aaeaa2

Franzluebbers, A.J., 2012. Grass roots of soil carbon sequestration. Carbon Manag. 3, 9–11. https://doi.org/10.4155/cmt.11.73

Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122, 1–23. https://doi.org/10.1016/j.geoderma.2004.01.021

Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., De Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.V., Wilcox, J., Del Mar Zamora Dominguez, M., Minx, J.C., 2018. Negative emissions - Part 2: Costs, potentials and side effects. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aabf9f

Gambhir, A., Tavoni, M., 2019. Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation. One Earth 1, 405–409. https://doi.org/10.1016/j.oneear.2019.11.006

Godde, C.M., Thorburn, P.J., Biggs, J.S., Meier, E.A., 2016. Understanding the impacts of soil, climate, and farming practices on soil organic carbon sequestration: A simulation study in Australia. Front. Plant Sci. 7, 1–15. https://doi.org/10.3389/fpls.2016.00661

Goglio, P., Williams, A.G., Balta-Ozkan, N., Harris, N.R.P., Williamson, P., Huisingh, D., Zhang, Z., Tavoni, M., 2020. Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes. J. Clean. Prod. 244, 118896. https://doi.org/10.1016/j.jclepro.2019.118896

Goh, K.M., 2004. Carbon sequestration and stabilization in soils: Implications for soil productivity and climate change. Soil Sci. Plant Nutr. 50, 467–476. https://doi.org/10.1080/00380768.2004.10408502

Goodman, R., Herold, M., 2015. Why Maintaining Tropical Forests is Essential and Urgent for a Stable Climate. SSRN Electron. J. https://doi.org/10.2139/ssrn.2622758

Gough, C., Mander, S., 2019. Beyond Social Acceptability: Applying Lessons from CCS Social Science to Support Deployment of BECCS. Curr. Sustain. Energy Reports 6, 116–123. https://doi.org/10.1007/s40518-019-00137-0

Hall, J.M., van Holt, T., Daniels, A.E., Balthazar, V., Lambin, E.F., 2012. Trade-offs between tree cover, carbon storage and floristic biodiversity in reforesting landscapes. Landsc. Ecol. 27, 1135–1147. https://doi.org/10.1007/s10980-012-9755-y

Hartman, P.J., 2017. Reviews of Science for Science Librarians: Forestry as a Climate Change Mitigation Tool. Sci. Technol. Libr. 36, 219–234. https://doi.org/10.1080/0194262X.2017.1337541

Hartmann, J., Kempe, S., 2008. What is the maximum potential for CO2 sequestration by “stimulated” weathering on the global scale? Naturwissenschaften 95, 1159–1164. https://doi.org/10.1007/s00114-008-0434-4

Hartmann, J., West, A.J., Renforth, P., Köhler, P., De La Rocha, C.L., Wolf-Gladrow, D.A., Dürr, H.H., Scheffran, J., 2013. Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. Rev. Geophys. 51, 113–149. https://doi.org/10.1002/rog.20004

Haszeldine, R.S., Flude, S., Johnson, G., Scott, V., 2018. Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 376. https://doi.org/10.1098/rsta.2016.0447

Hepburn, C., Adlen, E., Beddington, J., Carter, E.A., Fuss, S., Mac Dowell, N., Minx, J.C., Smith, P., Williams, C.K., 2019. The technological and economic prospects for CO2 utilization and removal. Nature 575, 87–97. https://doi.org/10.1038/s41586-019-1681-6

Hilaire, J., Minx, J.C., Callaghan, M.W., Edmonds, J., Luderer, G., Nemet, G.F., Rogelj, J., del Mar Zamora, M., 2019. Negative emissions and international climate goals—learning from and about mitigation scenarios. Clim. Change 157, 189–219. https://doi.org/10.1007/s10584-019-02516-4

Hunt, J.R., Celestina, C., Kirkegaard, J.A., 2020. The realities of climate change, conservation agriculture and soil carbon sequestration. Glob. Chang. Biol. 0–3. https://doi.org/10.1111/gcb.15082

IEA, 2020. Global energy and CO2 emissions in 2020 [WWW Document]. Glob. Energy Rev. 2020 .

IPCC, 2018. 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,.

Ishimoto, Y., Sugiyama, M., Kato, E., Moriyama, R., Tsuzuki, K., Kurosawa, A., 2017. Putting Costs of Direct Air Capture in Context. SSRN Electron. J. https://doi.org/10.2139/ssrn.2982422

Kantola, I.B., Masters, M.D., Beerling, D.J., Long, S.P., DeLucia, E.H., 2017. Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. Biol. Lett. 13. https://doi.org/10.1098/rsbl.2016.0714

Kirschbaum, M.U.F., Whitehead, D., Dean, S.M., Beets, P.N., Shepherd, J.D., Ausseil, A.G.E., 2011. Implications of albedo changes following afforestation on the benefits of forests as carbon sinks. Biogeosciences 8, 3687–3696. https://doi.org/10.5194/bg-8-3687-2011

Köhler, P., Hartmann, J., Wolf-Gladrow, D.A., 2010. Geoengineering potential of artificially enhanced silicate weathering of olivine. Proc. Natl. Acad. Sci. U. S. A. 107, 20228–20233. https://doi.org/10.1073/pnas.1000545107

Kreidenweis, U., Humpenöder, F., Stevanović, M., Bodirsky, B.L., Kriegler, E., Lotze-Campen, H., Popp, A., 2016. Afforestation to mitigate climate change: Impacts on food prices under consideration of albedo effects. Environ. Res. Lett. 11. https://doi.org/10.1088/1748-9326/11/8/085001

Kumar, S.K., 2017. Sustainable Management of Soil for Carbon Sequestration. Sci. Technol. J. 5, 132–140. https://doi.org/10.22232/stj.2017.05.02.10

Ladanai, S., Vinterbäck, J., 2009. Global Potential of Sustainable Biomass for Energy, Swedish University of Agricultural Sciences , Department of Energy and Technology.

Laganière, J., Angers, D.A., Paré, D., 2010. Carbon accumulation in agricultural soils after afforestation: A meta-analysis. Glob. Chang. Biol. 16, 439–453. https://doi.org/10.1111/j.1365-2486.2009.01930.x

Lal, R., 2013. Soil carbon management and climate change. Carbon Manag. 4, 439–462. https://doi.org/10.4155/cmt.13.31

Lal, R., 2008. Soil carbon stocks under present and future climate with specific reference to European ecoregions. Nutr. Cycl. Agroecosystems 81, 113–127. https://doi.org/10.1007/s10705-007-9147-x

Lal, R., Negassa, W., Lorenz, K., 2015. Carbon sequestration in soil. Curr. Opin. Environ. Sustain. 15, 79–86. https://doi.org/10.1016/j.cosust.2015.09.002

Lassaletta, L., Aguilera, E., 2015. Soil carbon sequestration is a climate stabilization wedge: Comments on Sommer and Bossio (2014). J. Environ. Manage. 153, 48–49. https://doi.org/10.1016/j.jenvman.2015.01.038

Lawford-Smith, H., Currie, A., 2017. Accelerating the carbon cycle: The ethics of enhanced weathering. Biol. Lett. 13. https://doi.org/10.1098/rsbl.2016.0859

Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., De-Gol, A.J., Willis, D.R., Shan, Y., Canadell, J.G., Friedlingstein, P., Creutzig, F., Peters, G.P., 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Chang. 10, 647–653. https://doi.org/10.1038/s41558-020-0797-x

Li, Yongfu, Hu, S., Chen, J., Müller, K., Li, Yongchun, Fu, W., Lin, Z., Wang, H., 2018. Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. J. Soils Sediments 18, 546–563. https://doi.org/10.1007/s11368-017-1906-y

Liu, X., Mao, P., Li, L., Ma, J., 2019. Impact of biochar application on yield-scaled greenhouse gas intensity: A meta-analysis. Sci. Total Environ. 656, 969–976. https://doi.org/10.1016/j.scitotenv.2018.11.396

Locatelli, B., Catterall, C.P., Imbach, P., Kumar, C., Lasco, R., Marín-Spiotta, E., Mercer, B., Powers, J.S., Schwartz, N., Uriarte, M., 2015. Tropical reforestation and climate change: Beyond carbon. Restor. Ecol. 23, 337–343. https://doi.org/10.1111/rec.12209

Lomax, G., Lenton, T.M., Adeosun, A., Workman, M., 2015. Investing in negative emissions. Nat. Clim. Chang. 5, 498–500. https://doi.org/10.1038/nclimate2627

Lorenz, K., Lal, R., 2014. Biochar application to soil for climate change mitigation by soil organic carbon sequestration. J. Plant Nutr. Soil Sci. 177, 651–670. https://doi.org/10.1002/jpln.201400058

Mac Dowell, N., Fennell, P.S., Shah, N., Maitland, G.C., 2017. The role of CO2 capture and utilization in mitigating climate change. Nat. Clim. Chang. 7, 243.

Mader, S., 2019. Plant trees for the planet: the potential of forests for climate change mitigation and the major drivers of national forest area. Mitig. Adapt. Strateg. Glob. Chang. https://doi.org/10.1007/s11027-019-09875-4

Magnússon, R., Tietema, A., Cornelissen, J.H.C., Hefting, M.M., Kalbitz, K., 2016. Tamm Review: Sequestration of carbon from coarse woody debris in forest soils. For. Ecol. Manage. 377, 1–15. https://doi.org/10.1016/j.foreco.2016.06.033

Majumder, S., Neogi, S., Dutta, T., Powel, M.A., Banik, P., 2019. The impact of biochar on soil carbon sequestration: Meta-analytical approach to evaluating environmental and economic advantages. J. Environ. Manage. 250, 109466. https://doi.org/10.1016/j.jenvman.2019.109466

Matthies, B.D., Valsta, L.T., 2016. Optimal forest species mixture with carbon storage and albedo effect for climate change mitigation. Ecol. Econ. 123, 95–105. https://doi.org/10.1016/j.ecolecon.2016.01.004

McGlashan, N., Shah, N., Caldecott, B., Workman, M., 2012. High-level techno-economic assessment of negative emissions technologies. Process Saf. Environ. Prot. 90, 501–510. https://doi.org/10.1016/j.psep.2012.10.004

McLaren, D., 2020. Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. Clim. Change 162, 2411–2428. https://doi.org/10.1007/s10584-020-02732-3

McLaren, D., 2012. A comparative global assessment of potential negative emissions technologies. Process Saf. Environ. Prot. 90, 489–500. https://doi.org/10.1016/j.psep.2012.10.005

McLaren, D., 2011. Negatonnes - An Initial Assessment of The Potential for Negative Emission Techniques to Contributr Safely and Fairly to Meeting Carbon Budgets in the 21st Century., Friends of the Earth.

Meysman, F.J.R., Montserrat, F., 2017. Negative CO2 emissions via enhanced silicate weathering in coastal environments. Biol. Lett. 13. https://doi.org/10.1098/rsbl.2016.0905

Microsoft, 2021. Microsoft carbon removal - Lessons from an early.

Minx, J.C., Lamb, W.F., Callaghan, M.W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., De Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente Vicente, J.L., Wilcox, J., Del Mar Zamora Dominguez, M., 2018. Negative emissions - Part 1: Research landscape and synthesis. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aabf9b

Mulligan, J., Rudee, A., Lebling, K., Levin, K., Anderson, J., Christensen, B., 2020. CarbonShot: Federal Policy Options for Carbon Removal in the United States, World Resources Institute.

Mykleby, P.M., Snyder, P.K., Twine, T.E., 2017. Quantifying the trade-off between carbon sequestration and albedo in midlatitude and high-latitude North American forests. Geophys. Res. Lett. 44, 2493–2501. https://doi.org/10.1002/2016GL071459

Nair, V.D., Nair, P.K.R., Dari, B., Freitas, A.M., Chatterjee, N., Pinheiro, F.M., 2017. Biochar in the agroecosystem-climate-change-sustainability Nexus. Front. Plant Sci. 8. https://doi.org/10.3389/fpls.2017.02051

Naudts, K., Chen, Y., McGrath, M.J., Ryder, J., Valade, A., Otto, J., Luyssaert, S., 2016. Mitigate Climate Warming. Science (80-.). 351, 597–601. https://doi.org/10.1126/science.aac9976

Nemet, G.F., Callaghan, M.W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., Lamb, W.F., Minx, J.C., Rogers, S., Smith, P., 2018. Negative emissions - Part 3: Innovation and upscaling. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aabff4

Nunes, L.J.R., Meireles, C.I.R., Gomes, C.J.P., Ribeiro, N.M.C.A., 2020. Forest contribution to climate change mitigation: Management oriented to carbon capture and storage.

Climate 8. https://doi.org/10.3390/cli8020021

Oelkers, E.H., Declercq, J., Saldi, G.D., Gislason, S.R., Schott, J., 2018. Olivine dissolution rates: A critical review. Chem. Geol. 500, 1–19. https://doi.org/10.1016/j.chemgeo.2018.10.008

Olsson, A., Campana, P.E., Lind, M., Yan, J., 2014. Potential for carbon sequestration and mitigation of climate change by irrigation of grasslands. Appl. Energy 136, 1145–1154. https://doi.org/10.1016/j.apenergy.2014.08.025

Orbuch, R., 2020. Stripe's first carbon removal purchases [WWW Document]. Stripe.

Pires, J.C.M., 2019. Negative emissions technologies: A complementary solution for climate change mitigation. Sci. Total Environ. 672, 502–514. https://doi.org/10.1016/j.scitotenv.2019.04.004

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Chang. 4, 678–683. https://doi.org/10.1038/nclimate2292

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164–174. https://doi.org/10.1016/j.agee.2016.01.005

Psarras, P., Krutka, H., Fajardy, M., Zhang, Z., Liguori, S., Dowell, N. Mac, Wilcox, J., 2017. Slicing the pie: how big could carbon dioxide removal be? Wiley Interdiscip. Rev. Energy Environ. 6, 1–21. https://doi.org/10.1002/wene.253

Qambrani, N.A., Rahman, M.M., Won, S., Shim, S., Ra, C., 2017. Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review. Renew. Sustain. Energy Rev. 79, 255–273. https://doi.org/10.1016/j.rser.2017.05.057

Raihan, A., Begum, R.A., Mohd Said, M.N., Abdullah, S.M.S., 2019. A Review of Emission Reduction Potential and Cost Savings through Forest Carbon Sequestration. Asian J. Water, Environ. Pollut. 16, 1–7. https://doi.org/10.3233/AJW190027

Renforth, P., 2012. The potential of enhanced weathering in the UK. Int. J. Greenh. Gas Control 10, 229–243. https://doi.org/10.1016/j.ijggc.2012.06.011

Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., Hausfather, Z., Havlík, P., House, J., Nabuurs, G.J., Popp, A., Sánchez, M.J.S., Sanderman, J., Smith, P., Stehfest, E., Lawrence, D., 2019. Contribution of the land sector to a 1.5 °C world. Nat. Clim. Chang. 9, 817–828. https://doi.org/10.1038/s41558-019-0591-9

Sanz-Pérez, E.S., Murdock, C.R., Didas, S.A., Jones, C.W., 2016. Direct Capture of CO2 from Ambient Air. Chem. Rev. 116, 11840–11876. https://doi.org/10.1021/acs.chemrev.6b00173

Schuiling, R.D., 2017. Olivine Weathering against Climate Change. Nat. Sci. 09, 21–26. https://doi.org/10.4236/ns.2017.91002

Sedjo, R., Sohngen, B., 2012. Carbon Sequestration in Forests and Soils. Annu. Rev. Resour. Econ. 4, 127–144. https://doi.org/10.1146/annurev-resource-083110-115941

Senbayram, M., Saygan, E.P., Chen, R., Aydemir, S., Kaya, C., Wu, D., Bladogatskaya, E.,

2019. Effect of biochar origin and soil type on the greenhouse gas emission and the bacterial community structure in N fertilised acidic sandy and alkaline clay soil. Sci. Total Environ. 660, 69–79. https://doi.org/10.1016/j.scitotenv.2018.12.300

Shackley, S., Sohi, S., Ibarrola, R., Hammond, J., Masek, O., 2013. Biochar, tool for climate change mitigation and soil management, in: Geoengineering Responses to Climate Change. Springer, New York, pp. 73–140. https://doi.org/10.1007/978-1-4614-5770-1_6

Smith, P., 2016. Soil carbon sequestration and biochar as negative emission technologies. Glob. Chang. Biol. 22, 1315–1324. https://doi.org/10.1111/gcb.13178

Smith, P., Adams, J., Beerling, D.J., Beringer, T., Calvin, K. V., Fuss, S., Griscom, B., Hagemann, N., Kammann, C., Kraxner, F., Minx, J.C., Popp, A., Renforth, P., Vicente Vicente, J.L., Keesstra, S., 2019. Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals. Annu. Rev. Environ. Resour. 44, 255–286. https://doi.org/10.1146/annurev-environ-101718-033129

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., Van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2015. Biophysical and economic limits to negative CO2 emissions. Nat. Clim. Chang. 6, 42–50. https://doi.org/10.1038/nclimate2870

Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ. 133, 247–266. https://doi.org/10.1016/j.agee.2009.04.021

Sommer, R., Bossio, D., 2015. Response to the discussion letter of Lassaletta and Aguilera "soil carbon sequestration is a climate stabilization wedge: Comments on Sommer and Bossio (2014)." J. Environ. Manage. 153, 132–133. https://doi.org/10.1016/j.jenvman.2015.01.033

Sommer, R., Bossio, D., 2014. Dynamics and climate change mitigation potential of soil organic carbon sequestration. J. Environ. Manage. 144, 83–87. https://doi.org/10.1016/j.jenvman.2014.05.017

Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., Courcelles, V. de R. de, Singh, K., Wheeler, I., Abbott, L., Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D., Lal, R., Lehmann, J., O'Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164, 80–99. https://doi.org/10.1016/j.agee.2012.10.001

Strefler, J., Amann, T., Bauer, N., Kriegler, E., Hartmann, J., 2018. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aaa9c4

Stuckert, N.R., Yang, R.T., 2011. CO2 capture from the atmosphere and simultaneous concentration using zeolites and amine-grafted SBA-15. Environ. Sci. Technol. 45, 10257–10264. https://doi.org/10.1021/es202647a

Sykes, A.J., Macleod, M., Eory, V., Rees, R.M., Payen, F., Myrgiotis, V., Williams, M., Sohi, S., Hillier, J., Moran, D., Manning, D.A.C., Goglio, P., Seghetta, M., Williams, A., Harris, J., Dondini, M., Walton, J., House, J., Smith, P., 2019. Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. Glob. Chang. Biol. 26, 1085–1108. https://doi.org/10.1111/gcb.14844

Taylor, L.L., Quirk, J., Thorley, R.M.S., Kharecha, P.A., Hansen, J., Ridgwell, A., Lomas, M.R., Banwart, S.A., Beerling, D.J., 2016. Enhanced weathering strategies for stabilizing climate and averting ocean acidification. Nat. Clim. Chang. 6, 402–406. https://doi.org/10.1038/nclimate2882

TERC, 2020. Climate and Carbon Cycle [WWW Document].

The Royal Society, 2018. Greenhouse Gas Removal. PostNote 1–5.

Thoni, T., Beck, S., Borchers, M., Förster, J., Görl, K., Hahn, A., Mengis, N., Stevenson, A., Thrän, D., 2020. Deployment of NETs at the National Level: A Need for Holistic Feasibility Assessments. Front. Clim. 2, 12.

Tisserant, A., Cherubini, F., 2019. Potentials, limitations, co-benefits, and trade-offs of biochar applications to soils for climate change mitigation. Land 8. https://doi.org/10.3390/LAND8120179

UNFCCC, 2015. Adoption of the Paris Agreement.

Viebahn, P., Scholz, A., Zelt, O., 2019. German Energy Research Program — Results of a Multi-Dimensional Analysis. Energies.

Voskian, S., Hatton, T.A., 2019. Faradaic electro-swing reactive adsorption for CO2 capture. Energy Environ. Sci. 12, 3530–3547. https://doi.org/10.1039/c9ee02412c

Waller, L., Rayner, T., Chilvers, J., Gough, C.A., Lorenzoni, I., Jordan, A., Vaughan, N., 2020. Contested framings of greenhouse gas removal and its feasibility: Social and political dimensions. Wiley Interdiscip. Rev. Clim. Chang. 11, 1–17. https://doi.org/10.1002/wcc.649

Wang, H., Yi, H., Zhang, X., Su, W., Li, X., Zhang, Y., Gao, X., 2020. Biochar mitigates greenhouse gas emissions from an acidic tea soil. Polish J. Environ. Stud. 29, 323–330. https://doi.org/10.15244/pjoes/99837

Wang, Y., Yan, X., Wang, Z., 2014. The biogeophysical effects of extreme afforestation in modeling future climate. Theor. Appl. Climatol. 118, 511–521. https://doi.org/10.1007/s00704-013-1085-8

Whitehead, D., 2011. Forests as carbon sinks - Benefits and consequences. Tree Physiol. 31, 893–902. https://doi.org/10.1093/treephys/tpr063

Whitmore, A.P., Kirk, G.J.D., Rawlins, B.G., 2015. Technologies for increasing carbon storage in soil to mitigate climate change. Soil Use Manag. 31, 62–71. https://doi.org/10.1111/sum.12115

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., Joseph, S., 2010. Sustainable biochar to mitigate global climate change. Nat. Commun. 1. https://doi.org/10.1038/ncomms1053

Wurzbacher, J.A., Gebald, C., Steinfeld, A., 2011. Separation of CO 2 from air by temperature-vacuum swing adsorption using diamine-functionalized silica gel. Energy Environ. Sci. 4, 3584–3592. https://doi.org/10.1039/c1ee01681d

Yadav, M.R., Yadav, R.., Parihar, C.M., Kumar, R., Bajiya, R., Yadav, N., Meena, R.K., H. Ram, H., Yadav, B., Yadav, D.K., 2017. Role of Biochar in Mitigation of Climate Change through Carbon Sequestration. Int. J. Curr. Microbiol. Appl. Sci. 6, 859–866. https://doi.org/10.20546/ijcmas.2017.604.107

Zhang, C., Zeng, G., Huang, D., Lai, C., Chen, M., Cheng, M., Tang, W., Tang, L., Dong, H., Huang, B., Tan, X., Wang, R., 2019. Biochar for environmental management: Mitigating greenhouse gas emissions, contaminant treatment, and potential negative impacts. Chem. Eng. J. 373, 902–922. https://doi.org/10.1016/j.cej.2019.05.139

Zimmerman, A.R., Gao, B., Ahn, M.Y., 2011. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. Soil Biol. Biochem. 43, 1169–1179. https://doi.org/10.1016/j.soilbio.2011.02.005

Zimmermann, M., Bird, M.I., Wurster, C., Saiz, G., Goodrick, I., Barta, J., Capek, P., Santruckova, H., Smernik, R., 2012. Rapid degradation of pyrogenic carbon. Glob. Chang. Biol. 18, 3306–3316. https://doi.org/10.1111/j.1365-2486.2012.02796.x

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