Chapter 8
Mitigation of Climate Change: Introduction

Abstract The annual global greenhouse gas (GHGs) emissions have continued to grow since the industrial revolution. The dominant driving force for the anthropogenic GHGs emission include population growth, economic growth, fossil fuel consumption and land use change. Since the beginning of industrial revolution to 2015, cumulative anthropogenic carbon dioxide (CO_2) emission of 600 ± 70 Pg C were released to the atmosphere, causing an increase in atmospheric CO_2 relative abundance of 144% compared to pre-industrial era. The atmospheric concentrations of methane (CH_4) and nitrous oxide (N_2O) have also increased significantly. As a result, changes in climate has caused impacts on natural and human systems across the globe, and continued GHGs emission will cause further climate change impacts. Accurate assessment of anthropogenic CO_2 emissions and their redistribution among the atmosphere, ocean and terrestrial biosphere provides better understanding of C cycling and also support the development of climate policies, and project future climate change. The mitigation options available combine measures to reduce energy use and CO_2 intensity of the end use sectors, reduction of net GHG emissions, decarbonization of the energy supply, and capture and sequestration of C through enhancement of natural C sinks or by engineering techniques. There has also been emphasis on engineering of climate as an alternative mitigation option. Geoengineering, a global large-scale manipulation of the environment, is considered as one of the effective means of mitigating global warming caused by anthropogenic greenhouse gases (GHGs) emission. Assessment of technical and theoretical aspects of solar radiation management (SRM) and carbon dioxide (CO_2) removal methods (CRM) as well as their potential impacts on global climate and ecosystems will be reviewed. Most of the proposed geological engineering methods involving land or ocean will use physical, chemical, or biological approaches to remove atmospheric CO_2, while those proposed for atmosphere or space will target radiation without affecting atmospheric CO_2 concentration. The CRM schemes tend to be slower, and able to sequester an amount of atmospheric CO_2 that is small compared to cumulative anthropogenic CO_2 emissions. In contrast, SRM approaches have relatively short lead times and can act rapidly to reduce temperature anomaly caused by GHGs emission. Overall, current research on geoengineering is

D. Ussiri and R. Lal, *Carbon Sequestration for Climate Change Mitigation and Adaptation*, DOI 10.1007/978-3-319-53845-7_8

scanty and various international treaties may limit some geoengineering experiments in the real world due to concerns of an unintended consequences.

Keywords Decarbonization of energy supply · Carbon capture · Geoengineering · Kaya identity · Climate engineering · Carbon sequestration in the ocean

Contents

8.1 Introduction

The concentration of greenhouse gases (GHGs) including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the atmosphere has been steadily increasing since the beginning of the Industrial Revolution in 1750. The CO_2 is the largest component of anthropogenic GHG, while CH_4 is the second most important GHG emitted by human activities. Anthropogenic CO_2 emissions from the combustion of fossil fuels have been the main contributor to the increasing CO_2 concentration in the atmosphere, followed by CO_2 emissions from land use and land use change (LULUC). Cumulative anthropogenic CO_2 emissions of 600 ± 70 Pg C (2200 ± 257 Pg CO_2) were released to the atmosphere between 1750 and 2015, of which, 260 ± 5 Pg C or about 40% of these anthropogenic CO_2 emissions (953 ± 18 Pg CO_2) have remained in the atmosphere since 1750, causing 144% increase in atmospheric CO_2 relative abundance from 1750 to 2015 (WMO 2016). The rest was removed from the atmosphere by sinks and stored in the natural carbon (C) cycle reservoir (Le Quéré et al. 2015, 2016). The natural sinks—ocean and terrestrial uptake accounts approximately equal measure, with ocean absorbing about 30% of the emitted anthropogenic CO_2 and causing ocean acidification. Terrestrial uptake consists of vegetation and soil sinks. The relative abundance of the atmospheric CH_4 and N_2O has also increased by 254% and 121, respectively relative to 1750 concentrations (WMO 2016). Anthropogenic CH_4 emissions are due to a wide range of activities, including production and transport of fossil fuels, livestock, rice cultivation, and decomposition of organic waste in solid waste landfills. The N_2O is emitted during agricultural and industrial activities and also during combustion of biomass.

Over the past 10,000 years during Holocene, the planet enjoyed a favorable stable climate window until humans flourished as a dominant force for change after industrial era, rapidly expanding their influence and exceeding a global geological change force. Humans have become a major transforming force that is rapidly pushing the planet towards new, undesirable state as the consensus continues to emerge about a future, hotter planet that will make it difficult with a sustainable society (Lenton et al. 2008). Energy is critical to global prosperity, as it underpins economic growth, social development, and poverty reduction. It has fueled global economic development since the Industrial revolution, and as many countries continue to aspire a more inclusive economic development, energy supply will continue to remain the major solution. Fossil fuels provide more than 80% of global energy needs, and the growing energy demands has led to increasing GHG emissions. Fossil CO_2 emissions have grown substantially over the past two centuries (Fig. 8.1). The energy sector generates approximately two thirds of global GHG emissions and more than 80% of total CO_2 emissions (Fig. 8.2). In 2012, energy sector produced 8.7 Pg C, the largest share of which came from power generation (IEA 2014). The CO_2 emissions are set to continue to grow, mainly driven by increases in emission from developing countries. Since economic growth and social development are coupled with increasing GHGs emission, the challenge of the 21st century is to decouple the two so as to achieve economic growth and social development while also achieving significant reductions in GHG emissions.

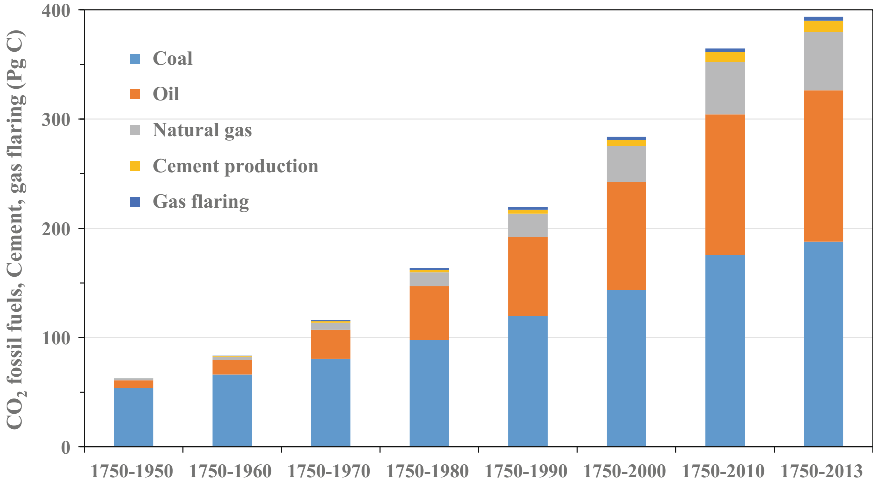

Fig. 8.1 Cumulative CO_2 emissions from fossil fuels combustion, cement production and gas flaring from 1750 showing decadal changes from 1950 to 2013

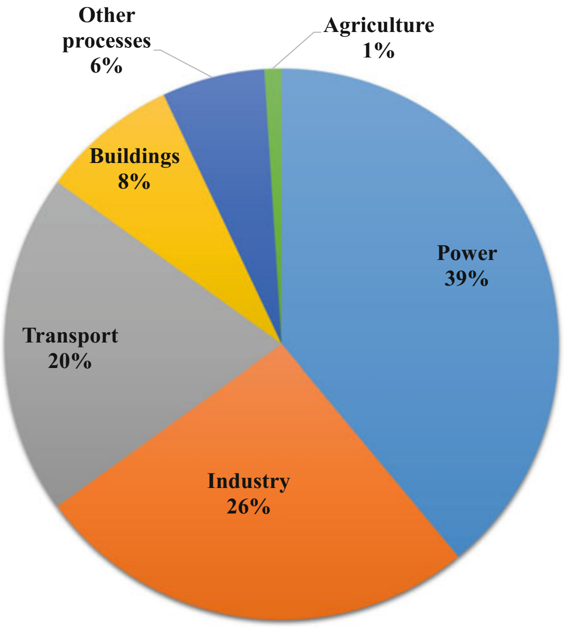

Fig. 8.2 Energy sector CO_2 emissions in 2012. *Source* IEA (2014)

Mitigation is a process of human intervention to reduce the sources or enhance the sinks of GHGs and other substances which may contribute directly or indirectly to climate change. Such substances include emissions of particulate matter that can directly alter radiation balance—such as black carbon (BC), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOC), and other compounds that can alter the concentration of ozone (O_3) which can impact the climate directly. Mitigation therefore, lowers the anticipated effects on climate as well as risks of extreme impacts, and it is generally considered as part of a broader policy strategy to adapt to climate change impacts. The ultimate goal of mitigation is to prevent dangerous anthropogenic interference with the climate system within a time frame to allow ecosystems to adapt and ensure that food production and economic development proceeds in a sustainable manner.

There is a strong interest in stabilizing the atmospheric abundance of GHGs to mitigate the risks of dangerous global warming. The potential pathways to climate stabilization and/or mitigation of climate change require deployment of a broad portfolio of solutions to increase energy efficiency, replace fossil fuel use and removal of GHGs. The technological solutions available to address the challenges of increasing GHGs and the associated climate change can be broadly grouped into two: (i) non-biological solutions and (ii) biological solutions. The non-biological solutions do not involve biosphere component of natural and the managed biosphere directly, and they include techniques such as (a) reducing the global energy use, (b) establishing wind and solar farms for the power generation, (c) developing low-, C neutral, or C negative fuels, (d) capturing and sequestering CO_2 from point and non-point source and sequestration in geological formation (CCS) or capturing CO_2 from the atmosphere through enhanced natural biological sequestration or engineering techniques, and (d) geoengineering modification of climate. The biological solutions that involve biosphere components of the natural and managed C cycle include: (a) reforestation and/or afforestation, (b) sequestration of soil organic C (SOC), and (c) use of bioenergy to replace fossil fuels. Biological solutions are distinctive in two main ways: first, terrestrial and ocean C sinks already exist, and are removing more than half of the anthropogenic CO_2 emissions from the atmosphere (Canadell et al. 2007b; Canadell and Schulze 2014; Le Quéré et al. 2015), although there are some indications of sink saturation over time (Canadell et al. 2007a). Therefore, understanding and managing these sinks is important. Second, the biological mitigation approaches require enhancement of net primary productivity (NPP), followed by additional harvesting of the Earth's NPP beyond the current 38% use (Running 2012), and there are clear limits to the global fraction further available for human exploitation. The global NPP has generally remained stable at 60.2 Pg C yr^{-1} over the past 30 years with only ~ 1 Pg yr^{-1} of internal variability (Running 2012). It is estimated that 53% of global NPP is not harvestable, which includes plant growth in root systems, preserved lands, and the critical ecosystem services and biodiversity and wilderness where no transport exists for harvesting. The objective of this chapter is to present an overview of the CO_2 emission mitigation strategies.

8.2 Drivers of Carbon Dioxide Emissions

Since about 1850, global use of fossil fuels (coal, oil, and natural gas) use has increased to dominate the energy supply, replacing many traditional use of biomass fuels and also providing new services. For example, in 2009, the world used 11,161 million tons of oil equivalent (Mtoe) or 469 exajoules (EJ) of commercial energy in total, of which, nearly 90% was from fossil fuel (Larson et al. 2012). Dependency on fossil fuel has created four major challenges globally: (i) widespread lack of access to affordable alternative modern energy carriers, (ii) global climate change, (iii) global air pollution, and (iv) energy insecurity (Larson et al. 2012). Due to advantages in cost, logical maturity, and established infrastructure, fossil energy sources are likely to remain a major component of global energy supply for several decades, especially coal-based power generation and liquid gas-based hydrocarbon fuels for transport and power generation, even as the world increasingly transitions to renewable energy (RE) technologies. Increasing demand for energy comes from worldwide economic growth and development, and growing energy demand from fossil fuels plays key role in increasing trends of CO_2 emissions. This rapid rise in fossil fuels combustion (including gas flaring) has produced corresponding growth in atmospheric CO_2 burden (Fig. 8.1). Various factors have been recognized as the main drivers of increase in GHG emissions, including consumption (Hertwich and Peters 2009; Karstensen et al. 2015), international trade (Peters and Hertwich 2008;

Feng et al. 2015), population growth (O'Neill et al. 2010; Krey 2014), economic growth (Blodgett and Parker 2010), structural changes to a service economy (Nansai et al. 2009), and energy consumption (Malla 2009; Karmellos et al. 2016). While emissions from land use and land use change has increased by 12% between 1970 and 2010, the major global GHG emission have, however, been associated with CO_2 emissions from fossil energy at 108% between 1970 and 2010 (Fig. 8.1).

It has been suggested that climate change is more of an issue of economic development for both developing and developed countries than it is an environmental issue (Moomaw et al. 1999). Kaya identity provides a framework for analyzing emissions by decomposing overall changes in GHG emission into underlying factors and analyze energy related CO_2 emissions as a function of four factors: (i) population, (ii) gross domestic production (GDP) per capita, (iii) energy intensity (i.e., total primary energy supply (TPES) per GDP), and (iv) carbon intensity (i.e., CO_2 emission per TPES) (Kaya 1990, 1995) model is therefore represented by Eq. (8.1):

$$\mathrm{CO_2\,emission} = \mathrm{Population} \times \mathrm{Affluence} \times \mathrm{Energy\,intensity} \times \mathrm{C\,intensity} \tag{8.1}$$

In other words, CO_2 emissions are expressed as a product of these four factors (Steckel et al. 2011; Peters et al. 2013; Raupach et al. 2007). Overall, understanding the observed magnitudes and patterns of the factors and drivers influencing global CO_2 emissions is a prerequisite for the prediction of future climate and the Earth system changes and for human governance of climate change and the Earth system.

8.3 Options for Mitigating Greenhouse Gases Emission

The United Nations Framework Convention on Climate Change (UNFCCC) calls for stabilization of atmospheric CO_2 concentration, even though there is no agreement on what specific level of CO_2 concentration should be. The Cancun agreement calls for limiting global average temperature increase below 2 °C relative to pre-industrial (1750) temperature, and also agreed to consider a goal of 1.5 °C (UNFCCC 2010). The Copenhagen Accord also reiterated the international commitment of holding the increase in global temperature below 2 °C, and take action to meet this objective consistent with science and on the basis of equity without quantifying the degree of mitigation required to meet this commitment or assessing whether it is still possible to achieve this commitment (UNFCCC 2009). The COP 22, Climate Summit in Paris, also recommended limiting global warming to below 2 °C and making effort to limiting it to below 1.5 °C. Scenarios analysis shows that in order to be confident of achieving equilibrium temperature increase of 2–2.4 °C, atmospheric GHG concentrations would need to be in the range of 445–490 ppm CO_2 equivalent (Schneider et al. 2007; Clarke et al. 2014). This implies that global emissions will need to decrease by 50–85% below 2000 concentration levels by 2050, and begin to decrease no later than 2015 (Anderson and Bows 2011).

It is recognized that stabilization of GHG concentration will only be achieved once the rate of addition of GHGs to the atmosphere equals to the rate at which natural systems can remove them., i.e., the rate of anthropogenic emissions is balanced by the rate of uptake by natural processes such as atmospheric reactions, net transfer to oceans, and uptake by biosphere (Allen et al. 2009). The global temperature increase is, to the first order, proportional to the amount of cumulative CO_2 emitted to the atmosphere (Rogelj et al. 2015), which implies that limiting the global warming to any temperature requires annual net CO_2 emissions to be phased out to virtually zero by the time when temperature stabilization has to be achieved (Matthews and Caldeira 2008). Based on an assessment of scenarios that take into account possible evolutions of our global society, the IPCC Synthesis Report (IPCC 2014) finds that to keep warming to below 2 °C with a likely (>66%) chance, such pathways would require cumulative emissions to be limited to around 1000 Pg CO_2 after 2011 with near-zero long-lived GHGs by the end of the century (Clarke et al. 2014; IPCC 2014). A wide variety of technological options have been proposed as potential mitigation strategies reduce CO_2 emissions and stabilize the atmospheric CO_2 concentration increase, while further technological options are still being developed. However, currently there is no mitigation option that can achieve full decarbonization or C neutrality of the global economy which have been proposed. In addition, the extent of use of the proposed mitigation will mainly depend on factors including cost, capacity, environmental impact, the rate at which the technology can be introduced, and social factors such as public acceptance.

The term "carbon sequestration" is generally used to describe both natural and deliberate processes by which CO_2 is either removed from the atmosphere or diverted from emissions sources and stored in the ocean, terrestrial environments (vegetation, soils, and sediments) and geologic formations. Before anthropogenic CO_2 emissions began, the natural processes that make up the global C cycle (Chaps. 5, 6 and 7) maintained a near balance between the uptake of CO_2 and its release back to the atmosphere. However, currently the natural mechanisms of CO_2 uptake by the environmental sinks are clearly not sufficient to offset the accelerating pace of anthropogenic CO_2 emissions. This makes stabilization of atmospheric CO_2 during this century and the goal of keeping global temperature increase below 2 °C relative to the pre-industrial even a much larger challenge. The atmospheric stabilization at any concentration requires that net emission level off and eventually drops to near zero. To achieve this level of stabilization it requires transformation of energy system worldwide, which will require many decades of development and deployment. For example, during the decade of 2006 to 2015, emissions from fossil fuels, cement production, and gas flaring is estimated at 9.3 ± 0.5 Pg C, and while natural ocean and net terrestrial uptake is estimated at 5.7 ± 0.9 Pg C yr^{-1}, and land use change emissions were 1.0 ± 0.5 Pg C yr^{-1}, respectively, and 4.5 Pg C yr^{-1} accumulated in the atmosphere (Le Quéré et al. 2015, 2016). Therefore, there is a need for more direct mitigation strategies to remove 4.5 Pg C yr^{-1} (about 45% of anthropogenic CO_2 emissions) from the atmosphere, which is a central issue in consideration for the current energy and environmental policies. Large-scale application of currently known mitigation strategies together with efficient use of energy and conservation can buy time until development of new technologies can make contribution (McCarl and Sands 2007), but the ultimate goal is transformation of energy production system to C-free energy sources.

Controlling atmospheric CO_2 increase will require deliberate mitigation with an approach that combines reducing CO_2 emissions and increasing CO_2 storage both by natural C cycle and artificially created systems. Technological options for reducing anthropogenic emissions of CO_2 include (i) reducing and eventually phasing out the use of fossil fuels, (ii) substituting less C—intensive fossil fuel for more C intensive fuels, (iii) replacing fossil fuel technologies with near-zero C alternatives, (iv) enhancing the absorption of atmospheric CO_2 by natural systems, (v) capturing and safe storage of atmospheric carbon. Options which have been under discussion currently encompass atmospheric CO_2 reductions through all possible mechanisms, including deliberate carbon sequestration; use of renewable non-fossil fuels and power sources; and increased energy conservation and efficiency, among others. Of these options, only deliberate carbon sequestration currently offers the possibility of direct removal of atmospheric CO_2, through enhancement of plant growth and enrichment of soil C storage.

8.3.1 Improving Energy Efficiency

The energy supply sector is the largest contributor to the global GHG emissions. Anthropogenic GHG emissions attributed to energy supply sector increased from 13% in 1970 to about 35% in 2010 (Le Quéré et al. 2015). The annual emission growth from the global energy supply sector accelerated from 1.7% yr^{-1} in 1990–2000 to 3.1% yr^{-1} in 2000–2010 (Bruckner et al. 2014), mainly because of rapid economic growth and the associated demand for power, heat, and transport services. In addition, increased share of coal in the global fuel mix has also contributed to this trend. In 2013, the energy supply sector emitted 21 Pg CO_2 equivalents or 16.7% higher emission than those in 2010 (IEA 2015a). Reduction in fossil fuel consumption can be achieved by improving the efficiency of energy conversion, transport and use, including enhancing less energy intensive economic activities. It is estimated that 25% of energy losses are due to the distribution system conductors and cables. High voltage direct current (HVDC) transmission has the potential to reduce transmission losses and is cost-effectiveness for long aboveground lines (Negra et al. 2006). Energy conversion efficiencies have been increased in the production of electricity—for example by improved turbines, combined heating, cooling and electric power generation systems to reduce CO_2 emission further. Technological improvement in power generation have achieved gains of factors of 2–4 in the energy consumption of the vehicles, lighting, and many other appliances since 1970, further improvements and wider application of improved technologies are also expected.

8.3.2 Switching to Less Carbon-Intensive Fossil Fuels

Switching from high-C to low-C fuels can be cost-effective when suitable supplies of natural gas are available. The C emission reductions can be significant when stand-alone coal-fired systems are replaced with natural gas fired combined heat and power systems (Burnham et al. 2012). A typical emission reduction is 420 kg CO_2 MWh^{-1} for the change from coal to natural gas in electric generation, which is about 50% emission reduction (de Gouw et al. 2014). This reduction is the result of the lower carbon content of natural gas (15.3 g C MJ^{-1} compared to, e.g., 26.2 g C MJ^{-1} for sub-bituminous coal). Even higher efficiency is achieved for the combined-cycle power plants. For example, if natural gas plant is coupled with the combined production of heat, cooling, and electric power, the reduction in emissions would be even greater (de Gouw et al. 2014). This makes a substantial contribution to emission reduction from particular plant but it is restricted to plants where supplies of lower C fuels sources are available.

8.3.3 Increased Use of Low or Near-Zero-Carbon Energy Sources

Switching to renewable energy (RE) sources or nuclear power could result into deep reduction in GHG emissions. Only a small fraction of the RE has been tapped so far, and most of RE has have low lifecycle GHG emissions compared to fossil fuels. The RE sources are capable of supplying electricity, but some sources are also able to supply thermal energy, mechanical energy, as well as production of fuels that can satisfy multiple energy service needs (Moomaw et al. 2011). While there is no single dominant RE technology that can dominate energy sector at the global level, bioenergy, wind and solar energy may experience the largest global incremental growth (Fischedick et al. 2011), and the mix of RE technologies are generally dependent on local conditions, with hydropower and geothermal playing significant role in some countries. Hydropower technology is technically and economically mature, while bioenergy technologies are diverse and span a wide range of development. Examples of mature technologies include conventional biomass-fueled power plants and heating systems as well as ethanol production from sugar and starch, while lignocellulose-based transport fuels are at pre-commercial stage. Solar energy (e.g., fuels produced from solar energy) ranges from research and technological development stage to more technically mature (e.g., combined solar power). However, even the technologies that are technically mature have not reached a state of economic competitiveness.

Other RE supplies which could become commercially available include wind, biomass, geothermal, and tidal wave power depending on geographical location. The installed wind power generation is currently contributing nearly 2.6% of global energy, and is projected to contribute up to 18% of global energy by 2050 (IEA 2015b). Many of the renewable sources could make significant contributions to electric generation, as well as transportation sectors, space heating or cooling, thereby displacing fossil fuels. Many of renewable sources face constraints of cost, intermittency of supply, land use competition, and other environmental factors.

Nuclear energy is utilized for electricity generation in 30 countries around the world (IAEA 2013). Nuclear electricity represented 11% of the global electricity share in 2012 with a total generation of 2346 TWh (IAEA 2013), which is down from 17% in 1993. The growing demand for electricity, energy diversification and climate change remains a major motivation for construction of new nuclear reactors. However, the extent to which nuclear power could be applied and the speed at which its use might be increased depends on the energy industry's ability to address concerns about costs, safety, long-term storage of nuclear wastes, nuclear proliferation, and terrorism. The role of nuclear power generation is therefore, more likely to be determined by the political process and public opinion rather than the technical factors.

8.3.4 Carbon Sequestration

The process of transfer atmospheric CO_2 that would otherwise remain in the atmosphere into other long-lived C pools so that it is securely stored, or otherwise securing C pool that would otherwise be emitted to the atmosphere as CO_2 is termed as C sequestration (Lal 2008). C sequestration can be biotic or abiotic process. Biotic is performed by living organisms including plants and some microorganisms which lead to atmospheric CO_2 removal by photosynthesis and storage in biomass and soil through various biological processes. Photosynthesis occurs naturally and involves terrestrial plants as well as phytoplankton in marine ecosystems. Management intervention of both higher plants and photosynthetic microorganisms in marine ecosystems can be imposed to enhance photosynthesis and storage of OC while minimizing respiration. Such interventions include increasing use efficiency of resources (e.g., water, nutrients). Abiotic sequestration involves engineering techniques and chemical reactions that transfer atmospheric CO_2 without intervention of living organisms—plants and microorganisms. The abiotic C sequestration has received considerable attention (IPCC 2005) because of larger sink capacity than biotic sequestration. The overall objective of human-driven C sequestration process is to balance the global C budget such that economic activities result into no net gain in atmospheric C pool. Such a strategy would necessitate sequestering nearly all CO_2 generated from anthropogenic activities through long-term storage, safe, and environmentally acceptable and stable techniques with minimum risk of leakage. Some biotic and abiotic sequestration options are briefly described below.

8.3.4.1 Biotic Sequestration

Land Use and Climate Mitigation

Land use has three primary roles in mitigation of climate change: (i) C storage in terrestrial ecosystems, both in biomass and soils (ii) mitigation of non-CO_2 GHGs, and (iii) bioenergy production for offsetting fossil fuels. Land also influences mitigation through biophysical factors, including albedo. Land use is an extensive driver of global climate change. For example, from 1950 to 2005, farmland—cropland and pasture increased from 28 to 38% of the global ice-free and inland waters land area (Hurtt et al. 2011). Land is also used for variety of other purposes such as urban and infrastructure. Currently, less than one quarter of global land area shows relatively minor signs of direct human use (Erb et al. 2007; Ellis et al. 2010). Changes in land use and management results into several factors that may impact mitigation both positively and negatively. The positive impacts include (i) the demand to store C in land by reducing deforestation, encouraging afforestation and reforestation, and altering soil management practices, (ii) reduction of non-CO_2 GHG emissions by changing land management practices in favor of those practices resulting into reduced CH_4 and N_2O emissions from agriculture and also livestock production, (iii) the demand for bioenergy.

Carbon Sequestration Through Enhancement of Natural Biological Sinks

Terrestrial C sequestration involves storage of C in vegetation, both aboveground and belowground biomass and in soils, a process generally termed as phytosequestration and soil C sequestration, respectively (Post et al. 2009). In terrestrial ecosystems, C storage mainly occurs by photosynthesis, followed by C formation of biomass in the form of live and dead OM which act as a major C sinks (Lal 2008). Natural terrestrial sinks play significant role in determining the concentration of CO_2 in the atmosphere. For example, only 40% of the anthropogenic CO_2 emitted remains in the atmosphere primarily owing to natural terrestrial and ocean C sinks which sequester atmospheric CO_2 and play an important role in the global C cycle. These sinks can also be enhanced to store more C from the atmosphere. Terrestrial C sequestration include scenarios increasing C storage in arable land soils (Chap. 10), forest soils and biomass (Chap. 11), and wetlands. The C storage capacity of soil is more than the storage capacity of both vegetation and atmosphere. Therefore, a small increase in soil C provides significant effects on overall C balance of the environment. Enhancing these sinks through changing agricultural and forestry management practices could significantly improve their C storage capacity, but this may be limited by land use practice, social, and environmental factors. In addition, the storage may not be permanent, and changes in land use or management practices may release the stored C back to the atmosphere.

Terrestrial plant production is the foundation of the biosphere C cycling. Water and atmospheric CO_2 are transformed into plant carbohydrate, and this plant matter then sustains the global food web and becomes source of food, fiber, and fuel for human. The net flux of carbon from the atmosphere into green plants per unit time is defined as the net primary productivity (NPP). The global NPP range from 59.2 to 65.5 Pg C yr^{-1} (Haberl et al. 2007; Tum et al. 2016), and for more than 30 years, the global NPP has stayed near 60.2 ± 1 Pg C yr^{-1} (Running 2012), suggesting equally small global variability of the key NPP drivers of photosynthesis such as global solar radiation and total global annual precipitation. Even though there are large regional variability within the Earth system, the final totals of energy and mass flows may even out. Based on recent estimates, humans are currently appropriating about 38% of NPP (Smith et al. 2012; Running 2012), leaving nearly 62% or approximately 36.5 Pg C yr^{-1} for future available exploitation. However, 53% of the global NPP is in non-harvestable form—including plant growth in root systems, preserved lands critical for ecosystem services and biodiversity, and wilderness areas where there are no transportation exists for harvesting. Therefore, there is clear limit to the global fraction of NPP available for further human exploitation—about 10% of NPP, equivalent to 5.4 Pg C yr^{-1} (Running 2012). Currently, agriculture is consuming 38% of the global surface land and the need to exploit larger fraction of land for biomass production for climate change mitigation places this goal in direct competition with agendas for food security and biodiversity conservation, all of which require increase quantities of biomass and land to meet their goal (Smith et al. 2013). In addition, the currently emerging bio-economy which is intending to replace many of the petroleum-based products by plant-based products will further increase the demands on biomass production—and if all the remaining 5.4 Pg C yr^{-1} of NPP were to be used for bioenergy, it will only satisfy 40% of the global primary energy consumption (Smith et al. 2012) without competing for arable lands currently under agriculture a real policy dilemma if previously allocated food production for human is transformed to bioenergy production (Tilman et al. 2009).

Significant amount of C is fixed in biomass, and their dead undecomposed or partially decomposed biomass remains in soils. The biological management of C for climate mitigation has two components: (i) reduction of emissions from biological systems, (ii) increase of C storage. These can be achieved in three ways: (a) protection of existing C from loss and reduction of the current high loss, (b) replenishing of the depleted storage by restoration of ecosystems and soils, and (c) creation of new storage by afforestation or reforestation of degraded lands. Biological approach to C management offers additional benefits of biodiversity as well as ranges of other benefits including soil C stabilization, as well as local climate amelioration and recycling of waste products. Improved management of the biological ecosystems can pay dividends in terms of water and nutrients availability and restoration of degraded lands, with positive impacts on livelihoods and help in poverty reduction (Lal 2007).

Utilization of wood biomass for construction to replace cement, or biomass for replacing of fossil fuels can minimize C footprint. However, this faces the limitation that a third of the terrestrial plant production is below-ground, which is not economically harvestable, and the other third occurs on difficult or remote terrain.

Thus, there is clear natural limit to the global fraction further available for human exploitation (Running 2012).

Environmental factors such as changing climate is also exacerbating the release of biologically stored C to the atmosphere. For example, Tundra region, with low temperatures for most of the year with prolonged season of snow cover is warming up. The active layer of soil near the surface tends to be water-logged in summer and frozen in winter. Rates of OM decomposition are low and large amount of dead plant materials accumulate in the soil (approximately 218 Mg C ha^{-1}) (Amundson 2001). Tundra plants allocate most of their biomass belowground, with an estimated aboveground biomass of 40 Mg ha^{-1} (Shaver et al. 1992). Below the active layer is perennially frozen permafrost with an estimated C storage of 1600 Pg, equivalent to nearly twice atmospheric pool (Schuur et al. 2008). Even relatively small warming of the tundra can result into thawing of the permafrost which could release as much as 40 Pg C into atmosphere within four years, enough to produce nearly 20 ppm increase in atmospheric CO_2 concentration (Schuur et al. 2008).

The main mitigation involving forest, agriculture, and other land uses involve one of four important strategies: (1) prevention of GHG emissions, (2) reduction of GHG emissions to the atmosphere by conserving existing C pools in soils or vegetation that would otherwise be lost, and (3) sequestration by enhancing the uptake of C in the terrestrial reservoirs and hence removing CO_2 from the atmosphere, and (4) reduction of CO_2 emissions by substituting biological products for fossil fuels or energy intensive products. In the following chapters, the deliberate C sequestration will be discussed. Because the goal of these activities is to mitigate the rise in atmospheric CO_2, the objective of this chapter is to examine them in the context of the global C cycle fluxes and reservoirs analyzed and discussed in previous section. The overall goal of the C sequestration activities is to mitigate the atmospheric CO_2 increase. Therefore, the examination of these activities in the overall context of the global C cycle, C reservoirs, and fluxes among the reservoirs and atmosphere is needed. Summarization of estimates of potential global sequestration capacities, and description of important uncertainties and limitations will also be outlined. This information is critical to determining whether deliberate C sequestration can effectively control the increase in atmospheric CO_2 concentration. For thousands of years the C cycle remained in balance, and the atmospheric CO_2 concentrations remained fairly constant until humans began rearranging C flows, first by burning trees and plowing the land, and later, more drastically by unearthing and combusting ancient fossilized C. The fossilized sunlight (Hughes 2009) invested in C stored millions of years ago is currently combusted into CO_2 at a rate of 10 Pg C yr^{-1} or more (Peters et al. 2013; Le Quéré et al. 2015). Some of this added CO_2 is absorbed by the ocean and on the land, but only about 60%, the rest, about 40% accumulates in the air, creating a concentration that is now surpassing 400 ppm, with the implications not only for climate (Lacis et al. 2010) but also for ocean chemistry (Dupont and Poertner 2013).

After the Industrial Revolution circa 1750, and especially the last 100 years or so, combustion of fossil fuels, land use change such as deforestation, cultivation of natural grasslands, and also changes in tillage practices and other factors have perturbed the balanced C cycle, resulting into increased atmospheric CO_2 concentration. There is a consensus that increasing concentrations of GHGs in the atmosphere, particularly CO_2 and CH_4 are contributing to global climate change (IPCC 2014). The atmospheric concentrations of CO_2 and CH_4 have increased from pre-industrial levels of 280 ppm and 722 ± 5 ppb respectively (Ciais et al. 2013) to current concentrations of 400 ± 0.1 ppm and 1845 ± 2 ppb, respectively (WMO 2016). Evidence indicates that the increase in atmospheric CO_2 concentrations are the result of expanded use of fossil fuels for energy production and transportation, land use conversion, and soil cultivation. The global total cumulative CO_2 emissions from burning of fossil fuels (coal, oil and natural gas), gas flaring and cement production from 1750 to 2015 amount to 410 Pg C (Ciais et al. 2013; Le Quéré et al. 2015, 2016). In addition, since 1750, anthropogenic land use changes have resulted into about 50 million km^2 been used for cropland and pasture, corresponding to about 38% of total ice-free land area (Foley et al. 2007, 2011) compared to estimated cropland and pasture area of 7.5–9 million km^2 in 1750 (Ramankutty and Foley 1999; Goldewijk 2001). Increase in atmospheric CH_4 concentration is attributed to anthropogenic activities including extraction and processing of fossil fuels, agriculture, and the positive feedback from the global warming. Predicted increased global fossil fuel energy use imply continued increase in C emissions (EIA 2015) and corresponding rise in CO_2 and CH_4 concentrations in the atmosphere unless a major changes are made in the way energy is produced and used, particularly how C is managed (Socolow et al. 2004).

Soil C sequestration can be achieved by enhancing concentration and pools of SOC and soil inorganic C (SIC) as a secondary carbonates through land use conversion and adoption of recommended management practices in agriculture and pasture grasslands (Chap. 10) and forest ecosystems (Chap. 11), restoration of degraded and drastically disturbed soils. Majority of atmospheric CO_2 captured by photosynthesis in terrestrial plants is converted to organic matter, some of it is translocated through plant roots into soil as root exudates. Dead plant biomass is also form add OC in soils where some of it is mineralized but some is retained as SOC (Jansson et al. 2010). The efficiency of soil C sequestration mainly depends on climate, temperature, rainfall, clay content, mineralogy, moisture content, and soil texture (Metting et al. 2001). Most soils under managed ecosystems contain a lower SOC pools than their counterparts under natural unmanaged ecosystems owing to depletion of the SOC as a result of imposed management. For example, conversion of forest or natural grasslands to arable land results into depletion of 25–30% of the original SOC pool within 20–50 years of conversion (Lal 2008). For enhanced SOC sequestration, proper management of ecosystems using various RMPs as well as advanced practices to decrease SOC mineralization and CO_2 emissions are considered essential (Metting et al. 2001). These include application of biochar, perennial crops, wood burial, farming C, and various plant products (Lal 2008; Nogia et al. 2016).

Bioenergy Production

Bioenergy is energy derived from biomass, which can be deployed as solid, liquid, and gaseous fuels for a wide range of uses, including transport, heating, electricity production, combined heat and power generation, and cooking (Chum et al. 2011). The deployment of large-scale bioenergy can cause both positive and negative effects, and their deployment needs to balance a range of environmental, social, and economic objectives that may not always be fully compatible (Creutzig et al. 2015). The consequences of large-scale implementation of bioenergy for climate change mitigation depend on the: (i) technology used, (ii) location, scales, and pace of implementation, (iii) land category used—forest, grassland, marginal lands, and croplands, and (iv) business model and practices adopted and how these integrate with or displace the existing land use. Bioenergy incentive can cause cropland expansion with increased forest and other lands conversion (Reilly et al. 2012; Rose et al. 2014). How much biomass for bioenergy is technically available in the future depends on evolution of social, political, and economic factors, including land tenure and regulation, diets, and technology. Detailed discussion on the role of bioenergy in climate change mitigation is discussed in Chap. 12.

Biological Carbon Sequestration in Ocean

Several biological processes lead to C sequestration in the ocean through photosynthesis. Phytoplankton photosynthesis is one of the mechanisms which fixes approximately 45 Pg C yr^{-1} (Falkowski et al. 2000). Some of particulate organic matter formed by phytoplankton is deposited at the ocean floor and hence sequestered. Nutrients limitation e.g., Fe is one of the limiting factors on phytoplankton growth in oceanic ecosystems. Several studies have demonstrated the importance of Fe fertilization in enhancing CO_2 uptake in ocean (Falkowski 1997; Boyd et al. 2000, 2007; Boyd and Ellwood 2010). However, the topic of ocean fertilization remains debatable due to unintended consequences especially on its impacts on ocean ecosystem biodiversity (Johnson and Karl 2002; Strong et al. 2009).

The world's oceans are the primary long-term sink for human-caused CO_2 emissions, currently accounting for a global net uptake of 2.9 Pg C annually. This uptake is not a result of deliberate sequestration, but occurs naturally through chemical reactions between seawater and CO_2 in the atmosphere. While absorbing atmospheric CO_2, these reactions cause the oceans to become more acidic. Many marine organisms and ecosystems depend on the formation of carbonate skeletons and sediments that are vulnerable to dissolution in acidic waters. Laboratory and field measurements indicate that CO_2-induced acidification may eventually cause the rate of dissolution of carbonate to exceed its rate of formation in these ecosystems. The impacts of ocean acidification and deliberate ocean fertilization on coastal and marine food webs and other resources are poorly understood. Scientists are studying the effects of oceanic C sequestration on these important environments.

Overall, the lack of permanence, high costs, and the impacts on the marine biodiversity has caused the abandonment of ocean CO_2 sequestration research.

8.3.4.2 Abiotic Sequestration

Carbon Capture and Storage (CCS)

This approach involves capturing CO_2 generated by fossil fuels combustion or released from industrial sources and then storing it away from the atmosphere for very long time. A complete end to end CCS system captures CO_2 from a large stationary point sources such as hydrocarbon-fueled power plants, refineries, cement production, and steel mills. The captured flue gas is purified to obtain nearly pure CO_2, compressed for volume reduction and then transported to the injection site where it is injected into suitable deep geologic structure—typically more than 800 m below the surface. The suite of measurements, monitoring, and verification technologies are applied during the injection and post-injection to ensure the safety, efficacy and permanence of the captured and stored CO_2 and its isolation from the atmosphere (IPCC 2005; Torvanger et al. 2013). Although the concept is straightforward, in practice it becomes more complicated. CCS requires the large-scale integration of technologies for CO_2 capture, purification, compression, transport and long-term storage sites and storage of CO_2 in geological formations where it is isolated from the atmosphere for long time. The potential storage sites include depleted oil and natural gas fields and deep saline formations. Captured CO_2 can also be used for enhanced oil and natural gas recovery, although there has been ongoing debate about the quantity of CO_2 remaining stored when used for enhanced oil and natural gas recovery, however. The potential contribution of CCS technology will be influenced by factors such as cost relative to other options, the time it will remain stored, the means of transport to storage sites, environmental risks, and acceptability of this approach to the societies. CCS requires additional energy compared to similar plant without CO_2 capture. It has been recognized that if CO_2 is captured from biomass energy such as ethanol processing facilities or electricity and heat generation from biomass coupled with CCS [i.e., biomass energy CO_2 capture and storage (BECCS)] it can yield net removal of CO_2 from the atmosphere (e.g., net negative CO_2 emissions) while also generating energy, because the captured CO_2 from the biomass is that which was absorbed from the atmosphere during plant growth (Mollersten et al. 2003; Selosse and Ricci 2014; Haro et al. 2015). In the future, CCS may also contribute significantly to emission reductions from transportation sector through H_2 generation and use for light and heavy-duty vehicles, electrification of vehicles, and production of synthetic fuels from captured CO_2. The CO_2 emission reduction based on fossil fuels requires existing CO_2 sources to have retrofits, rebuilds or new units replacements, all with CCS, otherwise a new point source adding CCS would only count as avoiding increasing emissions, unless it is based on biomass or replacing existing source without CCS.

The goal of CCS is to reduce emissions from large stationary sources such as power generation plants, natural gas processing, H_2 production, and industrial sources such as cement production or steel making. CCS can reduce the emission from fossil fuels by 65–85% when fully implemented to capture all CO_2 from power generation. The remaining 15–35% are the activities occurring beyond power plant boundary which cannot be controlled through CO_2 capture. However, in reality the optimal degree of emission reduction will depend on tradeoffs between the amount of emission reduction and cost of capture and the age of facility on which CCS is deployed.

While many governments as well as organizations in the international climate and energy domains have expressed the commitment to accelerating development and deployment of industrial-scale CCS projects, engineering advances and evolution of comparative cost will influence the pace, orientation, role, and ultimate scale of CCS deployment. While CCS is framed as a bridging technology among governments and industry, the technology is contested in the environmental movement (Verma et al. 2006; Greenpeace 2008; Anderson and Chiavari 2009). Among the reasons for skepticism expressed by environmental communities include the fear that CCS will divert political attention and financial investments from renewable energy and energy efficiency, high costs of deployment, its impacts on ground water and public safety, the infrastructure expansion, and whether the technology will offer a true CO_2 lock (Kirchsteiger 2008). In general, CCS is conceived by some as a technology fix for immediate problems with long-term negative consequences (Spreng et al. 2007). The expanding literature on public acceptance and stakeholder perception of CCS reflects an awareness of deep public skepticism toward CCS technology (Huijts et al. 2007; Shackley et al. 2009; Malone et al. 2010; Johnsson et al. 2010). Detailed analysis of CCS technology is presented in Chap. 13.

Direct Injection of CO_2 into the Ocean

Injection of pure stream of CO_2 stream in ocean has been widely considered by engineers for decades (Marchetti 1977). To be stable and minimize outgassing, CO_2 must be injected at great depths, however. Although the strategy seems promising, this storage technique is hurdled by the risk of affecting the marine biota present in the vicinity of injected CO_2. The location where CO_2 is injected becomes acidic in nature because of the reduction in pH by CO_2 which is toxic to marine biota in long run, and therefore, adversely affects deep sea biota (Auerbach et al. 1997). It is believed that if liquefied CO_2 is injected at $\sim$3000 m depth could be enough for stable injection of CO_2 in ocean. Some of the problems related to the ocean CO_2 injection are the function of temperature and pressure. In addition, the environmental impact remains the most essential and controversial problem of ocean CO_2 sequestration. Elevated atmospheric CO_2 impacts phytoplankton and coral reef organisms. The rate of calcification of corals macroalgae and phytoplankton decreases with increasing CO_2 concentration in ocean (Langdon et al. 2000). Lack of systematic study to evaluate the deep sea biology and CO_2 on organisms and ecosystem is currently lacking and therefore, currently there are no projects implementing CO_2 sequestration in sea.

Mineral Carbonation

Chemical sequestration involve chemical reactions that convert atmospheric CO_2 into modified and stable compound, one of which is chemical weathering of rocks by mineral carbonation, where rocks are sources of minerals (Maroto-Valer et al. 2005). In the process of mineral carbonation CO_2 reacts with various mineral metal oxides which are present in the form of rocks leading to formation of mineral carbonates (CO_3^{2-}) which remain stable in solid rocks and so CO_2 can be stored for longer period of time (Lal 2008). Mineral carbonation reactions occur naturally as well as through industrial processes, although efficiency of the process is too low at the industrial level to have significant impact on atmospheric CO_2.

8.4 Geoengineering Options for Climate Mitigation

The ideas of climate modification have a long history (Schneider 1996, 2001; Fleming 2006). The term 'geoengineering' of climate can be traced back to Marchetti (1977) who proposed the injection of CO_2 into sinking thermohaline ocean currents to reduce the atmospheric CO_2 burden and climate change. Since its introduction, the term has evolved considerably to encompass a broad ranges of ill-defined variety of approaches that aim to intentionally alter the Earth's climate system at a large-scale (Keith 2000). The US National Academy of Science report on global warming published in 1992 included a chapter on 'geoengineering', which was defined as large-scale engineering of the environment in order to combat or counteract the effects of changes in atmospheric chemistry (NAS 1992). However, the term and the ideas it entails has not been part of mainstream climate change mitigation discussion until recently when Crutzen (2006) drew attention of the scientific and policy makers to geoengineering concepts by suggesting albedo enhancement by stratospheric sulfur injection. Since then, geoengineering concepts have grown rapidly due to increased concern about the current pace of mitigation and the projected effects of climate change. Several assessments have been conducted at national level (Royal Society 2009; Rickels et al. 2011; GAO 2011) and international level (IPCC 2012) to establish scientific basis of the techniques.

Geoengineering, also called climate engineering has been defined as a broad set of methods and technologies that aim to deliberately alter the climate system in order to diminish impacts of climate change (Keith 2000; Izrael et al. 2009; Royal Society 2009). It is a large-scale manipulation of the planetary environment to counteract anthropogenic climate change. The scale and the intent are of the central importance in geoengineering approaches to climate alteration. Whereas mitigation refers to the activities that reduce anthropogenic GHGs emission, geoengineering intervention techniques aim to mediate the effects of elevated atmospheric GHGs concentration (Keith 2000), although the distinction is not mutually exclusive, as the following discussion shows. Geoengineering is different from weather modification and ecological engineering, even though the distinction may not be clear. Over time, geoengineering emphasis has shifted from broad range of approaches to the techniques specifically directed to large scale modification of climate, generally termed as climate engineering, and in some cases these two terms have been used interchangeably (Boucher et al. 2014). Geoengineering can be divided based on the location where the interventions are carried out into: (a) land-based geoengineering, (b) ocean-based geoengineering, (c) atmosphere-based geoengineering, and (d) space-based geoengineering. The Royal Society categorizes geoengineering of the climate into two broad classes based on methodologies employed, namely: (i) solar radiation management, and (ii) the GHGs removal, particularly CO_2 to intentionally reduce the atmospheric concentrations (Royal Society 2009). Table 8.1 outlines the major differences between solar radiation management and CO_2 removal techniques. Geoengineering is a new field of research and there are relatively very few research studies focused on these approaches. Therefore, the potential role as a viable component of climate change abatement policy is yet to be determined. However, the call for research into these technologies have increased in

Table 8.1 An overview of major differences between CO_2 removal and solar radiation management proposals

CO_2 removal	Solar radiation management
• Addresses the cause of human-induced climate change, i.e., high GHG concentrations	• Do not address the cause of human induced climate change (GHGs concentrations remains unchanged)
• It does not introduce novel global risks	• Introduces novel global risks
• Currently the techniques are expensive or comparable to costs of emission reduction	• Most techniques are less expensive to deploy relative to costs of emissions reduction
• May produce only modest climate effects within decades	• Can produce substantial climate effects within years of deployment
• They raise fewer and less difficult issue with respect to global governance	• Raises difficult issues with respect to both moral and global governance
• Can be judged largely on questions of related costs of deployment	• Will be judged largely on questions related to risks
• May be implemented incrementally with limited effects as society becomes more serious about reducing GHG concentrations or slowing the GHGs concentrations growth	• Could be implemented suddenly with large scale impacts, possibly both negative and positive, even before enough research is available to understand the risks relative to inaction.
• Requires cooperation by major CO_2 emitters to have significant effect	• Could be implemented unilaterally without cooperation of major CO_2 emitters
• Abrupt termination will have limited consequences	• Abrupt termination would produce significant consequences

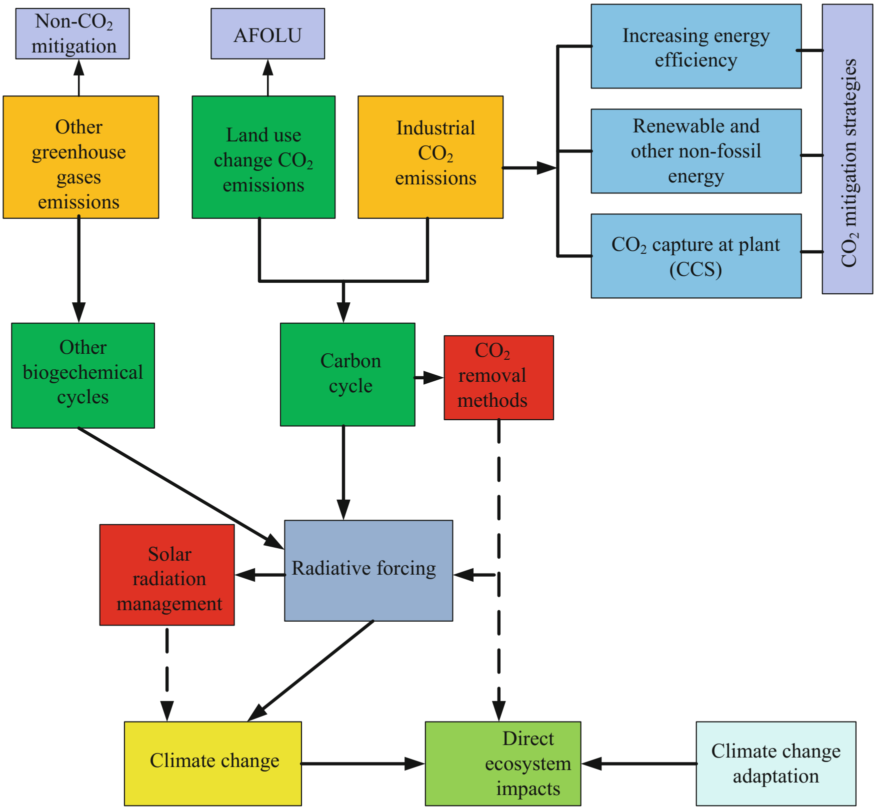

Fig. 8.3 Diagram illustrating proposed climate engineering (geoengineering) and its relationship to CO_2 mitigation methods and climate change adaptation. Adapted with modification from (IPCC 2012)

recent years (Caldeira and Keith 2010; Caldeira et al. 2013), mainly due to concerns that the pace of mitigation efforts are proving wholly ineffectual in containment of the projected effects of climate change at the global-scale due to the post 2000 trends in anthropogenic CO_2 emissions (Crutzen 2006; Canadell et al. 2007b; Cusack et al. 2014). Geoengineering approaches and their relationship with CO_2 mitigation climate change adaptation approaches are illustrated in Fig. 8.3.

In the general scientific discussions, geoengineering options have been framed in number of ways (i) as the last resort in case of climate emergence option to avoid global catastrophe (Caldeira and Keith 2010; McCusker et al. 2012), (ii) as a way of buying time for implementing conventional mitigation approaches (MacCracken 2009), and (iii) affordable fast-acting climate emergence (Caldeira and Keith 2010; Caldeira et al. 2013). Overall, most assessments agree that the geoengineering/ climate engineering should not be treated as a replacement for the conventional mitigation and adaptation due to high costs involved for some techniques, and the potential risks or pervasive uncertainties involved in almost all the techniques (Royal Society 2009; Rickels et al. 2011). Two key characteristics of geoengineering methods of a particular concern are that they use or affect the climate system—atmosphere, land, or ocean—globally or regionally, and could have substantive effects that cross national boundaries. Some scientists have also argued that geoengineering could become a distraction from urgently needed implementation of mitigation measures (Preston 2013; Lin 2013).

8.4.1 Solar Radiation Management

The term SRM refers to proposed techniques aiming at intentional modification of the Earth's shortwave radiative budget with the aim of countering warming associated with increasing GHGs concentration (Keith 2000; Boucher et al. 2013). This can be achieved by reducing the amount of solar energy absorbed at the surface through increased reflection of shortwave radiation from the sun within the atmosphere or at the surface (Keith 2000). The SRM methods aim to offset global warming by reducing the incidence and absorption of incoming solar (shortwave) radiation—often referred to as insolation without reducing the atmospheric concentration of GHGs. Overall, reducing incoming solar radiation does not ameliorate ocean acidification or other negative effects associated with the increasing CO_2 concentration. In addition, successful planetary cooling would be expected to increase ocean CO_2 uptake, and therefore, amplify ocean acidification. To balance the global mean radiative forcing of +4 $W\ m^{-2}$ that would arise from a doubling of CO_2 concentration the solar management method would therefore, need to provide similar reduction in absorbed solar radiation. The solar radiation management techniques proposed include (i) placing sunshades in space—to reflect a fraction of incoming solar radiation away before it enters the Earth system or injection of stratospheric aerosols (Crutzen 2006), (ii) cloud brightening (Latham 1990), (iii) stratospheric aerosol injection, (iv) tropospheric aerosols injection, (v) settlement and crop brightening, (vi) marine cloud brightening through increased water droplet concentration, (vii) enhanced cloud albedo, and (viii) outer space reflectors (Cusack et al. 2014; Baatz et al. 2016). This list is not exhaustive, and new proposals for new solar radiation management may be put forward in the future.

Assessment of solar management methods is generally limited by (i) gaps in understanding of some important processes, (ii) a scarcity of studies evaluating their effectiveness, and (iii) scarcity of experiments using some similar designs to allow for comparison and some recommendations. Although solar radiation management geoengineering could potentially reduce the global mean surface temperature, no solar radiation management technique could fully return climate to pre-industrial or low CO_2 like climate state (Tilmes et al. 2013; Kravitz et al. 2013). In addition to its effect on planet climate, many solar radiation methods could result into serious non-climatic side effects. For example, in addition to its effects on O_3, stratospheric aerosol geoengineering would scatter light and modify optical properties of the atmosphere. The potential harmful effects of increasing atmospheric CO_2 was acknowledged as early as 1965, and suggested that bright materials spread over the oceans could solve the problem (Keith 2000). Crutzen (2006) argued that global temperature rise could be limited by injecting sulfate into the stratosphere, where it will form aerosol and reflect a fraction of the incoming solar radiation back to space, similar to phenomenon observed after large volcanic eruptions.

8.4.1.1 General Assessment of Proposed Solar Radiation Management Methods

Solar radiation management methods provide easily described mechanisms for reducing sunlight reaching the planet and they are motivation for the idealized studies based on the observed short-term cooling effect which has been observed after strong volcanic eruptions (Crutzen 2006; Sekiya et al. 2016). However, because most of known aerosols artificially injected into the stratosphere will sediment out roughly within a year or less, the aerosols requires frequent replenishment to maintain a given level of RF (Rasch et al. 2008; Kravitz et al. 2012). For example, sulfate aerosols in the stratosphere have a lifetime of ~ 3 years, and the effect of this geoengineering method is reversed on a ~ 3 year timescale (Vaughan and Lenton 2011). Modeling studies indicate that injection of sulfate aerosol precursors of at least 0.1 Pg S—approximately the amount of sulfur injected by the Mt Pinatubo eruption in 1991, which decreased temperature by nearly 0.5 °C for short period is needed annually to maintain $-4\ \mathrm{W\ m^{-2}}$ RF (Pierce et al. 2010; Niemeier et al. 2011). Moreover, along with potential to mitigate some aspects of global warming, many of solar radiation modification methods involving aerosols change will also increase chemical ozone loss at high latitudes and delay recovery of the Arctic ozone hole, while also increasing ultraviolet (UV) radiation reaching the surface (Table 8.2; Tilmes et al. 2012). This will also damage marine and terrestrial ecosystems. Economic and engineering consideration for the implementation is beyond the scope of this review, since little comprehensive work has been published in literature.

8.4.1.2 Technical Potential

All solar radiation management techniques require research and development before they can be implemented (GAO 2011), and also continued maintenance for long-term effectiveness. Space-based reflectors present high management challenges, while ground-based whitening solutions are limited to small areas that could be brightened. Marine cloud brightening present technological challenges for continuous suspension of water droplets. The only other technically feasible option is stratospheric aerosols. However, technical questions remains about appropriate particle size, duration of recharge, cost effectiveness, health and ecological risks, and public acceptance.

Table 8.2 Characteristics of some of proposed solar radiation management and related methods

Method	Maximum achievable radiative forcing Wm^{-1}	Risk	References
Stratospheric aerosols	Unlimited	Ozone depletion Regional drought Reduce electric generation from solar power	Bewick et al. (2012), Robock et al. (2009)
Tropospheric aerosols		Serious negative impact on human health	Vaughan and Lenton (2011)
Space-based or Earth orbit reflectors	Unlimited	Slowing of the hydrological cycle with up to 2% decrease in global mean precipitation which can be more pronounced in the tropics	Angel (2006), Vaughan and Lenton (2011)
Enhanced cloud albedo	−4		Vaughan and Lenton (2011)
Enhanced surface albedo – Grassland albedo – Crop albedo – Human settlement albedo – Deserts albedo	−4.2		Vaughan and Lenton (2011), Bala and Nag (2012), Linner and Wibeck (2015)

8.4.2 *Carbon Dioxide Removal Methods*

Carbon dioxide removal methods aim at removing CO_2 from the atmosphere by deliberately modifying the carbon cycle processes, or by industrial chemical approaches. CO_2 removal methods leads to net removal of CO_2 from the atmosphere while CCS only decreases the rate at which CO_2 is added to at best zero. The C withdrawn from the atmosphere can then be stored in land, ocean, or in geological reservoirs. Some of the proposed techniques involve biological processes of enhancing natural C sinks, such as large-scale afforestation and/or reforestation, C sequestration in soils through biochar, biomass energy production coupled with carbon capture and storage, and other techniques for engineering new C sinks through industrial chemical approaches. Other proposed methods involve ocean—such as ocean fertilization and alkalinity addition to the ocean. Other proposed CO_2removal processes involve geological processes such as accelerated weathering of silicate and carbonate rocks on the land or in the ocean and direct capture of CO_2 (Vaughan and Lenton 2011). Some of the CO_2 removal methods

Table 8.3 Major CO_2 removal methods, their characteristics, and potential impacts

CO_2 removal method	Cumulative potential in a century	Limitations	References
Afforestation/reforestation	40–70 Pg C	Irreversible land changes from deforestation or past land uses Decreased biodiversity Competition for the land for agricultural production	Canadell and Raupach (2008)
Accelerated weathering on land	100 Pg C	Likely increase in pH of soils and rivers Effects on terrestrial/freshwater ecosystems	Kohler et al. (2010)
Increased weathering in ocean	No determined limit	Increased alkalinity effects on marine ecosystems	Rau (2008)
Ocean fertilization	280 Pg C	Likely to cause changes to regional ocean C cycle opposing CO_2 removal Environmental consequences and potential co-benefits	Caldeira et al. (2013)
Bioenergy with CO_2 capture and storage (BECCS)	125 Pg C	Land requirement Actual amount of land available for bioenergy production is likely significantly less	Kemper (2015)
Direct air capture	No determined limit	Not known	Keith et al. (2006)
Biochar creation	130 Pg C	Alteration of surface energy budget Localized surface warming or cooling Change in hydrological cycle	Woolf et al. (2010)
Enhanced upwelling to bring more nutrient to surface waters of oceans	1–2 Pg C	Causes changes to regional ocean C cycle opposing to CO_2 removal	Lenton and Vaughan (2009)

(Table 8.3) include: (i) bioenergy with carbon capture and storage (BECCS), (ii) biochar production and application in soils, (iii) ocean fertilization by adding limiting nutrients to surface waters, (iv) land based increased weathering by application of ground silicates to soils, (v) ocean-based increased weathering, (vi) direct air capture, and (vii) large-scale afforestation and reforestation, among others. Some methods that fall under CO_2 removal are also regarded as mitigation measures. Sometimes, the term “negative emission technologies” is used as an alternative to CO_2 removal methods (McGlashan et al. 2012; Tavoni and Socolow 2013; Tokarska and Zickfeld 2015), which can also be grouped into industrial technologies versus ecosystem manipulation. However, these categorizations do not capture all geoengineering options which have been proposed, and various studies have compiled and evaluated different schemes (Vaughan and Lenton 2011; Keith 2000; Boyd 2008; Feichter and Leisner 2009; Boucher et al. 2014; Zhang et al. 2015). Overall, all CO_2 removal methods have similar slow impact on the rate of warming as mitigation measures. Permanence of the stored CO_2 in the C reservoir is the major key towards the consideration for the efficacy of any CO_2 removal methods. In addition, the effect of many of the CO_2 removal techniques will decrease over time, due to response of land and ocean C reservoirs to ongoing atmospheric perturbations associated with continuation of anthropogenic GHG emissions. In the long-term, the only way to return atmospheric CO_2 concentration to pre-industrial levels is to permanently store an amount of CO_2 equivalent to the total emission to the atmosphere into crust, sediments, ocean, and terrestrial biosphere in some form of combination.

8.4.2.1 Land Carbon Sink Enhancement

Overall, more C was stored on the land in the pre-agriculture and pre-industrial state than today (Prentice et al. 2011). Therefore, there is clearly some potential to enhance the land carbon sink by increasing land C storage, with the majority of C storage potential in soils (Batjes 1996). The estimated long-term potential for increasing conventional vegetation and soil C storage is estimated to be ~ 190 Pg C by assuming the reversal of all cumulative land-use change emissions to date (Le Quéré et al. 2015, 2016), which is equivalent to a long-term radiative forcing of $\sim -0.24\ \mathrm{W\ m^{-2}}$ (Lenton and Vaughan 2009). Among the proposed land C sink enhancement are large-scale afforestation and reforestation, biochar production and application to soils, and BECCS. However, the general concern is that a large-scale afforestation and reforestation for increase in C storage on the land most likely would conflict with food production requirements to feed the increasing global population, unless sustainable intensification of existing agricultural lands can increase productivity and reduce the land area appropriated to food production (Lal 2016).

The conversion of land from non-forested to forested land is termed afforestation if the land has been without trees for >50 years, or reforestation if trees were lost in the last 50 years, and is currently considered as one of the mitigation options, although afforestation and reforestation have been included as geoengineering method due to the potential for negative CO_2 emissions. The large-scale afforestation tends to decrease the local land surface albedo and increase the adjacent regional surface air temperatures. This kind of albedo change may result in more warming than if no large-scale afforestation or reforestation was implemented (Keller et al. 2014). In some locations, this can outweigh the radiative forcing effect of enhanced C storage (Betts 2000). Forest cover also tends to enhance cloud cover and reflectivity through increasing evapotranspiration. Generally, in the tropics afforestation exerts a net cooling, while in the temperate regions the net effect is a marginal cooling and in high latitudes with seasonal snow cover afforestation is counterproductive (Bala et al. 2007).

Biochar is produced by the pyrolysis of the biomass (i.e., combustion of biomass in the absence of O_2). It can be produced as a byproduct of bioenergy production (Lehmann et al. 2006). When applied into the soils, biochar acts as a recalcitrant C reservoir and it can be used to increase land C sink. The long-term global storage potential for croplands and grasslands has been estimated at 224 and 175 Pg C, respectively, with a potential radiative forcing offset of ~ -0.52 W m^{-2} (Vaughan and Lenton 2011; Lenton and Vaughan 2009). However, the process of producing biochar involve additional energy penalty which brings additional CO_2 emissions. The more extensive bioenergy to replace fossil fuels results in C neutral energy production, and if CO_2 is captured and stored through geological sequestration, the process becomes C-negative. Therefore, BECCS amounts to creating a new C sink on land with potential economic benefits compared to CCS. BECCS can be applied to a variety of biofuel production pathways based on biomass, including forestry products, sugar cane, switchgrass, miscanthus, ethanol production from food products followed by capture and storage of the CO_2 produced in the fermentation process and in combustion at the power stations. Scientists have also suggested decreasing the amount of CO_2 emitted from a corn-based ethanol biofuel through the cultivation of microalgae (Rosenberg et al. 2011).

8.4.2.2 Bioengineering

The bioengineering approach involves engineering climate because of the albedo differences between plants (Ridgwell et al. 2009) or land cover type. In agriculture, crop plants have higher albedo than natural vegetation. Also different varieties of the same crops could have different albedo. The bioengineering could involve a change in variety of crops grown, which may not affect food production. Modeling assessment of impact of crop albedo bioengineering showed that increasing crop canopy albedo by 0.04, representing a potential increase of 20%, produces the cooling as large as 1 °C during summer time in Europe with greater cooling in South East Asia (Singarayer et al. 2009). The relatively low implementation costs of crop albedo bioengineering makes it potentially attractive compared to other geoengineering proposals (Ridgwell et al. 2009).

8.4.2.3 Accelerating Chemical Weathering on the Land

Silicate rocks are the most common rocks on Earth, and their weathering reduces atmospheric CO_2 concentration and also governs atmosphere—soil CO_2 uptake over geological timescales. Geoengineering proposal for artificially increasing weathering of silicate minerals include decomposing river chemistry into rock weathering products (Schulte et al. 2011).

8.4.2.4 Ocean Carbon Sink Enhancement

Oceans covers 70% of the Earth's surface and contains approximately 50 times more C in the surface layers than the atmosphere. Therefore, ocean-based geoengineering have large potential for CO_2 removal. Overall, the natural pre-industrial state of C cycle had an excess of C in the deep ocean relative to surface and atmosphere. The solubility pump where surface waters move from low to high latitudes, cooling, and absorbing CO_2 before sinking to depth has been responsible for maintaining the disequilibrium. The exchange of C between surface oceans and atmosphere is estimated to be 90 Pg C yr^{-1} for the 2010s (Ciais et al. 2013; Le Quéré et al. 2015, 2016), and the net annual effect of oceans is currently a C sink of 3.0 ± 0.5 Pg C yr^{-1} (Le Quéré et al. 2015, 2016). The present ocean C sink is driven by an anthropogenic excess of CO_2 in the air relative to the sea. The majority of the extra CO_2 entering the surface ocean is transported to depth by the solubility pump. The proposed climate geoengineering processes in the ocean attempts to enhance the elements of existing ocean sink. These include: (i) enhancing the solubility pump, and (ii) enhancing biological pump. The effectiveness of these techniques depends on successful transport of C to depth. The return timescale of C that is remineralized at different depths in the ocean is generally dictated by the movement of water masses and it can range from weeks to millennia. Detailed understanding of where remineralization is occurring within water column and the specific dynamics of water masses downstream of the targeted region is also required.

The proposed methods for enhancing the solubility pump focuses on increasing the absorption of CO_2 in the surface waters by increasing the sinking CO_2-rich waters or manipulating surface water chemistry (Zhou and Flynn 2005; Harvey 2008; Zhang et al. 2015). These include: (i) increasing downwelling, and (ii) increasing ocean alkalinity. Increasing downwelling can be achieved by cooling surface waters. However, the combination of high costs and uncertainty of the effectiveness limit this approach (Zhou and Flynn 2005). The alkalinity of the oceans can be increased through the addition of carbonate minerals (Harvey 2008). This engineered pH lowering technique exploits the ocean C chemistry, and will allow more anthropogenic CO_2 to be absorbed. The use of $CaCO_3$ which is found in abundance in the form of limestones, but can be processed to more soluble form into lime (CaO) has been advocated (Kheshgi 1995). However, mining substantial volumes of limestone can have a localized environmental impacts on mined land area. Also taking into consideration the energy costs of mining and processing limestone together with land and marine transportation will outweigh the benefits of this engineering process (Harvey 2008).

The proposed geoengineering for enhancing the biological pump involve enhancing export production by either directly adding limiting nutrients to the ocean surface (Lampitt et al. 2008) or by mechanically enhancing upwelling of nutrient-rich water from below (Karl and Letelier 2008). Specific proposals include: (i) iron fertilization (Jin et al. 2008), (ii) macronutrient fertilization, and (iii) enhancing upwelling (Lampitt et al. 2008; Caldeira et al. 2013). Several iron fertilization experiments have been conducted, majority in the Southern Ocean (Boyd et al. 2007; Lampitt et al. 2008). Based on experimental data and modeling, it is estimated that, on millennial timescale, the extra C that could be stored in the deep ocean through alleviating iron limitation range from 106 to 227 Pg C (Aumont and Bopp 2006). It has also been suggested that there is deficit of available N relative to P in the world ocean of an average 2.7 μmol kg^{-1} (Anderson and Sarmiento 1994), and removing the N deficit would result in a ~9% increase in export flux (Vaughan and Lenton 2011). However, plans to do macronutrients fertilization have been met with strong concern, resulting in memorandum issued by the United Nations Convention on Biodiversity that called for large-scale fertilization attempts to be prohibited. Overall, enhancing the biological C pump is a limited short-term climate engineering because the total export production from the surface layers of the global oceans is low, ~10 Pg C yr^{-1} and cannot be greatly increased (Vaughan and Lenton 2011). Therefore, enhancing primary production in the surface layer of the ocean does not directly translate into an equivalent long-term sink of CO_2, since most of the C fixed in the surface layer of ocean are recycled within the surface waters and degassed back to the atmosphere.

8.4.2.5 Direct Air Carbon Dioxide Capture and Storage

Direct air CO_2 capture refers to the chemical process by which a pure CO_2 stream is produced by capturing CO_2 from ambient air. The captured CO_2 could be sequestered in geological reservoirs or in deep ocean. Three methods have been proposed to capture CO_2 from the atmosphere: (i) adsorption on solids (Lackner et al. 2012), (ii) absorption into highly alkaline solution (Keith 2009; Mahmoudkhani and Keith 2009), and absorption into moderate alkaline solution with catalyst (Bao and Trachtenberg 2006) Using chemical engineering methods, CO_2 can be removed from the atmosphere using sorbent materials such as NaOH which selectively traps CO_2 (Keith et al. 2006). The sorbent can then be regenerated and reused. Direct air CO_2 capture is generally limited by thermodynamic barrier due to low concentration of CO_2 in ambient air.

8.5 Conclusions

The Earth has entered a period in which climate is changing more rapidly than ever experienced in recorded human history, primarily caused by rapid increase in atmospheric GHGs concentrations. As a result, global surface temperature is projected to rise over the 21st century under all assessed emission scenarios. Other changes include longer and more frequent heat waves, more intense extreme precipitation events, warmer and acidified oceans, and global sea level rise. The two main options for responding to risks of climate change involves mitigation, i.e., reducing and eventually eliminating human-caused emissions of CO_2 and other

GHGs, and adaptation i.e., reducing the vulnerability of human and natural ecosystems to changes in climate. Mitigation would require substantial reduction of anthropogenic GHGs to near zero over the next few decades. Implementing such reductions poses substantial technological, economic, social, and institutional challenges, and these challenges increases with delayed implementation of mitigation strategies. Some of the mitigation strategies discussed in the next chapters are decabonization of energy supply, reduction of net GHGs emission, enhancing biological C sinks in land based sectors and CO_2 capture and sequestration. A third potentially viable option been considered by scientific community involves climate engineering techniques generally referred to as geoengineering. Scientific discussion on research on geoengineering has currently become more acceptable than few years ago, and Intergovernmental Panel on Climate Change in their fifth assessment (IPCC AR5) devoted several sections on geoengineering of the climate, mostly due to lack political will to implement serious mitigation, living the geoengineering of climate as available choices to avoid catastrophic abrupt climate change. Overall, the general public seems to be opposed to SRM and some of CDR schemes research at present, mostly due to the fears of risks associated with unintended consequences, which may have impacts on human health, ecosystems, and biodiversity. Current geoengineering assessments have mostly focused on physical science aspects, while assessments on law, governance, economics ethics, and social policy of geoengineering is limited. Also, despite various assessments of their potential, geoengineering ideas are still far from deployment-ready. The drawbacks of SRM geoengineering methods remain large, and not easy to overcome, even though the SRM methods can act rapidly to mitigate the global temperature rise. Unwanted side-effects such as diminished rainfall in some regions which could occur alongside the intended effects, among others may limit scientific research on SRM. Importantly, once started, SRM geoengineering must be maintained for very long period, otherwise, when it is terminated, climate reverts rapidly to maintain global energy balance. Therefore, evaluating potential effectiveness, risks, and climate feedbacks of different geoengineering methods become important for governing large-scale field experiments.

References

Allen MR, Frame DJ, Huntingford C, Jones CD, Lowe JA, Meinshausen M, Meinshausen N (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458(7242):1163–1166. doi:10.1038/nature08019

Amundson R (2001) The carbon budget in soils. Annu Rev Earth Pl Sci 29(1):535–562. doi:10.1146/annurev.earth.29.1.535

Anderson K, Bows A (2011) Beyond 'dangerous' climate change: emission scenarios for a new world. Philos T R Soc A 369(1934):20–44. doi:10.1098/rsta.2010.0290

Anderson J, Chiavari J (2009) Understanding and improving NGO position on CCS. Energ Procedia 1(1):4811–4817. doi:10.1016/j.egypro.2009.02.308

Anderson LA, Sarmiento JL (1994) Redfield ratios of remineralization determined by nutrient data analysis. Glob Biogeochem Cy 8(1):65–80. doi:10.1029/93gb03318

Angel R (2006) Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). Proc Natl Acad Sci USA 103(46):17184–17189. doi:10.1073/pnas.0608163103

Auerbach DI, Caulfield JA, Adams EE, Herzog HJ (1997) Impacts of ocean CO_2 disposal on marine life: I. A toxicological assessment integrating constant-concentration laboratory assay data with variable-concentration field exposure. Environ Model Assess 2(4):333–343

Aumont O, Bopp L (2006) Globalizing results from ocean in situ iron fertilization studies. Glob Biogeochem Cy 20 (2). doi:10.1029/2005gb002591

Baatz C, Heyward C, Stelzer H (2016) The ethics of engineering the climate. Environ Value 25 (1):1–5. doi:10.3197/096327115x14497392134766

Bala G, Nag B (2012) Albedo enhancement over land to counteract global warming: impacts on hydrological cycle. Clim Dynam 39(6):1527–1542. doi:10.1007/s00382-011-1256-1

Bala G, Caldeira K, Wickett M, Phillips TJ, Lobell DB, Delire C, Mirin A (2007) Combined climate and carbon-cycle effects of large-scale deforestation (vol 104, pg 6550. Proc Natl Acad Sci USA 104(23):9911. doi:10.1073/pnas.0704096104

Bao LH, Trachtenberg MC (2006) Facilitated transport of CO_2 across a liquid membrane: comparing enzyme, amine, and alkaline. J Membr Sci 280(1–2):330–334. doi:10.1016/j.memsci.2006.01.036

Batjes NH (1996) Total carbon and nitrogen in the soils of the world. Eur J Soil Sci 47(2):151–163. doi:10.1111/j.1365-2389.1996.tb01386.x

Betts RA (2000) Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. Nature 408(6809):187–190. doi:10.1038/35041545

Bewick R, Sanchez JP, McInnes CR (2012) Gravitationally bound geoengineering dust shade at the inner Lagrange point. Adv Space Res 50(10):1405–1410. doi:10.1016/j.asr.2012.07.008

Blodgett J, Parker L (2010) Greenhouse gas emission drivers: population, economic development and growth, and energy use. Congressional Research Service, United States Congress Washington, DC

Boucher O, Randall D, Artaxo P, Bretherton C, Feingold G, Forster P, Kerminen V-M, Kondo Y, Liao H, Lohmann U, Rasch P, Satheesh SK, Sherwood S, Stevens B, Zhang XY (2013) Clouds and Aerosols. In: Stocker TF, Qin D, Plattner G-K et al (eds) Climate change 2013: the physical science basis. contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 571–657

Boucher O, Forster PM, Gruber N, Ha-Duong M, Lawrence MG, Lenton TM, Maas A, Vaughan NE (2014) Rethinking climate engineering categorization in the context of climate change mitigation and adaptation. Wiley Interdiscip Rev Clim Change 5(1):23–35. doi:10.1002/wcc.261

Boyd P, Ellwood M (2010) The biogeochemical cycle of iron in the ocean. Nat Geosci 3(10):675–682

Boyd PW (2008) Ranking geo-engineering schemes. Nat Geosci 1(11):722–724. doi:10.1038/ngeo348

Boyd PW, Watson AJ, Law CS, Abraham ER, Trull T, Murdoch R, Bakker DC, Bowie AR, Buesseler K, Chang H (2000) A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. Nature 407(6805):695–702

Boyd PW, Jickells T, Law CS, Blain S, Boyle EA, Buesseler KO, Coale KH, Cullen JJ, de Baar HJW, Follows M, Harvey M, Lancelot C, Levasseur M, Owens NPJ, Pollard R, Rivkin RB, Sarmiento J, Schoemann V, Smetacek V, Takeda S, Tsuda A, Turner S, Watson AJ (2007) Mesoscale iron enrichment experiments 1993–2005: synthesis and future directions. Science 315(5812):612–617. doi:10.1126/science.1131669

Bruckner T, Bashmakov IA, Mulugetta Y, Chum H, Navarro AdlV, Edmonds J, Faaij A, Fungtammasan B, Garg A, Hertwich E, Honnery D, Infield D, Kainuma M, Khennas S, Kim S, Nimir HB, Riahi K, Strachan N, Wiser R, Zhang X (2014) Energy systems In: Edenhofer O, Pichs-Madruga R, Sokona Y et al (eds) Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 511–597

Burnham A, Han J, Clark CE, Wang M, Dunn JB, Palou-Rivera I (2012) Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. Environ Sci Technol 46(2):619–627. doi:10.1021/es201942m

Caldeira K, Keith DW (2010) The need for climate engineering research. Issues Sci Technol 27(1): 57–62

Caldeira K, Bala G, Cao L (2013) The science of geoengineering. In: Jeanloz R (ed) Annual review of earth and planetary sciences, vol 41, pp 231–256. doi:10.1146/annurev-earth-042711-105548

Canadell JG, Raupach MR (2008) Managing forests for climate change mitigation. Science 320 (5882):1456–1457. doi:10.1126/science.1155458

Canadell JG, Schulze ED (2014) Global potential of biospheric carbon management for climate mitigation. Nat Comm 5. doi:10.1038/ncomms6282

Canadell J, Pataki D, Gifford R, Houghton R, Luo Y, Raupach M, Smith P, Steffen W (2007a) Saturation of the terrestrial carbon sink. In: Canadell J, Pataki D, Pitelka L (eds) Terrestrial ecosystems in a changing world. Global Change—The IGBP Series. Springer, Berlin pp 59–78. doi:10.1007/978-3-540-32730-1_6

Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G (2007b) Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc Natl Acad Sci USA 104(47):18866–18870. doi:10.1073/pnas.0702737104

Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, Gabrielle B, Eng AG, Lucht W, Mapako M, Cerutti OM, McIntyre T, Minowa T, Pingoud K (2011) Bioenergy. In: Edenhofer O, Pichs-Madruga R, Sokona Y et al (eds) IPCC special report on renewable energy sources and climate change mitigation. Cambridge University Press, Cambridge

Ciais P, Sabine CL, Govindasamy B, Bopp L, Brovkin V, Canadell J, Chhabra A, DeFries R, Galloway J, Heimann M, Jones C, Le Quéré C, Myeneni R, Piao S, Thornton P (2013) Carbon and other boigeochemical cycles. In: Stocker TF, Qin D, Plattner G-K et al (eds) Climate change 2013: pysical science basis. contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 465–570

Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, Fisher-Vanden K, Hourcade J-C, Krey V, Kriegler E, A. Löschel, McCollum D, Paltsev S, Rose S, Shukla PR, Tavoni M, Zwaan BCCvd, Vuuren DPv (2014) Assessing transformation pathways. In: Edenhofer O, Pichs-Madruga R, Sokona Y et al (eds) Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 413–510

Creutzig F, Ravindranath NH, Berndes G, Bolwig S, Bright R, Cherubini F, Chum H, Corbera E, Delucchi M, Faaij A, Fargione J, Haberl H, Heath G, Lucon O, Plevin R, Popp A, Robledo-Abad C, Rose S, Smith P, Stromman A, Suh S, Masera O (2015) Bioenergy and climate change mitigation: an assessment. GCB Bioenergy 7(5):916–944. doi:10.1111/gcbb.12205

Crutzen PJ (2006) Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? Clim Change 77(3–4):211–219. doi:10.1007/s10584-006-9101-y

Cusack DF, Axsen J, Shwom R, Hartzell-Nichols L, White S, Mackey KRM (2014) An interdisciplinary assessment of climate engineering strategies. Front Ecol Environ 12(5):280–287. doi:10.1890/130030

de Gouw JA, Parrish DD, Frost GJ, Trainer M (2014) Reduced emissions of CO_2, NO_x, and SO_2 from US power plants owing to switch from coal to natural gas with combined cycle technology. Earths Future 2(2):75–82. doi:10.1002/2013ef000196

Dupont S, Poertner H (2013) Marine science: get ready for ocean acidification. Nature 498 (7455):429

EIA (2015) International energy outlook 2015. US Department of Energy. http://www.eia.doe.gov/oiaf/ieo/pdf. Accessed Sept 2015

Ellis EC, Goldewijk KK, Siebert S, Lightman D, Ramankutty N (2010) Anthropogenic transformation of the biomes, 1700 to 2000. Glob Ecol Biogeogr 19(5):589–606. doi:10.1111/j.1466-8238.2010.00540.x

Erb K-H, Gaube V, Krausmann F, Plutzar C, Bondeau A, Haberl H (2007) A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. J Land Use Sci 2(3):191–224. doi:10.1080/17474230701622981

Falkowski PG (1997) Evolution of the nitrogen cycle and its influence on the biological sequestration of CO_2 in the ocean. Nature 387(6630):272–275. doi:10.1038/387272a0

Falkowski P, Scholes RJ, Boyle E, Canadell J, Canfield D, Elser J, Gruber N, Hibbard K, Hogberg P, Linder S, Mackenzie FT, Moore B, Pedersen T, Rosenthal Y, Seitzinger S, Smetacek V, Steffen W (2000) The global carbon cycle: a test of our knowledge of earth as a system. Science 290(5490):291–296. doi:10.1126/science.290.5490.291

Feichter J, Leisner T (2009) Climate engineering: a critical review of approaches to modify the global energy balance. Euro Phys J Spec Top 176:81–92. doi:10.1140/epjst/e2009-01149-8

Feng K, Davis SJ, Sun L, Hubacek K (2015) Drivers of the US CO_2 emissions 1997–2013. Nat Comm 6. doi:10.1038/ncomms8714

Fischedick M, Schaeffer R, Adedoyin A, Akai M, Bruckner T, Clarke L, Krey V, Savolainen I, Teske S, Ürge-Vorsatz D, Wright R (2011) Mitigation potential and costs In: Edenhofer O, Pichs-Madruga R, Sokona Y et al (eds) IPCC special report on renewable energy sources and climate change mitigation. Prepared by working group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 791–864

Fleming JR (2006) The pathological history of weather and climate modification: three cycles of promise and hype. Hist Stud PhysBiol 37:3–25. doi:10.1525/hsps.2006.37.1.3

Foley JA, Monfreda C, Ramankutty N, Zaks D (2007) Our share of the planetary pie. Proc Natl Acad Sci USA 104(31):12585–12586. doi:10.1073/pnas.0705190104

Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O/'Connell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockstrom J, Sheehan J, Siebert S, Tilman D, Zaks DPM (2011) Solutions for a cultivated planet. Nature 478(7369):337–342. doi:10.1038/nature10452

GAO (2011) Climate engineering: technical status, future directions, and potential responses. United States Government Accountability Office (US GAO), Center for Science, Technology, and Engineering, Report No. GAO-11–71, Washington, DC, 135 p

Goldewijk KK (2001) Estimating global land use change over the past 300 years: the HYDE Database. Glob Biogeochem Cy 15(2):417–433. doi:10.1029/1999gb001232

Greenpeace (2008) False hope: why carbon capture and storage won't save the climate. Greenpeace International, Amsterdam, 42 p

Haberl H, Erb KH, Krausmann F, Gaube V, Bondeau A, Plutzar C, Gingrich S, Lucht W, Fischer-Kowalski M (2007) Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proc Natl Acad Sci USA 104(31):12942–12945. doi:10.1073/pnas.0704243104

Haro P, Aracil C, Vidal-Barrero F, Ollero P (2015) Rewarding of extra-avoided GHG emissions in thermochemical biorefineries incorporating Bio-CCS. Appl Energy 157:255–266. doi:10.1016/j.apenergy.2015.08.020

Harvey LDD (2008) Mitigating the atmospheric CO_2 increase and ocean acidification by adding limestone powder to upwelling regions. J Geophys Res-Oceans 113 (C4). doi:10.1029/2007jc004373

Hertwich EG, Peters GP (2009) Carbon footprint of nations: a global. Trade-linked analysis. Environ Sci Technol 43(16):6414–6420. doi:10.1021/es803496a

Hughes JD (2009) The energy issue: a more urgent problem than climate change? In: Homer-Dixon TI (ed) Carbon shift: how the twin crises of depletion oil and climate change will define the future. Random House of Canada, Toronto, pp 58–95

Huijts NMA, Midden CJH, Meijnders AL (2007) Social acceptance of carbon dioxide storage. Energy Policy 35(5):2780–2789. doi:10.1016/j.enpol.2006.12.007

Hurtt GC, Chini LP, Frolking S, Betts RA, Feddema J, Fischer G, Fisk JP, Hibbard K, Houghton RA, Janetos A, Jones CD, Kindermann G, Kinoshita T, Goldewijk KK, Riahi K, Shevliakova E, Smith S, Stehfest E, Thomson A, Thornton P, van Vuuren DP, Wang YP (2011) Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Clim Change 109(1–2):117–161. doi:10.1007/s10584-011-0153-2

IAEA (2013) The power reactor information system (PRIS) and its extension to non-electrical applications. Decommissioning and delayed projects information. International Atomic Energy Agency, Vienna, p 112

IEA (2014) The way foward: five key actions to achieve a low-carbon energy sector. International Energy Agency (IEA), Paris, p 8

IEA (2015a) CO_2 emissions from fossil fuel combustion. International Energy Agency (IEA) statistics. International Energy Agency, Paris

IEA (2015b) Tracking clean energy progress 2015: energy technology perspectives 2015 excerpt iea input to the clean energy ministerial. International Energy Agency (IEA), Paris, p 98

IPCC (2005) IPCC special report on carbon dioxide capture and storage. Cambridge University Press, Cambridge

IPCC (2012) Meeting report of the Intergovernmental Panel on Climate Change expert meeting on geoengineering. IPCC Potsdam Institute for Climate Impact Research, Potsdam, p 99

IPCC (2014) Climate change 2014: synthesis report. contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change. In: Pachauri RK, Meyer L, Team CW (eds) Intergovernmental Panel on Climate Change, Geneva, p 151

Izrael YA, Ryaboshapko AG, Petrov NN (2009) Comparative analysis of geo-engineering approaches to climate stabilization. Russ Meteorol Hydrol 34(6):335–347. doi:10.3103/s1068373909060016

Jansson C, Wullschleger SD, Kalluri UC, Tuskan GA (2010) Phytosequestration: carbon biosequestration by plants and the prospects of genetic engineering. Bioscience 60(9):685–696. doi:10.1525/bio.2010.60.9.6

Jin X, Gruber N, Frenzel H, Doney SC, McWilliams JC (2008) The impact on atmospheric CO_2 of iron fertilization induced changes in the ocean's biological pump. BioGeosciences 5(2):385–406

Johnson KS, Karl DM (2002) Is ocean fertilization credible and creditable? Science 296 (5567):467–468

Johnsson F, Reiner D, Itaoka K, Herzog H (2010) Stakeholder attitudes on carbon capture and storage—an international comparison. Int J Greenh Gas Con 4(2):410–418. doi:10.1016/j.ijggc.2009.09.006

Karl DM, Letelier RM (2008) Nitrogen fixation-enhanced carbon sequestration in low nitrate, low chlorophyll seascapes. Mar Ecol Prog Ser 364:257–268. doi:10.3354/meps07547

Karmellos M, Kopidou D, Diakoulaki D (2016) A decomposition analysis of the driving factors of CO2 (carbon dioxide) emissions from the power sector in the European Union countries. Energy 94:680–692. doi:10.1016/j.energy.2015.10.145

Karstensen J, Peters GP, Andrew RM (2015) Allocation of global temperature change to consumers. Clim Change 129(1–2):43–55. doi:10.1007/s10584-015-1333-2

Kaya Y (1990) Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios. Paper presented to the IPCC Energy and In-dustry Subgroup, Response Strategies Working Group. Paris, France (Mimeo)

Kaya Y (1995) The role of CO_2 removal and disposal. Energ Convert Manage 36(6–9):375–380. doi:10.1016/0196-8904(95)00025-9

Keith DW (2000) Geoengineering the climate: history and prospect. Annu Rev Energy 25: 245–284. doi:10.1146/annurev.energy.25.1.245

Keith DW (2009) Why capture CO_2 from the atmosphere? Science 325(5948):1654–1655. doi:10.1126/science.1175680

Keith DW, Ha-Duong M, Stolaroff JK (2006) Climate strategy with CO_2 capture from the air. Clim Change 74(1–3):17–45. doi:10.1007/s10584-005-9026-x

Keller DP, Feng EY, Oschlies A (2014) Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. Nat Comm 5. doi:10.1038/ncomms4304

Kemper J (2015) Biomass and carbon dioxide capture and storage: a review. Int J Greenh Gas Con 40:401–430. doi:10.1016/j.ijggc.2015.06.012

Kheshgi HS (1995) Sequestering atmospheric carbon dioxide by using increasing ocean alkalinity. Energy 20(9):915–922. doi:10.1016/0360-5442(95)00035-f

Kirchsteiger C (2008) Carbon capture and storage-desirability from a risk management point of view. Safety Sci 46(7):1149–1154. doi:10.1016/j.ssci.2007.06.012

Kohler P, Hartmann J, Wolf-Gladrow DA (2010) Geoengineering potential of artificially enhanced silicate weathering of olivine. Proc Natl Acad Sci USA 107(47):20228–20233. doi:10.1073/pnas.1000545107

Kravitz B, Robock A, Shindell DT, Miller MA (2012) Sensitivity of stratospheric geoengineering with black carbon to aerosol size and altitude of injection. J Geophys Res-Atmos 117. doi:10.1029/2011jd017341

Kravitz B, Robock A, Forster PM, Haywood JM, Lawrence MG, Schmidt H (2013) An overview of the Geoengineering Model Intercomparison Project (GeoMIP). J Geophys Res-Atmos 118 (23):13103–13107. doi:10.1002/2013jd020569

Krey V (2014) Global energy-climate scenarios and models: a review. WIREs Clim Change 3 (4):363–383. doi:10.1002/wene.98

Lacis AA, Schmidt GA, Rind D, Ruedy RA (2010) Atmospheric CO_2: principal control knob governing earth’s temperature. Science 330(6002):356–359. doi:10.1126/science.1190653

Lackner KS, Brennan S, Matter JM, Park AHA, Wright A, van der Zwaan B (2012) The urgency of the development of CO2 capture from ambient air. Proc Natl Acad Sci USA 109(33):13156–13162. doi:10.1073/pnas.1108765109

Lal R (2007) Soil science and the carbon civilization. Soil Sci Soc Am J 71(5):1425–1437. doi:10.2136/sssaj2007.0001

Lal R (2008) Carbon sequestration. Philos T R Soc B 363(1492):815–830. doi:10.1098/rstb.2007.2185

Lal R (2016) Beyond COP21: potential and challenges of the “4 per Thousand” initiative. J Soil Water Conserv 71(1):20A–25A. doi:10.2489/jswc.71.1.20A

Lampitt RS, Achterberg EP, Anderson TR, Hughes JA, Iglesias-Rodriguez MD, Kelly-Gerreyn BA, Lucas M, Popova EE, Sanders R, Shepherd JG, Smythe-Wright D, Yool A (2008) Ocean fertilization: a potential means of geoengineering? Philos T R Soc A 366(1882):3919–3945. doi:10.1098/rsta.2008.0139

Langdon C, Takahashi T, Sweeney C, Chipman D, Goddard J, Marubini F, Aceves H, Barnett H, Atkinson MJ (2000) Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. Glob Biogeochem Cy 14(2):639–654. doi:10.1029/1999gb001195

Larson ED, Li Z, Williams RH (2012) Fossil Energy. In: Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L (eds) Global energy assessment: toward a sustainable future. Cambridge University Press, International Institute for Applied Systems Analysis, Cambridge, Laxenburg, pp 901–992

Latham J (1990) Control of global warming? Nature 347(6291):339–340

Le Quéré C, Moriarty R, Andrew RM, Canadell JG, Sitch S, Korsbakken JI, Friedlingstein P, Peters GP, Andres RJ, Boden TA, Houghton RA, House JI, Keeling RF, Tans P, Arneth A, Bakker DCE, Barbero L, Bopp L, Chang J, Chevallier F, Chini LP, Ciais P, Fader M, Feely RA, Gkritzalis T, Harris I, Hauck J, Ilyina T, Jain AK, Kato E, Kitidis V, Goldewijk KK, Koven C, Landschuetzer P, Lauvset SK, Lefevre N, Lenton A, Lima ID, Metzl N, Millero F, Munro DR, Murata A, Nabel JEMS, Nakaoka S, Nojiri Y, O’Brien K, Olsen A, Ono T, Perez FF, Pfeil B, Pierrot D, Poulter B, Rehder G, Roedenbeck C, Saito S, Schuster U, Schwinger J, Seferian R, Steinhoff T, Stocker BD, Sutton AJ, Takahashi T, Tilbrook B, van der Laan-Luijkx IT, van der Werf GR, van Heuven S, Vandemark D, Viovy N, Wiltshire A, Zaehle S, Zeng N (2015) Global carbon budget 2015. Earth Sys Data 7(2):349–396. doi:10.5194/essd-7-349-2015

Le Quéré C, Andrew RM, Canadell JG, Sitch S, Korsbakken JI, Peters GP, Manning AC, Boden TA, Tans PP, Houghton RA, Keeling RF, Alin S, Andrews OD, Anthoni P, Barbero L, Bopp L, Chevallier F, Chini LP, Ciais P, Currie K, Delire C, Doney SC, Friedlingstein P, Gkritzalis T, Harris I, Hauck J, Haverd V, Hoppema M, Klein Goldewijk K, Jain AK, Kato E, Körtzinger A, Landschützer P, Lefèvre N, Lenton A, Lienert S, Lombardozzi D, Melton JR, Metzl N, Millero F, Monteiro PMS, Munro DR, Nabel JEMS, Nakaoka SI, O'Brien K, Olsen A, Omar AM, Ono T, Pierrot D, Poulter B, Rödenbeck C, Salisbury J, Schuster U, Schwinger J, Séférian R, Skjelvan I, Stocker BD, Sutton AJ, Takahashi T, Tian H, Tilbrook B, van der Laan-Luijkx IT, van der Werf GR, Viovy N, Walker AP, Wiltshire AJ, Zaehle S (2016) Global carbon budget 2016. Earth Sys Data 8(2):605–649. doi:10.5194/essd-8-605-2016

Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems: a review. Mitig Adapt Strat Glob Change 11(2):395–419. doi:10.1007/s11027-005-9006-5

Lenton TM, Vaughan NE (2009) The radiative forcing potential of different climate geoengineering options. Atmos Chem Phys 9(15):5539–5561. doi:10.5194/acp-9-5539-2009

Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ (2008) Tipping elements in the Earth's climate system. Proc Natl Acad Sci USA 105(6):1786–1793. doi:10.1073/pnas.0705414105

Lin AC (2013) Does geoengineering present a moral hazard? Ecol Law Quart 40(3):673–712

Linner B-O, Wibeck V (2015) Dual high-stake emerging technologies: a review of the climate engineering research literature. Wiley Interdiscip Rev Clim Change 6(2):255–268. doi:10.1002/wcc.333

MacCracken MC (2009) On the possible use of geoengineering to moderate specific climate change impacts. Environ Res Lett 4(4). doi:10.1088/1748-9326/4/4/045107

Mahmoudkhani M, Keith DW (2009) Low-energy sodium hydroxide recovery for CO_2 capture from atmospheric air-Thermodynamic analysis. Int J Greenh Gas Con 3(4):376–384. doi:10.1016/j.ijggc.2009.02.003

Malla S (2009) CO_2 emissions from electricity generation in seven Asia-Pacific and North American countries: a decomposition analysis. Energy Policy 37(1):1–9. doi:10.1016/j.enpol.2008.08.010

Malone EL, Dooley JJ, Bradbury JA (2010) Moving from misinformation derived from public attitude surveys on carbon dioxide capture and storage towards realistic stakeholder involvement. Int J Greenh Gas Con 4(2):419–425. doi:10.1016/j.ijggc.2009.09.004

Marchetti C (1977) On geoengineering and the CO_2 problem. Clim Change 1(1):59–68. doi:10.1007/BF00162777

Maroto-Valer MM, Fauth DJ, Kuchta ME, Zhang Y, Andresen JM (2005) Activation of magnesium rich minerals as carbonation feedstock materials for CO_2 sequestration. Fuel Process Technol 86(14–15):1627–1645. doi:10.1016/j.fuproc.2005.01.017

Matthews HD, Caldeira K (2008) Stabilizing climate requires near-zero emissions. Geophys Res Lett 35(4). doi:10.1029/2007gl032388

McCarl BA, Sands RD (2007) Competitiveness of terrestrial greenhouse gas offsets: are they a bridge to the future? Clim Change 80(1–2):109–126. doi:10.1007/s10584-006-9168-5

McCusker KE, Battisti DS, Bitz CM (2012) The climate response to stratospheric sulfate injections and implications for addressing climate emergencies. J Climate 25(9):3096–3116. doi:10.1175/jcli-d-11-00183.1

McGlashan N, Shah N, Caldecott B, Workman M (2012) High-level techno-economic assessment of negative emissions technologies. Process Saf Environ Prot 90(6):501–510. doi:10.1016/j.psep.2012.10.004

Metting FB, Smith JL, Amthor JS, Izaurralde RC (2001) Science needs and new technology for increasing soil carbon sequestration. Clim Change 51(1):11–34. doi:10.1023/a:1017509224801

Mollersten K, Yan JY, Moreira JR (2003) Potential market niches for biomass energy with CO_2 capture and storage—opportunities for energy supply with negative CO_2 emissions. Biomass Bioenerg 25(3):273–285. doi:10.1016/s0961-9534(03)00013-8

Moomaw W, Ramakrishna K, Gallagher K, Fried T (1999) The Kyoto Protocol: a blueprint for sustainable development. J Environ Dev 8(1):82–90

Moomaw W, Yamba F, Kamimoto M, Maurice L, Nyboer J, Urama K, Weir T (2011) Renewable energy and climate change. In: Edenhofer O, Pichs-Madruga R, Sokona Y et al (eds) IPCC Special report on renewable energy sources and climate change mitigation. Prepared by working group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 161–207

Nansai K, Kagawa S, Suh S, Fujii M, Inaba R, Hashimoto S (2009) Material and energy dependence of services and its implications for climate change. Environ Sci Technol 43 (12):4241–4246. doi:10.1021/es8025775

NAS (1992) Policy implications of greenhouse warming: mitigation, adaptation, and the science base. National Academy Press, Washington, DC

Negra NB, Todorovic J, Ackermann T (2006) Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms. Electr Pow Syst Res 76(11):916–927. doi:10.1016/j.epsr.2005.11.004

Niemeier U, Schmidt H, Timmreck C (2011) The dependency of geoengineered sulfate aerosol on the emission strategy. Atmos Sci Lett 12(2):189–194. doi:10.1002/asl.304

Nogia P, Sidhu GK, Mehrotra R, Mehrotra S (2016) Capturing atmospheric carbon: biological and nonbiological methods. Int J Low Carbon Technol 11(2):266–274. doi:10.1093/ijlct/ctt077

O'Neill BC, Dalton M, Fuchs R, Jiang L, Pachauri S, Zigova K (2010) Global demographic trends and future carbon emissions. Proc Natl Acad Sci USA 107(41):17521–17526. doi:10.1073/pnas.1004581107

Peters GP, Hertwich EG (2008) CO_2 embodied in international trade with implications for global climate policy. Environ Sci Technol 42(5):1401–1407. doi:10.1021/es072023k

Peters GP, Andrew RM, Boden T, Canadell JG, Ciais P, Le Quéré C, Marland G, Raupach MR, Wilson C (2013) Commentary: the challenge to keep global warming below 2 degrees C. Nature Clim Change 3(1):4–6

Pierce JR, Weisenstein DK, Heckendorn P, Peter T, Keith DW (2010) Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft. Geophys Res Lett 37. doi:10.1029/2010gl043975

Post WM, Amonette JE, Birdsey R, Garten CT, Jr., Izaurralde RC, Jardine PM, Jastrow J, Lal R, Marland G, McCarl BA, Thomson AM, West TO, Wullschleger SD, Metting FB (2009) Terrestrial biological carbon sequestration: science for enhancement and implementation. In: McPherson BJ, Sundquist ET (eds) Carbon sequestration and its role in the global carbon cycle, vol 183. Geophysical Monograph Series. American Geophysical Union, Washington, DC, pp 73–88. doi:10.1029/2008gm000753

Prentice IC, Harrison SP, Bartlein PJ (2011) Global vegetation and terrestrial carbon cycle changes after the last ice age. New Phytool 189(4):988–998. doi:10.1111/j.1469-8137.2010.03620.x

Preston CJ (2013) Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal. Wiley Interdiscip Rev Clim Change 4(1):23–37. doi:10.1002/wcc.198

Ramankutty N, Foley JA (1999) Estimating historical changes in global land cover: croplands from 1700 to 1992. Glob Biogeochem Cy 13(4):997–1027. doi:10.1029/1999GB900046

Rasch PJ, Tilmes S, Turco RP, Robock A, Oman L, Chen C-C, Stenchikov GL, Garcia RR (2008) An overview of geoengineering of climate using stratospheric sulphate aerosols. Philos T R Soc A 366(1882):4007–4037. doi:10.1098/rsta.2008.0131

Rau GH (2008) Electrochemical splitting of calcium carbonate to increase solution alkalinity: implications for mitigation of carbon dioxide and ocean acidity. Environ Sci Technol 42 (23):8935–8940. doi:10.1021/es800366q

Raupach MR, Marland G, Ciais P, Le Quéré C, Canadell JG, Klepper G, Field CB (2007) Global and regional drivers of accelerating CO_2 emissions. Proc Natl Acad Sci USA 104(24):10288–10293. doi:10.1073/pnas.0700609104

Reilly J, Melillo J, Cai Y, Kicklighter D, Gurgel A, Paltsev S, Cronin T, Sokolov A, Schlosser A (2012) Using land to mitigate climate change: hitting the target, recognizing the trade-offs. Environ Sci Technol 46(11):5672–5679. doi:10.1021/es2034729

Rickels W, Klepper G, Dovern J, Betz G, Brachatzek N, Cacean S, Güssow K, J. H, Hiller S, Hoose C, Leisner T, Oschlies A, Platt U, Proelß A, Renn O, Schäfer SMZ (2011) Large-scale intentional interventions into the climate system? Assessing the climate engineering debate. Scoping report conducted on behalf of the German Federal Ministry of Education and Research (BMBF). Kiel Earth Institute, Kiel, 170 p

Ridgwell A, Singarayer JS, Hetherington AM, Valdes PJ (2009) Tackling regional climate change by leaf albedo Bio-geoengineering. Curr Biol 19(2):146–150. doi:10.1016/j.cub.2008.12.025

Robock A, Marquardt A, Kravitz B, Stenchikov G (2009) Benefits, risks, and costs of stratospheric geoengineering. Geophys Res Lett 36. doi:10.1029/2009gl039209

Rogelj J, Schaeffer M, Meinshausen M, Knutti R, Alcamo J, Riahi K, Hare W (2015) Zero emission targets as long-term global goals for climate protection. Environ Res Lett 10 (10):105007. doi:10.1088/1748-9326/10/10/105007

Rose SK, Kriegler E, Bibas R, Calvin K, Popp A, van Vuuren DP, Weyant J (2014) Bioenergy in energy transformation and climate management. Clim Change 123(3–4):477–493. doi:10.1007/s10584-013-0965-3

Rosenberg JN, Mathias A, Korth K, Betenbaugh MJ, Oyler GA (2011) Microalgal biomass production and carbon dioxide sequestration from an integrated ethanol biorefinery in Iowa: a technical appraisal and economic feasibility evaluation. Biomass Bioenerg 35(9):3865–3876. doi:10.1016/j.biombioe.2011.05.014

Royal Society (2009) Geoengineering the climate: science, governance and uncertainty. The Royal Society, Report 10/09 London, 82 p

Running SW (2012) A measurable planetary boundary for the biosphere. Science 337 (6101):1458–1459. doi:10.1126/science.1227620

Schneider SH (1996) Geoengineering: could or should we do it? Clim Change 33(3):291–302. doi:10.1007/bf00142577

Schneider SH (2001) Earth systems engineering and management. Nature 409(6818):417–421. doi:10.1038/35053203

Schneider SH, Semenov S, Patwardhan A, Burton I, Magadza CHD, Oppenheimer M, Pittock AB, Rahman A, Smith JB, Suarez A, Yamin F (2007) Assessing key vulnerabilities and the risk from climate change. Climate change 2007. In: Parry ML, Canziani OF, Palutikof JP, Linden PJvd, Hanson CE (eds) Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 779–810

Schulte P, van Geldern R, Freitag H, Karim A, Negrel P, Petelet-Giraud E, Probst A, Probst J-L, Telmer K, Veizer J, Barth JAC (2011) Applications of stable water and carbon isotopes in watershed research: weathering, carbon cycling, and water balances. Earth Sci Rev 109(1–2):20–31. doi:10.1016/j.earscirev.2011.07.003

Schuur EAG, Bockheim J, Canadell JG, Euskirchen E, Field CB, Goryachkin SV, Hagemann S, Kuhry P, Lafleur PM, Lee H, Mazhitova G, Nelson FE, Rinke A, Romanovsky VE, Shiklomanov N, Tarnocai C, Venevsky S, Vogel JG, Zimov SA (2008) Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. Bioscience 58 (8):701–714. doi:10.1641/b580807

Sekiya T, Sudo K, Nagai T (2016) Evolution of stratospheric sulfate aerosol from the 1991 Pinatubo eruption: roles of aerosol microphysical processes. J Geophys Res-Atmos 121 (6):2911–2938. doi:10.1002/2015jd024313

Selosse S, Ricci O (2014) Achieving negative emissions with BECCS (bioenergy with carbon capture and storage) in the power sector: new insights from the TIAM-FR (TIMES Integrated Assessment Model France) model. Energy 76:967–975. doi:10.1016/j.energy.2014.09.014

Shackley S, Reiner D, Upham P, de Coninck H, Sigurthorsson G, Anderson J (2009) The acceptability of CO_2 capture and storage (CCS) in Europe: an assessment of the key determining factors Part 2. The social acceptability of CCS and the wider impacts and repercussions of its implementation. Int J Greenh Gas Con 3(3):344–356. doi:10.1016/j.ijggc.2008.09.004

Shaver GR, Billings WD, Chapin FS, Giblin AE, Nadelhoffer KJ, Oechel WC, Rastetter EB (1992) Global change and the carbon balance of Arctic ecosystems. Bioscience 42(6):433–441. doi:10.2307/1311862

Singarayer JS, Ridgwell A, Irvine P (2009) Assessing the benefits of crop albedo bio-geoengineering. Environ Res Lett 4(4). doi:10.1088/1748-9326/4/4/045110

Smith WK, Zhao M, Running SW (2012) Global bioenergy capacity as constrained by observed biospheric productivity rates. Bioscience 62(10):911–922. doi:10.1525/bio.2012.62.10.11

Smith P, Haberl H, Popp A, K-h Erb, Lauk C, Harper R, Tubiello FN, de Siqueira Pinto A, Jafari M, Sohi S, Masera O, Boettcher H, Berndes G, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, Mbow C, Ravindranath NH, Rice CW, Abad CR, Romanovskaya A, Sperling F, Herrero M, House JI, Rose S (2013) How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob Chang Biol 19(8):2285–2302. doi:10.1111/gcb.12160

Socolow R, Hotinski R, Greenblatt JB, Pacala S (2004) Solving the climate problem: technologies available to curb CO_2 emissions. Environment 46(10):8–19

Spreng D, Marland G, Weinberg AM (2007) CO_2 capture and storage: another Faustian Bargain? Energy Policy 35(2):850–854. doi:10.1016/j.enpol.2006.10.009

Steckel JC, Jakob M, Marschinski R, Luderer G (2011) From carbonization to decarbonization?-Past trends and future scenarios for China's CO2 emissions. Energy Policy 39(6):3443–3455. doi:10.1016/j.enpol.2011.03.042

Strong AL, Cullen JJ, Chisholm SP (2009) Ocean fertilization: science, policy, and commerce

Tavoni M, Socolow R (2013) Modeling meets science and technology: an introduction to a special issue on negative emissions. Clim Change 118(1):1–14. doi:10.1007/s10584-013-0757-9

Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, Pacala S, Reilly J, Searchinger T, Somerville C, Williams R (2009) Beneficial biofuels: the food, energy, and environment trilemma. Science 325(5938):270–271. doi:10.1126/science.1177970

Tilmes S, Kinnison DE, Garcia RR, Salawitch R, Canty T, Lee-Taylor J, Madronich S, Chance K (2012) Impact of very short-lived halogens on stratospheric ozone abundance and UV radiation in a geo-engineered atmosphere. Atmos Chem Phys 12(22):10945–10955. doi:10.5194/acp-12-10945-2012

Tilmes S, Fasullo J, Lamarque J-F, Marsh DR, Mills M, Alterskjaer K, Muri H, Kristjansson JE, Boucher O, Schulz M, Cole JNS, Curry CL, Jones A, Haywood J, Irvine PJ, Ji D, Moore JC, Karam DB, Kravitz B, Rasch PJ, Singh B, Yoon J-H, Niemeier U, Schmidt H, Robock A, Yang S, Watanabe S (2013) The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). J Geophys Res-Atmos 118(19):11036–11058. doi:10.1002/jgrd.50868

Tokarska KB, Zickfeld K (2015) The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. Environ Res Lett 10(9). doi:10.1088/1748-9326/10/9/094013

Torvanger A, Lund MT, Rive N (2013) Carbon capture and storage deployment rates: needs and feasibility. Mitig Adapt Strat Glob Change 18(2):187–205. doi:10.1007/s11027-012-9357-7

Tum M, Zeidler JN, Gunther KP, Esch T (2016) Global NPP and straw bioenergy trends for 2000–2014. Biomass Bioenerg 90:230–236. doi:10.1016/j.biombioe.2016.03.040

UNFCCC (2009) Copenhagen Accord conference of the parties, fifteenth session, Copenhagen, 7–18 Dec 2009. United Nations Framework on Climate Change Conference (UNFCCC), UNFCCC/CP/2009/L.7 Copenhagen, Denmark

UNFCCC (2010) Report of the conference of the parties. United Nations Framework Convention on Climate Change (UNFCCC), FCCC/CP/2010/7/Add.1 Cancun, Mexico, 31 p

Vaughan NE, Lenton TM (2011) A review of climate geoengineering proposals. Clim Change 109 (3–4):745–790. doi:10.1007/s10584-011-0027-7

Verma P, Stephens JC, IEEE (2006) Environmental advocacy groups' perspectives on carbon capture and storage. In: 2006 IEEE EIC climate change conference, vols 1 and 2, pp 51–55

WMO (2016) World Meteorological Organization (WMO) greenhouse gas bulletin: the state of greenhouse gases in the atmosphere based on global observation through 2015. Bulletin No. 12. World Meteorological Organization (WMO), Global Atmosphere Watch (GAW), Geneva, Switzerland, 8 p

Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. Nat Comm 1. doi:10.1038/ncomms1053

Zhang Z, Moore JC, Huisingh D, Zhao Y (2015) Review of geoengineering approaches to mitigating climate change. J Cleaner Prod 103:898–907. doi:10.1016/j.jclepro.2014.09.076

Zhou S, Flynn PC (2005) Geoengineering downwelling ocean currents: a cost assessment. Clim Change 71(1–2):203–220. doi:10.1007/s10584-005-5933-0