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Impacts of Land-Based Greenhouse Gas Removal Options on Ecosystem Services and the United Nations Sustainable Development Goals

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Keywords

Greenhouse gas removal (GGR), carbon dioxide removal (CDR), negative emission technology (NET), afforestation/reforestation (AR), wetland restoration, soil carbon sequestration (SCS), biochar, terrestrial enhanced weathering, bioenergy with carbon capture and storage (BECCS), ecosystem services, Nature's Contributions to People (NCPs), UN Sustainable Development Goals (SDG)

Abstract

Land-based greenhouse gas removal (GGR) options include afforestation or reforestation (AR), wetland restoration, soil carbon sequestration (SCS), biochar, terrestrial enhanced weathering (TEW), and bioenergy with carbon capture and storage (BECCS). We assess the opportunities and risks associated with these options through the lens of their potential impacts on ecosystems services (Nature's Contributions to People; NCPs) and the United Nations Sustainable Development Goals (SDGs). We find that all land-based GGR options contribute positively to at least some NCPs and SDGs. Wetland restoration and SCS almost exclusively deliver positive impacts. A few GGR options, such as afforestation, BECCS, and biochar potentially impact negatively some NCPs and SDGs, particularly when implemented at scale, largely through competition for land. For those that present risks or are least understood, more research is required, and demonstration projects need to proceed with caution. For options that present low risks and provide cobenefits, implementation can proceed more rapidly following no-regrets principles.

Contents

1. INTRODUCTION

Perhaps the most remarkable outcome of the Paris Climate Agreement was a renewed focus on the aim of limiting global average temperature increase to "well below 2°C above preindustrial levels," and "pursuing efforts" to limit it to 1.5°C. This has stimulated a new focus on understanding the challenges of achieving this target (1). Immediate and aggressive mitigation action in all sectors is clearly necessary to meet even the 2°C target, and this probably also requires some atmospheric greenhouse gas removal (GGR; GGR options are also known as negative emission technologies or carbon dioxide removal technologies) during this century. For the 1.5°C target, additional atmospheric GGR is even more likely to be required, and in greater quantity, to supplement immediate and aggressive mitigation (1).

In this article, we review the main opportunities and risks associated with pursuing the Paris Climate targets through land-based GGR options, such as afforestation or reforestation (AR), wetland restoration, soil carbon sequestration (SCS), biochar, terrestrial enhanced mineral weathering, and bioenergy with carbon capture and storage (BECCS), which work by removing greenhouse gases (GHGs) from the atmosphere. We explore this through the lens of the functions provided by each land-based GGR option, their impact on ecosystems services [classified according to the new Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) classification known as Nature's Contributions to People (NCPs) (2); Diaz et al. (3) provide a description of how NCPs map onto the ecosystems services defined by the Millennium Ecosystem Assessment (4)], and their impact on the United Nations (UN) Sustainable Development Goals (SDGs) (5).

The global implications of widespread implementation of GGR options on land competition, GHG emissions, physical climate feedbacks (e.g., albedo), water requirements, nutrient use, energy, and cost have recently been assessed (6). No GGR option is a magic bullet solution (7, 8). Impacts on NCPs, and other constraints, vary greatly between GGR options, with the main impacts being on competition for land, water, biodiversity, and nutrients as well as some physical climate impacts [such as albedo (6)]. As such, different land-based GGR options will influence SDGs to different extents and in different directions.

We assess the impacts of land-based GGR options on NCPs and the SDGs. Sections 2–7 discuss in turn each land-based GGR option, and Section 8 discusses the main findings and concludes with next steps.

GGR: greenhouse gas removal

AR: afforestation or reforestation

SCS: soil carbon sequestration

BECCS: bioenergy with carbon capture and storage

2. AR

The planting of additional trees will sequester CO_2. In particular, GGR can be achieved through the planting of trees on land that has not been forested recently (afforestation) or the restocking of recently depleted land with (restoration) or without (reforestation) an emphasis on restoring ecological processes (8). UN statistics (9) state that during 1990 to 2015 the total global forest area decreased from 4.28 to 3.99 billion hectares, and the area of planted forests increased from 167.5 to 277.9 million hectares. Below we describe how AR can impact functions delivered by AR, NCPs, and the SDGs, with the interactions summarized in **Figure 1**.

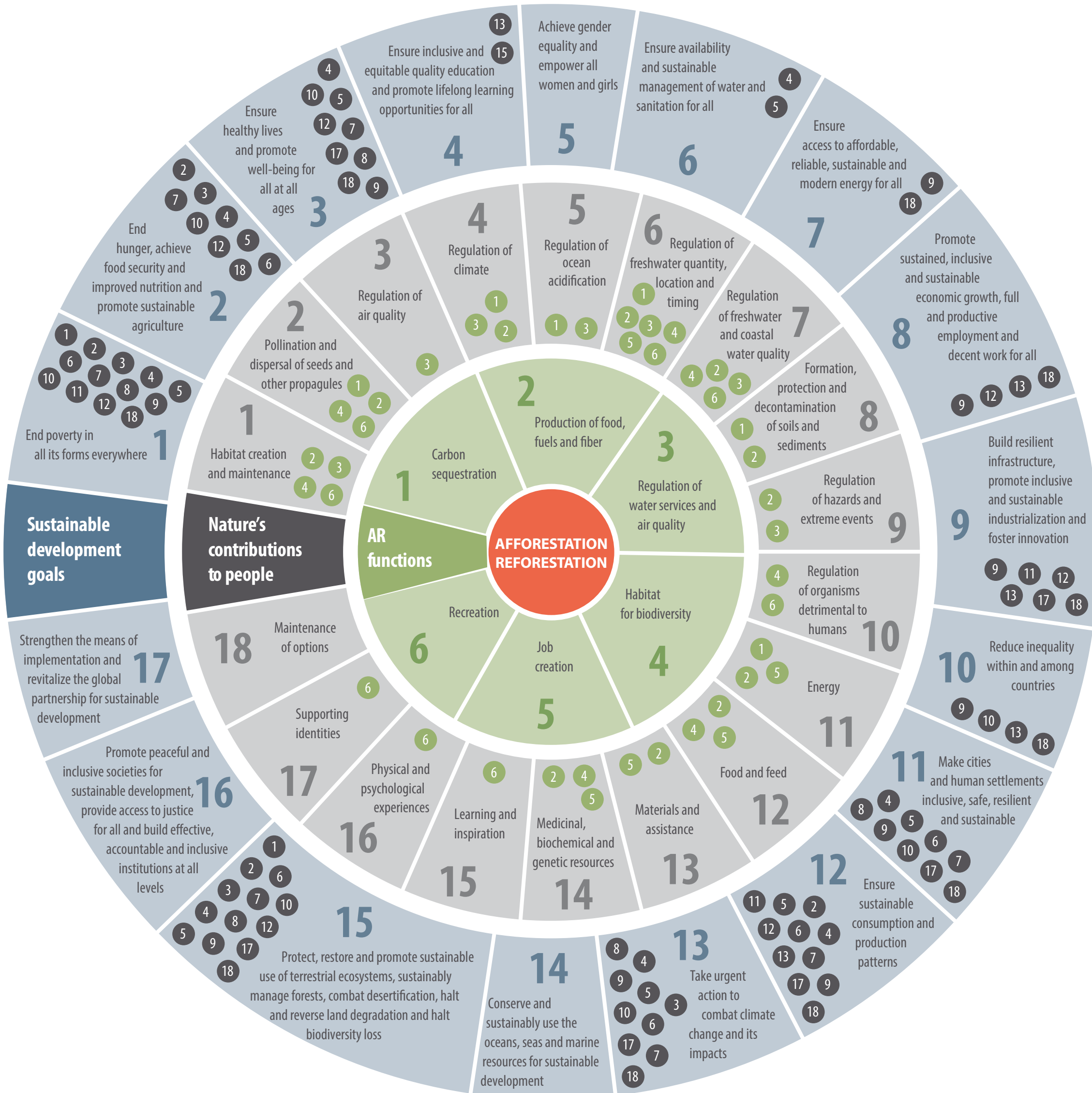

Figure 1

Summary of the impact of afforestation or reforestation on ecosystem functions, on Nature's Contributions to People (NCPs), and on the United Nations Sustainable Development Goals (SDGs), showing the impact of each function on each NCP, and the contribution of the NCPs to each of the SDGs.

2.1. Functions Delivered by AR

Depending on the management of AR areas after establishment, they deliver a series of functions: carbon sequestration, production of food, fuels, and fiber, regulation of water services and air quality, and habitat for biodiversity, complemented by more societal services such as jobs and recreation (see also Section 1.2). Sustainable and adaptive forest management and its certification ensure the parallel provision of multiple services and functions (e.g., carbon sequestration and fuelwood) and act as environmental safeguards for, e.g., biodiversity (10); a narrow focus on one goal can lead to trade-offs between NCPs and SDGs (e.g., in the case of large-scale monocultures).

2.2. NCPs Impacted by AR

Similarly to already existing ones, forests established through AR contribute to the largest terrestrial biome and carbon stock. Hence, many ecosystems services and almost all NCPs are impacted by AR directly or indirectly—mostly in a positive way, although large-scale AR could create competition for land for food production or for biodiversity conservation (6, 9).

2.2.1. Regulating NCPs. Most of the secondary forests (AR) provide temporary and permanent habitats, including those for nesting, feeding, and mating opportunities for a large variety of fauna and flora species. In many cases, AR activities have a positive effect on biodiversity and habitat for wildlife. Through forest landscape restoration, these NCPs are given more emphasis, allowing for human livelihoods as well as ecological integrity and ecosystems services across a landscape (11).

AR can positively impact air quality, e.g., through the filtering capacity of forests. However, large-scale forest fires could have the opposite effect by creating massive haze problems, i.e., in tropical countries such as Indonesia and Malaysia.

The arguably largest impact on an NCP is that of AR on climate regulation. The net global forest carbon sink is estimated at 4.0 +/− 2.9 $GtCO_2$ year^{-1} (12). Although the tropics show the largest CO_2 fluxes and the boreal forest has over decades been the most stable sink, the carbon sink of the temperate forest increased substantially due to large-scale AR in mostly China. The full literature range of AR potentials for carbon removals is 0.5–7 $GtCO_2$ year^{-1} in 2050, but with additional sustainability constraints the upper limit is 3.6 $GtCO_2$ year^{-1} (8). Figures available from varying scenarios for 2100 are estimated at up to 12.1 $GtCO_2$eq year^{-1} (13), requiring a substantial land area of up to 970 Mha (14). In 2018, the Intergovernmental Panel on Climate Change's (IPCC's) *Special Report on Global Warming of 1.5°C* (1) indicated 20 Mha GtCeq^{-1} for the required land by AR. An additional 1.5 $GtCO_2$eq year^{-1} could be delivered from a range of improved forestry practices (15). Existing AR areas are already removing an estimated 0.77–1.54 $GtCO_2$ year^{-1} (16).

An important caveat is that any sequestration by forest is reversible from climate changes and/or direct human actions, with the highest risks being natural disturbances (i.e., fire), climate variability, permafrost thawing, and land use change. Furthermore, large-scale afforestation in Northern latitudes might change albedo, thereby offsetting any climate benefits in terms of GGR (12), although the reverse is true in the tropics.

AR can positively affect local temperature through its cooling effect and precipitation. The largest potential for AR measures is located in the semiarid regions (17). Particularly large-area AR (>200 million ha) enhances precipitation. Furthermore, forests and forest soils have a substantial water retention and filtering capacity, which can positively impact freshwater quality and quantity. However, further to potential water supply, AR also has a significant water demand. Smith et al. (6) estimate the total water use for forests from AR to be approximately 1,765 m^3 t^{-1} Ceq year^{-1} (up to 1,040 km^3 year^{-1} for removing 12.1 $GtCO_2$ year^{-1}).

With constant growth and decomposition of biomass—under certain sustainability constraints and thus accepting lower-scale deployment than seen in many 1.5°C and 2°C scenarios—AR positively affects the formation of soils, soil quality, nutrients, and soil organic carbon (SOC). Also, AR positively impacts the Regulation of Hazards and Extreme Events by providing physical protection and flood- and erosion control. However, AR activities can also bring massive alteration with respect to nutrient cycles, can reduce soil carbon storage, and can change hydrology—especially when applied on grassy biomes. Trees require more water and soil nutrients compared with grasses and forbs (18, 19).

Finally, AR can have a positive impact on the Regulation of Organisms Detrimental to Humans, such as large predators, by providing large enough living space and habitats.

2.2.2. Material NCPs. Biomass is one of the most common energy sources, and a substantial portion of the global population depends on it. Any AR activity positively impacts this material NCP through additional biomass production. Sustainable forest management allows for a substantial contribution of AR to carbon sequestration and biomass production; however, most of the world's production forests are not managed sustainably, especially in the Global South (10), where the largest potentials lie (20).

In addition, AR provide both Food and Feed to large parts of the global population from nonwood forest products, including forest fruits, mushrooms, game meet, and medicinal plants.

Also on biomass, AR provides a positive impact because AR areas are contributing directly to continuous and increased production. Management options need to bridge conservation management and sustainable forest management, e.g., for biomass production. To ensure highest levels of environmental safeguards, sustainable and adaptive forest management including forest management certification is recommended (10).

2.2.3. Nonmaterial NCPs. Additionally, nonmaterial NCPs such as Learning and Inspiration are impacted positively, given AR provide inter alia landscapes and inspire humans for art, design, and science. Furthermore, AR provide Physical and Psychological Experiences through scenic beauty in landscapes for recreation, relaxation, forest healing, etc. Forests from AR can also become home to spiritual and cultural locations/landscapes, myths, and Maintenance of Options, etc., which is enhanced by long lifetimes.

2.3. SDGs Impacted by AR

Of the 17 SDGs, few [SDGs 5, Gender Equality; 14, Life Below Water; 16, Peace, Justice and Strong Institutions; and 17, Partnerships for the Goals] are not directly impacted by AR. In the case of six [SDGs 1, No Poverty; 3, Good Health and Well-being; 11, Sustainable Cities and Communities; 12, Responsible Consumption and Production; 13, Climate Action; and 15, Life on Land], there is particularly strong overlap with respect to AR impacts on the corresponding NCPs (see Section 1.2). **Figure 1** presents a full picture of the series of direct and indirect effects, as well as the impacts between AR functions, NCPs, and SDGs. Below, we provide the evidence for a few prominent examples of the potential impacts of AR on the SDGs.

2.3.1. SDGs 1 and 3: No Poverty and Good Health and Well-being. There is relatively little literature that explicitly examines the impact of AR on SDGs 1 and 2 across the globe, but there are indications that AR programs can contribute to local livelihoods and decreasing poverty (e.g., 21, 22).

2.3.2. SDG 2: Zero Hunger. For AR to withdraw CO_2 from the atmosphere to the extent that we see in ambitious climate stabilization pathways (7), large areas of land have to be set aside (6). This can create competition for land with food production and lead to higher food prices (23, 24). However, AR practices involving, e.g., agroforestry, also affect local food supply positively (22). The impact is thus dependent on the mode of implementation and local context.

2.3.3. SDG 8: Decent Work and Economic Growth. AR programs could create new income opportunities for rural land owners (21). Taking into account the suitability of the tropical basins for reforestation to remove CO_2 (8), this could also imply financial transfers from North to South under global carbon pricing.

2.3.4. SDG 9: Industry, Innovation and Infrastructure. Depending on the mode of implementation, AR could lead to enhanced forest infrastructure. This could provide a positive impact on forest industries.

3. WETLAND RESTORATION

The restoration of wetlands, including both freshwater wetlands (peatlands including swamps, bogs, fens, riparian, and lake wetlands) and coastal wetlands (salt marshes, mangroves, and seagrass), deliver high density and globally significant hydrological services, climate benefits, and other NCPs, disproportionate to their limited global extent. Wetland functions can be restored by re-establishing wetland hydrology and/or reinitiating native vegetation. Here we describe wetland functions, as linked with a range of NCPs and SDGs, as summarized in **Figure 2**.

3.1. Functions Delivered by Peatland/Wetland Restoration

Wetlands cover less than 9% of the global landscape (25), but wetlands are estimated to deliver 23% of global ecosystems service values (26). Wetlands have the potential to deliver 2.7 $GtCO_{2e}$ $year^{-1}$ of additional climate mitigation (and associated avoided ocean acidification), more than half of which is offered by wetland restoration (1.7 $GtCO_{2e}$ $year^{-1}$), with restoration opportunities distributed across all climate domains. This wetland restoration potential is made up in equal parts by opportunities in coastal (0.84 $GtCO_{2e}$ $year^{-1}$) and freshwater wetlands (0.82 $GtCO_{2e}$ $year^{-1}$). Although the accounting for this climate mitigation potential is complicated by methane emissions that can result from the restoration of wetland hydrology, this is more than offset by the avoided CO_2 emissions by halting the oxidation of peat and muck. The above numbers represent the net climate benefits and include additional biomass sequestration due to restoration of forested wetlands (15). Avoided oxidation of wetland soil carbon is urgent because it cannot be reversed within the decadal timescales during which action is called for by the Paris Climate Agreement.

The largest economic value of wetlands is associated with their regulation of water (25). Freshwater and coastal wetlands also remove sediments and pollutants from water and air (27). In coastal systems, this is of major importance to the survival of nearby coral reefs (28). Freshwater wetlands are so effective at water filtration that they are constructed for wastewater treatment (29).

Water treatment and biodiversity habitat may not be fully compatible uses for wetlands because increased nutrient loading of wetlands is associated with reduction in plant diversity due to dominance by more aggressive plant species (30). Coastal wetlands, in particular, are critical for commercially important fish and shrimp, and a wide diversity of marine organisms, particularly for juvenile lifecycle stages (31). Freshwater and coastal wetlands provide the additional high valuable hydrologic service of flood abatement (26), as described in Section 3.2.

For the reasons above, and because they are disproportionately exposed to human impacts, wetlands are a priority for conservation and restoration. Approximately half of global wetlands have been lost, and ongoing oxidation of damaged wetlands emits more than 1 $GtCO_2e$ $year^{-1}$ (15). Wetlands are exposed to elevated rates of loss and degradation due to conversion for agriculture

Figure 2

Summary of the impact of wetland restoration on ecosystem functions, on Nature's Contributions to People (NCPs), and on the United Nation's Sustainable Development Goals (SDGs), showing the impact of each function on each NCP, and the contribution of the NCPs to each of the SDGs.

and aquaculture, disconnection from floodplains and other hydrologic alterations, eutrophication, invasive species, as well as multiple emerging threats from climate change such as floods, drought, and sea level rise (25, 32). However, wetlands are resilient and dynamic ecosystems. For example, some mangroves may be able to accrete on their own accumulated peat to keep pace with sea level rise (33).

3.2. NCPs Impacted by Wetland Restoration and Their Contribution to SDGs

Most NCPs are directly impacted by wetland restoration, as linked to the functions described above. The extent to which wetland restoration provides Regulation of Climate is described above, in particular by avoiding peat oxidation. The hydrologic functions of wetlands detailed above deliver Regulation of Freshwater and Coastal Water Quality as well as Formation, Protection and Decontamination of Soils and Sediments. Natural freshwater wetlands remove pollutants from agricultural and urban runoff to the extent that, for example, Hey et al. (34) proposed massive wetland restoration to reverse both eutrophication and degraded freshwater quality in the Mississippi watershed, and hypoxia in the Gulf of Mexico. Wetlands constructed for wastewater treatment also specifically help to regulate detrimental organisms and biological processes. Restoration of wetland biodiversity is more complex and gradual than restoration for hydrologic services and carbon storage. Also, there are trade-offs between uses of restored wetlands, as increased nutrient loading of wetlands is associated with reduction in plant diversity (25).

The hydrologic functions of wetlands also deliver Regulation of Hazards and Extreme Events. Both coastal and inland wetlands function as a sponge to absorb and slow the flow of water, flattening the hydrograph and thereby reducing maximum peak flood levels. Most critical to this function are wetlands located within riparian zones and floodplains upstream of settlements, as well as coastal wetlands located between storm surges and human settlements. Rewetting peats also provides Regulation of Air Quality by halting and avoiding peat fires. For example, 500,000 people were hospitalized in 2015 in Indonesia due to fires on drained peatlands, which cost the country $16 billion (35). Furthermore, forested wetlands filter particulate matter and pollutant gasses from the air (36).

The second largest economic value of wetlands identified by Costanza et al. (26) involves NCP Habitat Creation and Maintenance, which is linked to the material NCP Food and Feed, particularly for coastal wetlands, as discussed above. Freshwater wetlands have been converted for crops requiring anoxic conditions (e.g., rice, cranberries). With ditching and draining, wetlands are converted to support a wider variety of upland food, feed, and energy crops. Native wetland restoration in places currently providing high food, feed, and energy crop yields may invoke trade-offs between intensive delivery of NCP Food and Feed and NCP Energy, versus delivering a wide array of other NCPs and functions discussed above. Restoration of some wetland sites may not be justified, given food security concerns. Opportunities can be explored to intensify upland agriculture to make up for displaced wetland crop yields, justified by higher NCP values per hectare of wetlands compared to most upland sites (24). Approximately half of global peatlands, about one-third of mangroves, and more than half of salt marshes can be cost-effectively restored for climate mitigation alone (15).

Wetlands provide a range of nonmaterial NCPs (Learning and Inspiration, Physical and Psychological Experiences, and Supporting Identities) both directly, as demonstrated by the leading role of cultural values in recent wetland conservation efforts (37), and indirectly by supporting the integrity of other ecosystems through functions discussed above. Likewise, wetlands deliver the overarching Maintenance of Options through on-site biodiversity value of wetlands, and by supporting the ecological integrity of other downstream and marine ecosystems.

3.3. SDGs Impacted by Wetland Restoration

Here we describe the potential impacts of wetland restoration on more than half of the SDGs, as related to the functions supported by wetlands, and the NCPs impacted by wetlands; however, due to space limitations we have not include text on all the relationships indicated in **Figure 2**. Although many other societal issues must be addressed to achieve the goals of Zero Hunger and

No Poverty, wetland restoration has a notable role to play, given wetlands, especially mangroves, are critical to fisheries productivity. The primary anthropogenic driver of mangrove loss is expansion of agriculture and aquaculture (38), thus presenting food yield trade-offs between on-site food production versus distributed fisheries productivity. On the basis of functions and the NCPs reviewed above, wetlands help to deliver Clean Water and Sanitation as well as Good Health and Well-being, as linked with water and air quality, flood abatement, and not least avoiding impacts of extreme weather events associated with climate change. These outcomes are also linked with achieving Sustainable Cities and Communities.

Wetland construction for treatment of wastewater, and various other wetland restoration approaches, to deliver the wide range of high-value NCPs discussed above, could provide significant employment in developing and developed countries in support of Decent Work and Economic Growth. Some wetland restoration, in particular mangroves, improve the yield and sustainability of native fisheries and associated coral reefs, which in turn support the livelihood of coastal communities. Wetland restoration delivers these SDGs while simultaneously delivering SDGS Climate Action, Life Below Water, and Life on Land, as linked with the range of functions discussed above.

4. SCS

SCS can be achieved across a range of different land uses, including cropland, grazing land, and forestry—and can be promoted by a range of practices (39). Practices that increase soil organic matter content include (*a*) land use change to an ecosystem with higher-equilibrium soil carbon levels; (*b*) management of vegetation, including high-input carbon practices, e.g., improved rotations, cover crops, and perennial cropping systems; (*c*) nutrient management to increase plant carbon returns to the soil, e.g., through optimized fertilizer application rate, type, timing, and precision application; (*d*) reduced tillage intensity and residue retention; and (*e*) improved water management, including irrigation in arid conditions (40). Below we describe how SCS can impact soil functions, NCPs, and the SDGs, with the interactions summarized in **Figure 3**.

4.1. Functions Delivered by SCS

Soil organic matter stock is a headline indicator of soils health (41) and soil quality (42); as such, SCS will improve many functions provided by soils (43). There are seven functions provided by soils (44), of which most are positively impacted by SCS (45). Biomass production, including agriculture and forestry, can be enhanced by SCS (46). Storing, filtering and transforming nutrients, substances, and water benefit from SCS by enhancing soil health and reducing erosion (47). Biodiversity pool, such as habitats, species, and genes, is improved by SCS through enhanced habitats for soil biota. Physical and cultural environment for humans and human activities is positively affected by SCS, as a healthy soil is important in defining a landscape that can be sustainably used for human activities. Soils are a source of raw materials for products such as pharmaceuticals, clay for bricks and ceramics, silicon from sand used in electronics, and other minerals (48); the biological materials are promoted by SCS through improved soil health. Acting as a carbon pool is greatly impacted by SCS as it increases soil organic carbon stocks (40). Acting as an archive of geological and archaeological heritage is protected by SCS, given it helps prevent erosion (41, 45).

4.2. NCPs Impacted by SCS

Soils underpin many NCPs (49, 50). A few of the 18 NCPs are not directly impacted by SCS, namely, the regulating NCPs Pollination and Dispersal of Seeds and Other Propagules and

Figure 3

Summary of the impact of soil carbon sequestration (SCS) on soil functions, on Nature's Contributions to People (NCPs), and on the United Nation's Sustainable Development Goals (SDGs), showing the impact of each function on each NCP, and the contribution of the NCPs to each of the SDG.

Regulation of Ocean Acidification. The overarching NCP, Maintenance of Options, is not affected by SCS. Although nonmaterial NCPs Learning and Inspiration, Physical and Psychological Experiences, and Supporting Identities are not directly affected by SCS, many of the landscapes that do provide these NCPs are shaped by their underlying soils (e.g., peatlands, deserts, forests); as such, managing land to increase SCS could have indirect impacts on these nonmaterial NCPs. Below we describe the NCPs directly impacted by SCS.

4.2.1. Regulating NCPs. The regulating NCPs Habitat Creation and Maintenance and Regulation of Organisms Detrimental to Humans are supported by SCS through Habitat Creation and Maintenance by soil life (51). Several soil functions are enhanced by SCS by conferring improved soil health (41). SCS can help suppress soilborne crop diseases (52). Sediment particles with an organic coating have been found to have more pathogens attached to them (53), potentially preventing pathogens being moved by infiltration (54) and runoff (55), although knowledge is limited (56). For NCPs Regulation of Freshwater Quantity, Location and Timing and Regulation of Hazards and Extreme Events, SCS (particularly in peatlands) helps to regulate the timing and magnitude of peak water flow, particularly after heavy precipitation (57). SCS also renders soils less prone to water and wind erosion by improving soil structure (45), and some practices implemented to increase SCS, such as increasing ground cover, can reduce the vulnerability of soils to degradation and landslides (58). NCPs Regulation of Freshwater and Coastal Water Quality and Formation, Protection and Decontamination of Soils and Sediments are also supported by the filtering and storing function of soils. SCS enhances soil health (41), reduces soil erosion (43), and buffers various pollutants, which in turn protects freshwater and coastal waters. Implementing SCS will not decontaminate soils and sediments; however, soil carbon is a vital component of soils, thus SCS is a critical component of soil formation (50), and it also protects soils from global change pressures (59).

4.2.2. Material NCPs. NCPs Energy, Food and Feed, and Materials and Assistance are all positively affected by SCS, which improves productivity of food- (45, 60), energy-, and fiber crops, and can improve yield stability across years (61). Because SCS can also help to prevent degradation and desertification (62), it also supports the productivity of Food and Feed in vulnerable agroecosystems. Given soil organic matter content is a headline indicator of soil health (41), SCS would be expected to enhance the NCP Medicinal, Biochemical and Genetic Resources, by maintaining the resource for medicines isolated from soil organisms [e.g., penicillin, statins, and cyclosporins (51)].

4.2.3. Overarching NCPs. SCS could potentially increase ammonia emissions (63), but air quality is also impacted by dust, which would decline under reduced wind erosion (64). For NCP Regulation of Climate, SCS could provide very significant GGR, in the range of 2–5 $GtCO_2$ $year^{-1}$ (8, 40, 65). As long as soil organic carbon sinks are not increased by methods that increase emissions of other GHGs (66), SCS should have a positive impact, while also improving resilience to climate change (41, 59).

4.3. SDGs Impacted by SCS

Of the 17 SDGs, few (SDGs 4, Quality Education; 5, Gender Equality; 10, Reduced Inequality; 16, Peace, Justice and Strong Institutions; and 17, Partnerships for the Goals) are not directly impacted by SCS. Below, we describe the potential impacts of SCS on remaining SDGs.

SDGs No Poverty and Zero Hunger cannot be solved solely by improving soils, but healthy soil can produce more food and goods, thereby contributing positively to food security and incomes for the world's poorest people. SCS can further help to deliver Clean Water and Sanitation, by helping to reduce soil erosion (41, 45). Healthy soils would also be expected to provide a more effective buffer for various pollutants. Through the combination of improved agricultural productivity, improved water and air quality, and the potential of soil (organisms) to provide medicines, SCS can contribute positively to SDG 3, Good Health and Well-being. This may also help to achieve Decent Work and Economic Growth and Industry, Innovation and Infrastructure, which in turn might contribute to developing Sustainable Cities and Communities, and give people access to Affordable and Clean Energy (through energy crops). Climate Action is supported by SCS by creating a large (but potentially reversible) sink for atmospheric CO_2 and improved resilience to climate change (e.g., 41, 45). For Life Below Water, SCS can help to prevent erosion and polluted substances from reaching water bodies. For Life on Land, SCS can help to improve soil health, thereby enhancing potential for biodiversity and healthy ecosystems. **Figure 3** summarizes the impact of SCS on soil functions, on NCPs, and on the SDGs described in this section, and it shows how the contribution to the SDGs is related to each soil function and NCP.

5. BIOCHAR

Biochar is the solid product of biomass pyrolysis, the thermochemical conversion of organic materials under low- to no-oxygen conditions. Pyrolysis products comprise a solid (biochar), a liquid (bio-oil), and a gaseous phase (permanent pyrogas) in varying fractions. Theoretically, all products can be used for pyrolysis carbon capture and storage PyCCS (67), which has a GGR potential comparable to BECCS (68), with estimates between 0–5 $GtCO_2$ $year^{-1}$ for BECCS and 0–2 $GtCO_2$ $year^{-1}$ for biochar in 2050 (8).

Pyrolysis techniques are highly diverse and range from large-scale industrial to small-scale (67), low-tech methods applicable even without electricity in rural communities (69). The resulting biochar-C [pyrogenic C (PyC)] is more recalcitrant against decomposition than other biogenic materials [mean residence time 556 years (70)]. The idea to use PyC in soils originated in research on anthropogenic black earth soils such as "*Terra preta do Indio*" in the Amazon basin, man-made fertile soils rich in PyC, which were formed by a combination of organic residues and charcoal (71). Similar soils also occur in Australia and Europe and are still actively formed today from charcoal and organic residues in South Africa (72). The potential from biochar will likely be largest when PyCCS is combined with other natural climate solutions (15), given biochar can increase SOC stocks significantly (73), so it will likely aid in also sequestering more non-PyC SOC ("return on investment") (74). Below we describe how biochar can impact soil functions, NCPs, and the SDGs, with the interactions summarized in **Figure 4**.

5.1. Functions Delivered by Biochar

Recycling agricultural and forestry biomass wastes as feedstock for biochar production avoids competition for land due to yield increases in the (sub)tropics when using biochar in agricultural soils (75), and because residue eliminates the need to set aside land for biochar production, thus contributing to the self-sufficiency of communities. Residues can come from forests, mills, crop residue, or urban wastes.

For reducing emissions of traditional residue burning, subsistence farming uses burning for recycling ash nutrients and hygienizing residues for pest and pathogen control or for cooking. Using the low-emission technique of flame-curtain (Kon-Tiki) pyrolysis instead can considerably reduce emissions of CO, NO_x, and soot (69) while still recycling nutrients and killing pests and pathogens. Also, using cooking stoves improves women's health by reducing indoor air pollution and the risk of injuries.

For energy cogeneration, the use of the permanent pyrogases for heat generation by combustion is useful for many locations where a demand for heat exists and where fossil energy sources can be replaced, e.g., for drying materials, animal stables, greenhouse- or house heating. Additionally, biochar inherently retards the return of biomass C to the atmosphere as CO_2 due to its recalcitrance when added to soil (40, 76), thereby acting as a GGR technology and high-recalcitrance carbon pool.

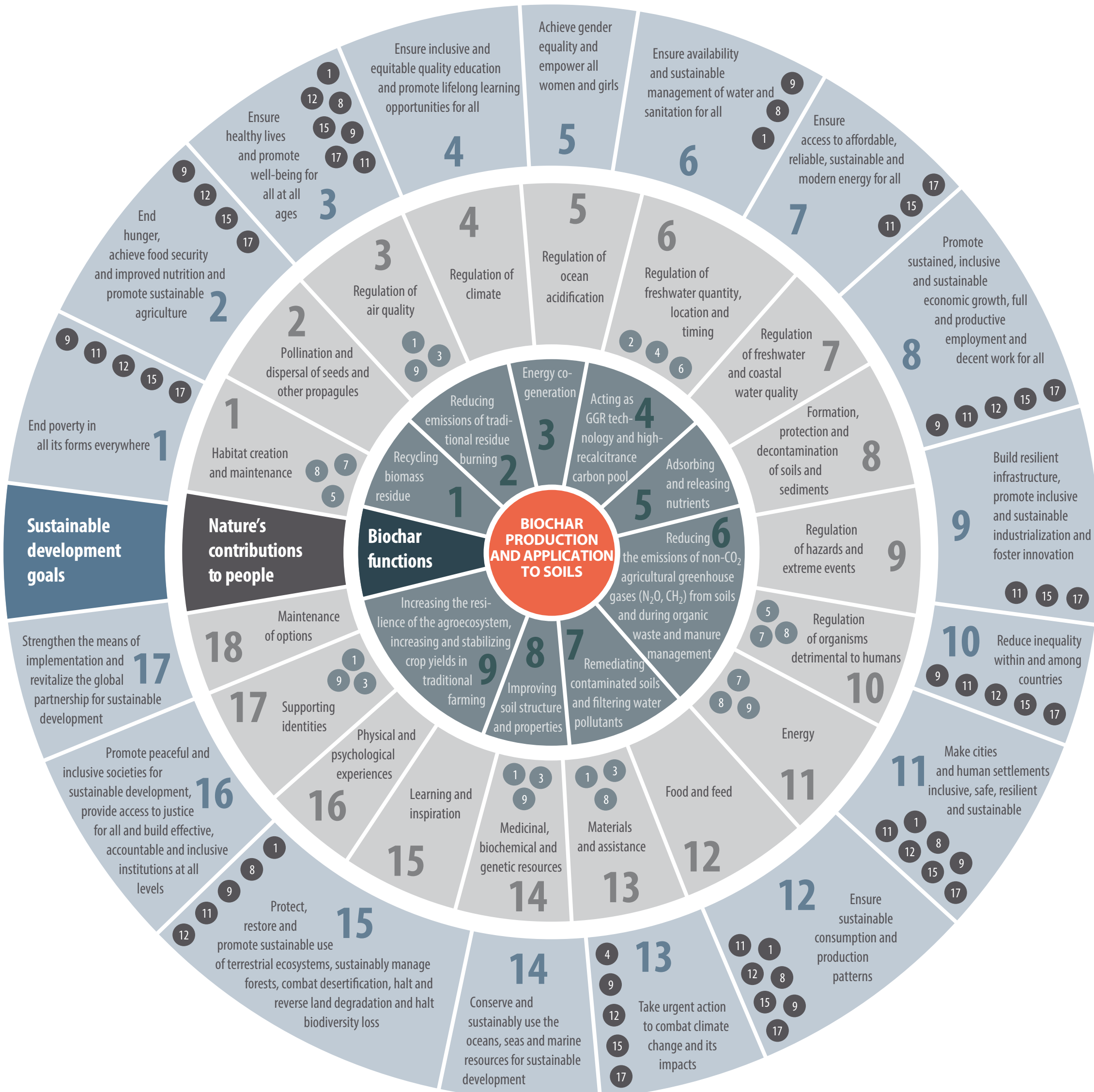

Figure 4

Summary of the impact of biochar on ecosystem functions, on Nature's Contributions to People (NCPs), and on the United Nation's Sustainable Development Goals (SDGs), showing the impact of each function on each NCP, and the contribution of the NCPs to each of the SDG.

For adsorbing and releasing nutrients, biochar can increase the pH and the cation exchange capacity in poor, acidic soils, thereby improving soil fertility and productivity (77). Biochar can take up and release nitrate in non-water-saturated environments, particularly when organically coated (78). The captured nitrate is largely available to plants and can improve growth (79).

In terms of non-CO_2 greenhouse gases and emissions of other gases, biochar additions of $>1\%$ significantly reduce N_2O emissions from soils (80). Biochar can reduce NH_3 volatilization and increase N retention in composting (81) or in N-rich waste stream management, including animal husbandry (82). The high reactivity and specific surface area of biochar can absorb both nutrients and pollutants (83), and thus contribute to soil remediation and water purification (84).

Biochar application can decrease soil compaction, increase soil porosity, reduce bulk density, and increase soil water content (85). Moreover, soil microbial biomass (73, 86), root growth and root biomass, and legume nodule formation increase with biochar addition (74), as does symbiotic N_2 fixation (87).

The improvement in soil fertility after the application of biochar to soils may increase crop yields and enhance agroecosystem resilience (88, 89). This would increase food security and ultimately maintain traditional farming and rural livelihoods due to reduced external inputs (e.g., agrochemicals) (90).

5.2. NCPs Impacted by Biochar

Biochar addition to soils can deliver a range of NCPs. These are described is Sections 5.2.1 to 5.2.4.

5.2.1. Regulating NCPs. For Habitat Creation and Maintenance, the improvement in soil fertility properties after biochar addition improves habitats for soil organisms. For Formation, Protection and Decontamination of Soils and Sediments, the high reactivity of biochar's surface may contribute to the immobilization of soil and water pollutants, and the improvement in soil structure and properties can increase nutrient cycling and retention. For Regulation of Hazards and Extreme Events, adding biochar to soils will improve soil formation and protection, which will make soils less prone to erosion, degradation, and contamination. However, all of this can only be achieved when biochar production adheres to well-established clean technical standards, and when feedstock generation is sustainable, without negative impacts on planetary boundaries (e.g., biodiversity, N and P use) or food safety.

5.2.2. Material NCPs. For Energy, biochar production can also be used to generate energy. Furthermore, the increase in crop yields after biochar application could increase the productivity of bioenergy crops (see Section 4.2.2). For Food and Feed, biochar addition to soils fosters the improvement of biological and physicochemical properties of soils, thus leading to an increase in crop productivity and stability.

5.2.3. Nonmaterial NCPs. For Learning and Inspiration, a wide variety of methodologies exist for pyrolysis (from cooking stoves to the farm- and industrial scale). By recycling biomass residues and adapting pyrolysis to specific local conditions, agroecosystems can be made more resilient, which represents an ideal opportunity to improve learning and inspiration for future generations. In terms of Supporting Identities, biochar from biomass residues has been used for millennia by indigenous farmers. Hence, fostering biochar production means preserving or reviving (ancient) traditions, supporting cultural identities.

5.2.4. Overarching NCPs. The high recalcitrance of biochar's organic C delivers C sequestration in the range of 0.3–2 $GtCO_2$ $year^{-1}$ (8, 38) or more, depending on the amount of land surface that is dedicated to this pathway and the C fractions besides biochar that are used for storage (68). Furthermore, non-CO_2 GHGs from soils are reduced (80). Moreover, increasing root biomass (74) likely aids in the buildup of additional SOC. These climate-regulation add-ons distinguish biochar use in soils from other GGRs.

5.3. SDGs Impacted by Biochar

TEW: terrestrial enhanced weathering

For SDG 1, No Poverty, reducing costs and dependency on external resources together with the increase in crop productivity would help farmers to be self-sufficient while increasing incomes. For SDG 2, Zero Hunger, food security will benefit from higher yields and higher agroecosystem resilience (see Section 4.3). For SDG 3, Good Health and Well-being, by increasing crop yields, aiding soil remediation and water purification, biochar application to soils can contribute significantly to peoples' nutritional health. For SDG 6, Clean Water and Sanitation, biochar can adsorb soil pollutants, thus avoiding leaching and, therefore, water pollution. For SDG 7, Affordable and Clean Energy, the pyrolysis of biomass represents an affordable source of energy, produced from an accessible feedstock. For SDG 8, Decent Work and Economic Growth, the achievement of SDGs No Poverty and Zero Hunger is linked to the improvement of life conditions of farmers in rural areas. Furthermore, the lower dependence on external agents can improve autonomy and, thus, working conditions of farmers. For SDG 9, Industry, Innovation and Infrastructure, the development of pyrolyzers for farmers will allow the deployment of cost-effective pyrolysis technology for smallholder farmers such as through the simple, clean Earth-dug Kon-Tiki technique (69). Medium-scale (e.g., house-heating) and large-scale (i.e., industrial) plants are also feasible; i.e., pyrolysis is a mature GGR option. For SDG 10, Reduced Inequality, biochar can make rural small farmers more self-sufficient and improve the health of women (e.g., clean cooking technology, improved yields in their home or forest gardens) and will increase female income, contributing to decreased hunger and poverty and thus reducing the inequalities between rural and urban areas. For SDG 11, Sustainable Cities and Communities, biochar functions in macadam-based urban planting substrates could contribute to the achievement of this SDG. Improving city tree growth and survival is of vital importance to adapt cities to the challenges of future heat waves (transpiration cooling) as well as storm water management after increasingly extreme precipitation events. In addition, biochar use can help rural communities maintain stable yields, ensuring future food production and hence preserving livelihoods. For SDG 12, Responsible Consumption and Production, the increase in crop yields from biochar will contribute positively. The use of biochar in animal husbandry, which is currently the dominant route of use in European agriculture, may permit reduced use of antibiotics and contribute to animal (and hence human) health (82). For SDG 13, Climate Action, the high recalcitrance of the organic C in biochar, together with the decrease on N_2O and CH_4 emissions from soils amended with biochar contributes to climate regulation. Furthermore, the increase in the resilience of agroecosystems aids the adaptation to, and mitigating of, the impacts of climate change in the future. For SDG 15, Life on Land, by improving soil fertility and decreasing soil and water pollutants, biochar addition would increase the capacity of the ecosystem to provide habitats for (soil) organisms and to ensure soil health.

6. TEW

Weathering of minerals is a fundamental driver in the formation of soil (91). As the soil skeleton, the mineral component is the structure that physically supports the other soil functions. During soil development, parent rock is weathered, nutrients are released, and secondary minerals (e.g., clays, carbonates) are formed. Terrestrial enhanced weathering (TEW) is promoted by the application of crushed rock to the land (92, 93). Silicate rocks containing minerals rich in calcium and magnesium and lacking metal ions such as nickel and chromium are probably most suitable for TEW [e.g., basalt (94)], which reduce soil solution acidity during dissolution, and promote the chemical transformation of CO_2 to bicarbonate ions (HCO_3^-). The bicarbonate ions may precipitate in soils and drainage waters as a solid carbonate mineral (95), or remain dissolved and increase alkalinity levels in the ocean (96). In addition to CO_2 storage, some rocks contain elevated concentrations of potassium, phosphorus, and silicon, so could also be an alternative source of nutrients for supporting agricultural production (94, 97). Humanity has been adding minerals [currently hundreds of millions of tonnes per year (98, 99)] such as biomass ash and agricultural lime to the land surface to improve soil fertility and crop production since antiquity. Uncertainty surrounding silicate mineral dissolution rates in soils, the fate of the released products, the extent of overburden legacy reserves that might be exploited, location, availability of rock extraction sites, and the impact on ecosystems remain poorly quantified and require further research to better understand feasibility (94, 100, 101). There is a need for field-scale development and demonstration of the carbon capture potential of TEW in agricultural and forestry settings to help understand possible co-benefits and the challenges and opportunities of the approach (102).

6.1. Functions Delivered by TEW

The functions presented in Section 4 derived from good soil management are also applicable to TEW. Loss of soil through erosion is a considerable challenge for agricultural sustainability equating to greater than a hundred billion tonnes of soil over the past 200 years (103). Stabilization of soils by amending with silicates for TEW may become an important mechanism of soil restoration, given that erosion is expected to increase under climate change (94). Weathering of silicate minerals in soils increases the cation exchange capacity, resulting in increased nutrient retention and availability (104, 105) and could enhance biomass production, including in agriculture and forestry. This could also stimulate organic carbon input from roots and symbiotic mycorrhizal fungi (94), leading to stabilization in soil aggregate formation (106), and the interaction between organic carbon and minerals, which ultimately improves soil quality (107) and reduces erosion rates (94). Production of alkalinity by chemical weathering aids reversal of soil acidification, which in turn improves crop nutrient uptake and yields. Silicic acid formation following weathering is readily taken up by plants and can increase resistance to pests and diseases (94). Some silicate rocks contain elevated concentrations of trace elements that are essential for human nutrition (108) and crop production (109). Harvesting removes these nutrients from the soil, resulting in their gradual depletion (see, e.g., 110). Experiments testing the impact of crushed rock addition to plant growth trials have variable results, with some experiments demonstrating increased mobilization, uptake, or yield (111).

6.2. NCPs Impacted by TEW

The impact of TEW on the NCPs is described in this section. Sections 6.2.1 to 6.2.3 describe the impacts on regulating, material and overarching NCPs.

6.2.1. Regulating NCPs. For Habitat Creation and Maintenance, see Section 4.2.1, given the same evidence is relevant for TEW. For the Regulation of Ocean Acidification, TEW could reduce ocean acidification, caused by the dissolution of atmospheric CO_2 into the surface ocean (112), given the dissolution of silicate minerals applied to the land consumes acidity and creates drainage waters with slightly elevated alkalinity, which may ameliorate ocean acidification once they reach the ocean (113). For the Regulation of Freshwater Quantity, Flow and Timing, increasing organic carbon content of soils (e.g., through organo-clay aggregate formation) (114) improves soil water retention (115), and may reduce the amount of additional water needed for irrigation of croplands. Stabilizing and maintaining soils, particularly those that are exposed to the risk of erosion, may improve water retention and limit the impact of flooding (64). For the Formation, Protection and

Decontamination of Soils and Sediments, accelerating the weathering of minerals in soils may lead to the formation of clay, and mineral organic aggregates, thus replenishing the material lost through erosion and increasing the cation exchange capacity of rebuilt soils (94).

6.2.2. Material NCPs. In terms of the material NCP Energy, processing an additional 10 billion tonnes of rock would require up to 3,000 TWh, which would consume approximately 0.1–6% of global electricity in 2100. This would place additional, yet marginal, demands on the future energy system. The emissions associated with this additional energy generation may reduce the net carbon removal by up to 30% with present-day grid average emissions (98), but this efficiency loss would decrease with decarbonized power. The discussion in Section 6.3 on Zero Hunger provides more details about Food and Feed.

6.2.3. Overarching NCPs. The primary purpose of TEW is as a mechanism to regulate climate. More details are provided in Section 6.3 for SDG 13 on Climate Action.

6.3. SDGs Impacted by Enhanced Mineral Weathering

For SDG 1, No Poverty, the supply chain associated with mineral addition to the land surface may provide local economic growth through mineral extraction, processing, and transport. However, the mining industry has a poor track record for alleviating local poverty (116). For SDG 2, Zero Hunger, TEW may provide benefits by supply of plant growth–limiting nutrients, reversing soil acidification, restoring plant-available silica pools, increasing soil cation exchange capacity and augmenting pest resistance, which could all increase crop yields (94). Furthermore, given the cost of mineral fertilizers limits their application in some areas, TEW could improve societal access and increase yields (117, 118). For SDG 6, Clean Water and Sanitation, the primary benefit is a potential decrease in water requirements for cropland irrigation (see Section 6.2.1). However, water is managed in mineral aggregate extraction [e.g., dust suppression (119)], and this can impact local flows of freshwater in streams and groundwater (120, 121). Because amending agricultural soils with crushed silicate rocks improves yields, TEW can potentially reduce consumption of rock-derived fertilizers that represent a finite resource, benefiting SDG 12, Responsible Consumption and Production. Reversing soil acidification as a result of TEW with silicates offers an opportunity for reducing calcium carbonate production for liming operations (99). For SDG 13, Climate Action, TEW removes CO_2 from the atmosphere and potentially mitigates other GHG emissions from soils. Interactions with other GGR strategies (e.g., feedstock for biochar, BECCS) and with AR could further promote CO_2 removal, but these interactions require field-scale demonstration and assessment (102). The emissions from mineral extraction, comminution, and transport lower the efficiency of the removal (100, 101). Helping neutralize soil acidification of croplands linked to application of nitrogenous fertilizers can also reduce soil CO_2 efflux. For SDG 14, Life Below Water, TEW may promote the flow of elevated alkalinity freshwater to coastal environments and the ocean, which may mitigate the impacts of ocean acidification and reduce associated impacts on corals and fisheries (113). Increasing silica concentrations in runoff into coastal oceans can favor the growth of diatoms over problematic nonsiliceous algae (94). For SDG 15, Life on Land, existing agricultural lands could be made more productive via TEW, which could lead to land sparing by reducing land demand for croplands, which could decrease pressure on biodiversity (118). Any significant expansion of the mining industry would require careful assessment to avoid possible detrimental effects on biodiversity (118) (**Figure 5**).

Figure 5

Summary of the impact of terrestrial enhanced weathering on ecosystem functions, on Nature's Contributions to People (NCPs), and on the United Nation's Sustainable Development Goals (SDGs) showing the impact of each function on each NCP and the contribution of the NCPs to each of the SDG.

7. BECCS

Bioenergy and BECCS are produced on the land but could be used to decarbonize the energy system (122). The production and use of bioenergy raises many issues (e.g., trade-offs between economic development and sustainability, potential conflicts for land between energy and nonenergy uses). Various papers have assessed the effects of future bioenergy and BECCS production on Ecosystem Services (6, 123). Although different bioenergy feedstocks do exist (124), we focus on dedicated lignocellulosic bioenergy crops as they are seen to play a major role for BECCS. In contrast, the interaction between bioenergy from residues and NCPs and SDGs is primarily indirect (125), as these feedstocks affect soil carbon and hence reflect the NCP and SDG interaction described in Section 4 on SCS.

7.1. Functions Delivered by BECCS

BECCS delivers two primary functions: energy and carbon sequestration. BECCS can be used to produce electricity, refined liquids, hydrogen, and natural gas, all of which can be used in the provision of energy services (e.g., kilometers traveled; heating, cooling, and cooking, etc.). BECCS also removes carbon from the atmosphere as bioenergy is grown, reducing CO_2 concentrations.

7.2. NCPs Impacted by BECCS

The implications of BECCS on NCPs and SDGs depends on the feedstock, scale of deployment, and other factors. We focus on large-scale cellulosic BECCS plantations, as these are what typically emerges from Integrated Assessment Scenarios (IAMs) in low-stabilization scenarios. BECCS at smaller scales or using other feedstocks could lead to different impacts.

7.2.1. Regulating NCPs. BECCS is often deployed at very large scales in future IAM scenarios for climate regulation with annual removal rates up to 15 $GtCO_2$ $year^{-1}$ in 2100 (1). This 15 $GtCO_2$ per $year^{-1}$ estimate does not include any potential additional emissions due to fertilization of bioenergy crops or related expansion of agricultural land. However, these emissions are included in models quantifying the mitigation potential of BECCS. In addition, perennial cellulosic bioenergy crops (e.g., poplar) can have biophysical effects on the climate via changes in albedo and evapotranspiration (126). BECCS may help with the Regulation of Ocean Acidification, since ocean acidification is strongly linked to carbon emissions and the atmospheric CO_2 concentration (127). As BECCS removes carbon from the atmosphere, it can help reduce ocean acidification. For Regulation of Freshwater Quantity, Location and Timing, bioenergy crops have an impact through changes in the surface runoff in freshwater ecosystems (128), and by increasing agricultural water withdrawals (129, 130). Since bioenergy can affect freshwater quality via nitrogen runoff from fertilizer application, it has an impact on Regulation of Freshwater and Coastal Water Quality.

7.2.2. Material NCPs. One of the primary functions of BECCS is the provision of energy. In 2016, bioenergy accounted for ~10% of global primary energy (131). IAMs estimate that in 2100 bioenergy could provide up to 50% of global primary energy, all of which could be used in combination with CCS (122). Bioenergy and BECCS could potentially conflict with the production of Food and Feed, as both could compete for the same land. Several studies indicate that large-scale bioenergy production and use could result in increased food prices (132, 133) and increased food insecurity (134).

7.2.3. Overarching NCPs. It is possible that large-scale BECCS could harm the Maintenance of Options, although there are no studies examining this link. There is no evidence linking BECCS to any of the other overarching NCPs.

7.3. SDGs Impacted by BECCS

Of the 17 SDGs, few (SDGs 4, Quality Education; 5, Gender Equality; 10, Reduced Inequalities; 10, Sustainable Cities and Communities; 16, Peace, Justice and Strong Institutions; and 17, Partnerships for the Goals) are not directly impacted by BECCS. Below, we describe the potential impacts of BECCS on SDGs. BECCS has the potential to both help and hinder SDG 1 No Poverty goal. On the one hand, it can provide additional options for local income creation for agricultural producers (135). On the other hand, enhanced competition for land and associated increases in food prices could affect expenditures for food (133, 136); additionally, BECCS could lead to potential displacement of small-scale farmers due to unclear land tenure rights. As discussed above, BECCS can increase competition for land and other inputs, resulting in increased food prices and negative effects on food security and SDG 2, Zero Hunger (133, 136). For SDG 3, Good Health and Well-being, BECCS could be beneficial via reduced air pollution if BECCS replaces fossil energy use (137, 138), as the CCS portion of the plant removes air pollutants in addition to CO_2. Large-scale production of biomass based on dedicated crops could require additional fertilizer inputs (139, 140), potentially affecting SDG 6, Clean Water and Sanitation, which could have subsequent impacts on SDG 3, Good Health and Well-being. Replacing fossil energy with low cost BECCS (1) has the potential to enhance SDG 7, Affordable and Clean Energy, through decreases in air pollution and CO_2 concentrations (137). However, nitrogen pollution could increase due to increased use of fertilizers for enhanced yields of bioenergy crops (139, 140). For SDG 8, Decent Work and Economic Growth, feedstock production for BECCS could create new income opportunities for rural land owners and labor, and hence help to support rural livelihoods; however, this may depend on the previous land use. With 2.5 billion people in the world relying on agriculture for work (141), biomass production for BECCS would be expected to contribute positively to SDG 8 (135). BECCS could affect SDG 9, Industry, Innovation, and Infrastructure in different ways. On the one hand, newly generated agricultural income options could lead to lower investments in innovation and manufacturing in other sectors, especially in biomass producing countries. On the other hand, due to the cleaner energy provided by BECCS, CO_2 emission of industrial production would be lower. BECCS, especially if replacing fossil fuels, can strongly affect SDG 12, Responsible Consumption and Production. However, if it is not managed well (e.g., large-scale expansion of dedicated bioenergy crops), this has the potential for inefficient use of natural resources, such as land demand and associated deforestation, water use for irrigation, and nitrogen fertilization (142). As noted above, BECCS supports SDG 13, Climate Action, by removing carbon from the atmosphere. However, the additional emissions due to fertilization of bioenergy crops and expansion of agricultural land, as well as changes in albedo and evapotranspiration, must be taken into account (143). Furthermore, use of residues as feedstock for BECCS could negatively affect SOM and hence soil carbon stocks (125). BECCS can affect SDG 14, Life Below Water. Fertilization of dedicated lignocellulosic bioenergy crops could affect coastal as well as freshwater eutrophication. BECCS indirectly affects Life Below Water by reducing ocean acidification, as noted above. BECCS could also have large implications for SDG 15, Life on Land. Conversion of natural land such as tropical forest due to large-scale bioenergy crop production for BECCS could destroy the habitats of many species (144). In addition, nitrogen fertilization, as well as use of pesticides, could affect Life on Land negatively (145) (**Figure 6**).

8. DISCUSSION

Across all of the land-based GGR options considered, all GGRs contribute positively to at least some NCPs and SDGs. The number of NCPs and SDGs for which benefits occur vary between

Figure 6

Summary of the impact of Bioenergy Carbon Capture and Storage (BECCS) on ecosystem functions, on Nature's Contributions to People (NCPs), and on the United Nation's Sustainable Development Goals (SDGs), showing the impact of each function on each NCP, and the contribution of the NCPs to each of the SDG.

GGR options, but wetland restoration and SCS deliver almost exclusively positive impacts. All GGR options, by definition, have positive impacts on NCP 4, Regulation of Climate, and SDG 13, Climate Action, whereas impacts on the other SDGs are variable both in sign and magnitude across GGR options, consistent with the findings of Smith et al. (6), Minx et al. (7) and Fuss et al. (8).

There are a few GGR options that have a potentially negative impact on some NCPs and SDGs, particularly when implemented at scale. The GGR options with potential negative impacts are characterized by increasing competition for land, water, and other resources such as nutrients (6–8). In particular, large-scale AR (strongly depending on forest type and location), BECCS, and the feedstock required for biochar production potentially increase competition for land, but even these potential impacts are context and scale specific. For example, if BECCS is implemented at a very large scale, it can have a large water footprint and increase competition for land such that food security, biodiversity conservation, and freshwater sources could suffer (6, 146); conversely, bioenergy grown for BECCS could have positive benefits for biodiversity (147), soil carbon (148), and other ecosystems services (123, 149), if energy crops such as *Miscanthus* or short-rotation coppice willow or poplar were grown on land formerly growing annual crop monocultures (see Sections 7.2 and 7.3). Similarly, large-scale afforestation using tree monocultures could have negative consequences for biodiversity (150), whereas reforestation or restoration of native woodlands could be very beneficial for biodiversity (15; see also Section 2.3). This emphasizes the need to assess impacts in a scale- and context-specific manner.

Interestingly, the impacts of most GGR options are assessed in isolation, considering one option at a time. Although there are a few examples that have considered more than one GGR option and trade-offs between them [e.g., afforestation and BECCS (142)], most do not. Some GGR options are mutually exclusive on the same area of land; for example, afforestation and growing biomass as feedstock for biochar or BECCS cannot be done together. However, some can be combined. For example, biochar can be applied to land used to grow energy crops of forests, and SCS can also be applied on land used for afforestation and land growing biomass as feedstock for biochar or BECCS. TEW could also be combined with SCS and to enhance productivity of trees and other biomass (94), although the exact nature of the synergies is still relatively unquantified. One R&D priority is, therefore, to build the evidence base on synergies and trade-offs between different GGR options, with respect to both their additivity and the processes potentially providing synergies between GGR options. For example, in different situations the addition of ground minerals used for TEW will raise soil pH, which could either increase SCS rates by increasing plant productivity—and thereby carbon inputs into the soil (94)—or could lower SCS rates in acid soils, where low pH can act to slow decomposition. Interactions such as these, as well as the context specificity of such interactions, are poorly understood and should be subject to process-based studies to elucidate interactions. Furthermore, building the processes by which GGR options deliver GGR removal into ecosystem and land surface models, and ultimately into IAMs, should also be a research priority. This will allow the potential for a combination of GGR options to be explored, so that new portfolios of GGR options can be considered in combination rather than as single, competing options.

In addition to R&D needs, there is a need for large-scale demonstration projects, which are a necessary step in moving any potential GGR option toward implementation. Demonstration projects need to be of sufficient scale to allow potential barrier and logistical constraints to be exposed. Some practices delivering GGR options (e.g., practices that result in SCS) are well characterized and are already being applied, although not exploited to their full extent (40), whereas others (e.g., TEW, biochar) are at an earlier stage in technology development. Demonstration projects are essential for scaling-up of technologies, for realizing economies of scale, for reducing the costs of GGR, and for "learning by doing" (6).

Some GGR options (e.g., afforestation, BECCS, biochar, TEW) present some potential risks to the codelivery of NCPs, or the delivery of some of the SDGs. For these options, more research is required to understand under which conditions these risks can be minimized and/or managed. Such risk management could involve excluding some GGR options from certain regions, areas, or environments, or could involve managing their position within broader landscape units. Larger-scale demonstration projects for these GGR options should proceed with caution and careful monitoring to get early warning of any potential adverse outcomes, with risk management plans in place should they occur.

Other GGR options (e.g., wetland restoration and SCS) present few risks, and indeed can provide a range of co-benefits across many NCPs and SDGs. These options could be implemented rapidly, with rapid rollout of demonstration projects, but still with careful monitoring. These options can be regarded as no-regrets options, given they provide a range of benefits, even if all of the GGR potential is not realized.

Because GGR options are likely to be required if we are to collectively deliver the Paris targets, a portfolio of GGR options will be needed to deliver the GGR necessary. To this end, no-regrets options could be implemented quickly, with other options going through R&D and large-scale demonstration as they progress through the technology readiness levels.

SUMMARY POINTS

1. All greenhouse gas removals (GGRs) contribute positively to at least some of Nature's Contributions to People (NCPs) and Sustainable Development Goals (SDGs).
2. The number of NCPs and SDGs for which benefits occur vary between GGR options, but wetland restoration and soil carbon sequestration (SCS) deliver almost exclusively positive impacts. These options can be regarded as no-regrets options, given they provide a range of benefits, even if all of the GGR potential is not realized.
3. All GGR options have positive impacts on the NCP Regulation of Climate, and the SDG 13, Climate Action, but impacts on other SDGs are variable in both sign and magnitude.
4. A few GGR options potentially impact negatively on some NCPs and SDGs, particularly when implemented at scale. The GGR options with potential negative impacts are characterized by increasing competition for land, water, and other resources such as nutrients.
5. Large-scale afforestation/reforestation (AR), bioenergy carbon capture and storage (BECCS), and the feedstock required for biochar production potentially increase competition for land, but even these potential impacts are context- and scale specific.
6. Some GGR options are mutually exclusive so cannot be practiced on the same piece of land; for example, afforestation and growing biomass as feedstock for biochar or BECCS cannot be done together. However, some GGR options can be combined.
7. Because GGR options are likely to be required if we are to collectively deliver the Paris targets, a portfolio of GGR options will be needed to deliver the GGRs necessary. To this ends, no-regrets options could be implemented quickly, with other options going through R&D and large-scale demonstration as they progress through the technology readiness levels.

FUTURE ISSUES

1. One R&D priority is to build the evidence base on synergies and trade-offs between different GGR options, with respect to both their additivity and the processes potentially providing synergies between GGR options.

2. The processes by which GGR options deliver GGR removal should be built into ecosystem- and land surface models, and ultimately into integrated assessment models.
3. Demonstration projects are essential for scaling-up of technologies, for realizing economies of scale, to reduce the costs of GGR, and for "learning by doing."
4. More research is required to understand under which conditions risks can be minimized and/or managed within a GGR portfolio. Such risk management could involve excluding some GGR options from certain regions, areas, or environments or could involve managing their position within broader landscape units.

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